

**INVESTIGATING THE COOLING PERFORMANCE OF ARTIFICIAL
SHADING DEVICES ON ENHANCING OUTDOOR THERMAL
COMFORT IN HOT HUMID CLIMATE**

BY

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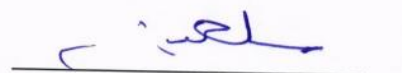
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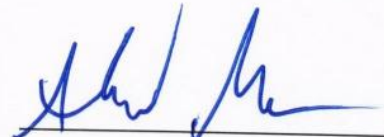
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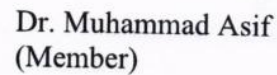

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To my beloved parents, for their endless support, guidance, and sacrifices—your belief in me has been my greatest strength. To my brother and sister, for your encouragement and unwavering presence.

May Allah bless you all with health, happiness, and protection.

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LIST OF ABBREVIATIONS

UHI	:	Urban Heat Island
KSA	:	Kingdom of Saudi Arabia
DMA	:	Dammam Metropolitan Area
BWh	:	Hot desert climates
PET	:	physiological equivalent temperature
GHGs	:	Green House Gases
IPCC	:	Intergovernmental Panel on Climate Change
CFD	:	Computational Fluid Dynamics
OTC	:	Outdoor Thermal Comfort
KFUPM	:	King Fahd University of Petroleum and Minerals
SVF	:	Sky View Factor
H/W	:	Height to Width Ratio
OTC	:	Outdoor Thermal Comfort
T_a	:	Air Temperature
V_a	:	Wind Speed
T_{mrt}	:	Mean Radiant Temperature

RH	:	Relative Humidity
PET	:	Physiologically Equivalent Temperature
SDGs	:	Sustainable Development Goals
SR	:	Solar Radiation
GI	:	Green Infrastructure
HDPE	:	Heavy Duty Polyethylene
PVC	:	Polyvinyl chloride
EPW	:	Energy Plus Weather File
MAE	:	Mean Absolute Error

ABSTRACT

Full Name : [Islam Mohamed Al-Hafiz Hassan Al-Tahir]
Thesis Title : [Investigating The Cooling Performance of Artificial Shading Devices on Enhancing Outdoor Thermal Comfort in Hot Humid Climate]
Major Field : [Architecture and City Design]
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The global rise in urban air temperatures significantly affects human health, thermal comfort, and the overall quality of life in cities. While urban greenery provides natural shading, artificial shading devices are a viable alternative where planting trees is not feasible. However, the impacts of artificial shading devices on enhancing the outdoor thermal environment are not well-explored. This study aims to assess the cooling performance of artificial shading devices on enhancing human thermal comfort in open spaces. Field measurements were carried out at the central square of King Fahd University in Dhahran city, Saudi Arabia, situated in a hot desert climate zone (BWh), during the summer of 2023. The objective was to assess the outdoor thermal environment and evaluate the cooling performance of three commonly used covering materials in Saudi Arabia namely, Cotton Canvas, HDPE, and PVC membrane. Subsequently, the microclimate model ENVI-met V5.0.0 was employed to analyze the effects of various shading scenarios on enhancing student thermal comfort. Various properties and configurations of shading devices were simulated, including four coverage ratios, double roofing scenario with three different sizes of air gap between the two layers and finally simulating the best-case scenario at three different heights to see the impact of the shading height. The study found that double roofing 100% staggered shading was the most effective scenario in terms of

reducing mean radiant temperature and physiological equivalent temperature (PET) by up to 20°C and 11°C, respectively. The cooling effects of shading devices increased with increasing in coverage ratios and the height of the shade had a negligible impact, except at the edge of the shaded area. The optimal height of the shade should be determined based on the height of the surrounding context. Furthermore, double roofing air gap with small size of 25 cm enhanced the shading device's cooling performance by acting as thermal insulation, increasing the PET index reduction by an average of 2.2°C. These results highlight the significant impact of artificial shading devices and provide a framework for improving outdoor thermal comfort in similar university plazas.

ملخص الرسالة

الاسم الكامل: إسلام محمد الحافظ حسن الطاهر

عنوان الرسالة: دراسة أداء التبريد لأجهزة التظليل الاصطناعي في تعزيز الراحة الحرارية الخارجية في ظل المناخ الحار الرطب.

التخصص: الهندسة المعمارية وتصميم المدينة

تاريخ الدرجة العلمية: مايو / 2024

في الآونة الأخيرة، ظهر تأثير الارتفاع العالمي في درجة حرارة الهواء في المناطق الحضرية بشكل كبير على صحة الإنسان وراحته الحرارية وجودة الحياة بشكل عام في المدن. في حين توفر المساحات الخضراء الحضرية تظليلاً طبيعياً، فإن أجهزة التظليل الاصطناعي تعد بديلاً قابلاً للتطبيق عندما لا تكون زراعة الأشجار ممكنة. بالرغم من ذلك، فإن تأثيرات أجهزة التظليل الاصطناعي على تعزيز البيئة الحرارية الخارجية لم يتم استكشافها بشكل جيد. تهدف هذه الدراسة إلى تقييم الأداء التبريدي لأجهزة التظليل الاصطناعي في تعزيز الراحة الحرارية للإنسان في الأماكن المفتوحة. تم إجراء قياسات ميدانية في الساحة المركزية لجامعة الملك فهد في مدينة الظهران بالمملكة العربية السعودية، الواقعة في منطقة مناخية صحراوية حارة، خلال صيف عام 2023. وكان الهدف هو تقييم البيئة الحرارية الخارجية وتقييم أداء التبريد لثلاثة مواد تغطية شائعة الاستخدام في المملكة العربية السعودية وهي: القماش القطني، والبولي إيثيلين عالي الكثافة (HDPE)، وغشاء PVC. تم نمذجة المناخ المحلي باستخدام برنامج ENVI-met V5.0.0 لدراسة وتحليل تأثيرات سيناريوهات التظليل المختلفة على تعزيز الراحة الحرارية للطلاب. تمت محاكاة خصائص وتكوينات مختلفة لأجهزة التظليل، بما في ذلك أربعة نسب تغطية، وسيناريو السقف المزدوج بثلاثة أحجام مختلفة للفقوة الهوائية بين الطبقتين، وأخيراً محاكاة السيناريو الأفضل على ثلاثة ارتفاعات مختلفة وذلك لدراسة تأثير الارتفاع لأجهزة التظليل. وجدت الدراسة أن التظليل المتدرج بنسبة 100% للأسقف المزدوجة كان السيناريو الأكثر فعالية من حيث تقليل متوسط درجة الحرارة الإشعاعية ودرجة الحرارة المكافئة الفسيولوجية (PET) بما يصل إلى 20 درجة مئوية و11 درجة مئوية على التوالي. وتزداد التأثيرات التبريدية لأجهزة التظليل مع زيادة نسب التغطية، وكان لارتفاع الظل تأثير ضئيل، إلا عند حافة المنطقة المظللة. يجب تحديد الارتفاع الأمثل للظل بناءً على ارتفاع السياق المحيط. علاوة على ذلك، عززت فجوة الهواء ذات السقف المزدوج والتي يبلغ حجمها 25 سم أداء التبريد لجهاز التظليل من خلال العمل كعزل حراري، مما أدى إلى زيادة انخفاض

مؤشر PET بمعدل 2.2 درجة مئوية. تسلط هذه النتائج الضوء على التأثير الكبير لأجهزة التظليل الاصطناعي وتوفر إطارًا لتحسين الراحة الحرارية الخارجية في ساحات الجامعات المماثلة.

CHAPTER 1

INTRODUCTION

1.1 General Background

Over the past 50 years, the world has experienced tremendous population growth and urbanization. The world's population has grown significantly from approximately 1.6 billion in 1900 to 7.6 billion in 2018, with more than 55 percent of them residing in urban areas (UN DESA, 2019). It is projected that by 2050, urban areas will be home to approximately 68% of the global population, marking a 13% rise from current levels (UN DESA, 2022). The natural environment, resources, and general well-being of people may all be significantly impacted due to population growth and urbanization.

Over the past century, greenhouse gas (GHGs) emissions have exhibited a consistent upward trend since the time of the Industrial Revolution (Lamb et al., 2021). The UN Intergovernmental Panel on Climate Change (IPCC) has established a clear correlation between greenhouse gases (GHGs) and the increasing global temperatures (Joos et al., 2001). The recent surge in greenhouse gases (GHGs), notably CO₂, has precipitated an undeniable trend of global warming, foreboding its persistence for the foreseeable future. According to the (IPCC, 2014), global temperatures have risen by 0.85 °C from 1880 to 2012. This temperature escalation carries particular significance for urban environments, where the phenomenon known as Urban Heat Island (UHI) exacerbates

the warming effect. Urban areas, as documented, tend to register higher temperatures than their rural counterparts, posing substantial risks to human health and amplifying pollution levels (George et al., 2007).

Scientific research has provided substantial evidence that the UHI effect can have negative impacts on both the natural environment and human health. The environmental impacts can include increasing energy consumption, air quality degradation, changes in precipitation patterns, stress on water resources, and accelerated deterioration of urban infrastructure (Piracha & Chaudhary, 2022). Moreover, increased urban air temperatures can have negative threats on the health and thermal comfort of urban residents in outdoor environments and reduce the livability of the city (Alcoforado & Andrade, 2008; Marzluff et al., 2008). Therefore, understanding the UHI effect and its impact on urban environments and on the residents of the cities becomes a crucial factor to develop sustainable and resilience cities that provide optimal thermal comfort for their inhabitants and improving livability and vitality in urban spaces (Huang et al., 2019; D. Lai et al., 2020).

Urban heat islands manifest in urban areas due to two primary factors: surface materials and urban geometry (Vujovic et al., 2021). There are many urban cooling strategies that can help to diminish the UHI effect and reduce the impacts of global warming on urban areas. For instance, shading and vegetation serve as effective means to reduce sun exposure, while light-colored materials help diminish sun absorption. However, the integration of vegetation and light-colored materials is not devoid of challenges. Trees, for instance, may restrict nighttime radiation cooling, and light-colored materials can lead to glare and discomfort.

The thesis endeavors to investigate the impact of outdoor shading devices on improving thermal comfort and urban airflows within an educational building environment situated in the hot-humid climate of Dhahran city, Saudi Arabia. This analysis entails an optimization process aimed at refining the proposed urban design for the central square of the KFUPM campus. In this study, ENVI-met served as the primary Computational Fluid Dynamics (CFD) software for simulating various shading scenarios for analysis. A validation study was conducted to assess the sensitivity and accuracy of ENVI-met in predicting microclimatic parameters within the urban environment.

1.2 Context of The Research Location

1.2.1 Saudi Arabia

Saudi Arabia, a country spanning vast deserts and diverse landscapes, is administratively divided into 13 provinces, each with its own unique characteristics and cultural heritage, Figure 1. Around a century ago, Saudi Arabia was primarily an isolated desert nation, with only the port of Jeddah and a few settlements surrounding Riyadh serving as small commercial hubs. However, since then, Saudi Arabia has undergone rapid transformation from an agriculturally based and underdeveloped economy to a modern nation. This transition has led to significant development and urbanization across its cities, accompanied by the establishment of advanced infrastructure (Al-Rasheed, 2010). The Kingdom of Saudi Arabia is renowned for possessing the largest oil reserves globally and holds the title of the world's largest oil exporter.

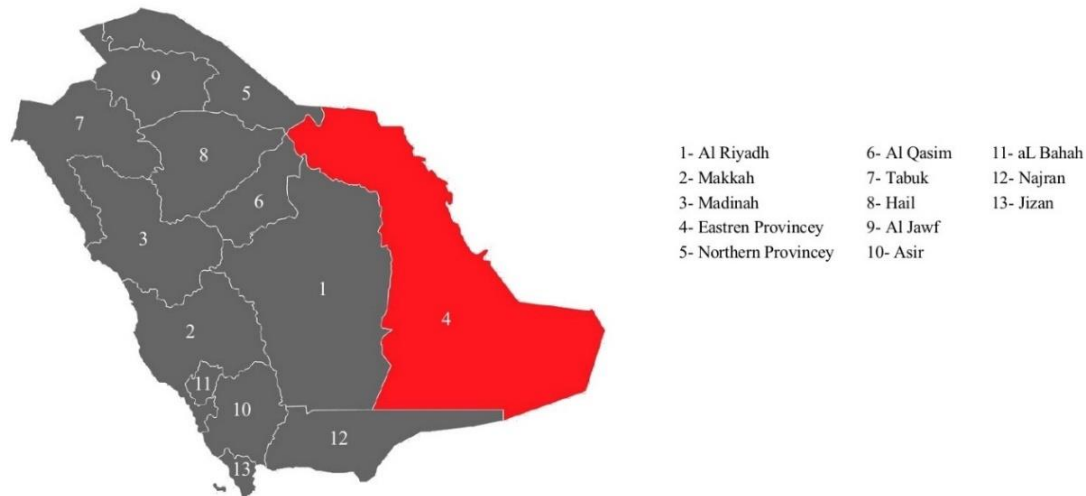


Figure 1: Provinces in Saudi Arabia.

Source: Author

1.2.2 Saudi Arabia population growth and urbanization process

Saudi Arabia ranks as the third largest country in the Middle East, covering an area of 2,149,690 square kilometers. It is bordered by the Red Sea to the west and the Arabian Gulf to the east. According to the Central Department of Statistics and Information in 2016, the population of Saudi Arabia stands at approximately 36.41 million, with an estimated 13.4 million non-Saudi residents.

As reported in the "World Urbanization Prospects, 2014," Saudi Arabia's urban areas are experiencing rapid urbanization, with the urban population nearly tripling from 9.32 million in 1980 to 29.8 million in 2014. Furthermore, this trend of population growth and rapid urbanization is projected to continue, reach 39.32 million in 2030 with up to 90% living in metropolitan areas, Figure 2. A significant portion of this substantial urban population growth in Saudi Arabia is expected to take place in major metropolitan areas such as Riyadh, Jeddah, Mecca, Taif, Medina, the Dammam area,

and Al-Ahsa, see Figure 3. This influx of people is likely to worsen urban challenges within these cities.

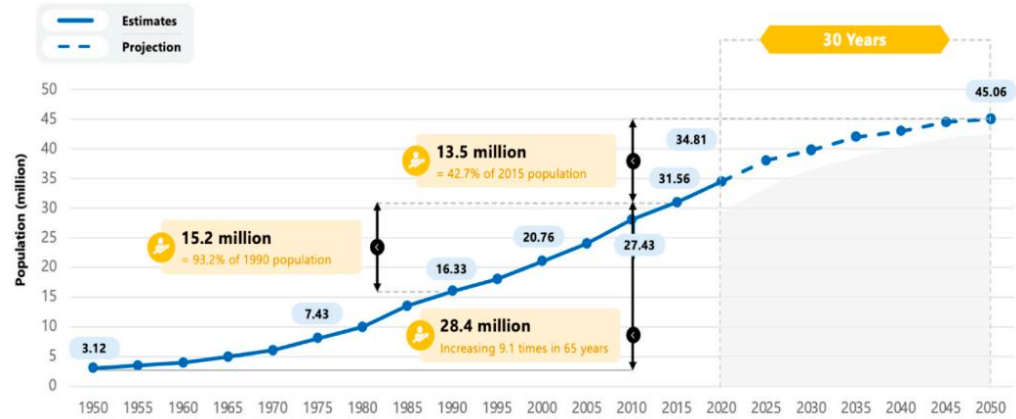
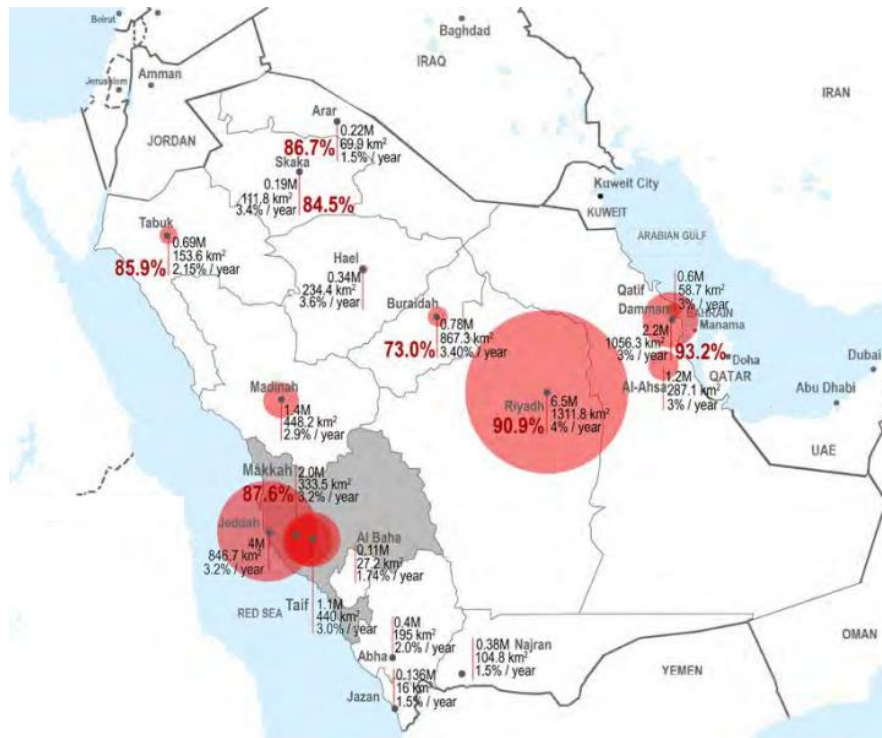


Figure 2: Population Growth in Saudi Arabia increase between 1950 and 2050.

Source: (Almulhim & Cobbinah, 2023) data extracted from UN-Habitat 2019; General Authority for Statistics 2022.



Saudi Arabia predominantly has a desert climate, except for the southwestern region, which has a semi-arid climate. Summers in the central region are extremely hot and dry, with temperatures ranging from 27 °C to 43 °C inland and 27 °C to 38 °C along the coast, Figure 4. Nighttime temperatures across the country tend to drop significantly. Conversely, in the northern regions bordering Yemen to the southwest, the climate is milder with moderate temperatures and increased humidity due to the influence of monsoons from the Indian Ocean. Vegetation mainly consists of small herbs and shrubs adapted to low water requirements, reflecting the arid desert conditions. Nonetheless, the southwestern part of Saudi Arabia features areas adorned with grass and trees. The wildlife includes various species such as sand rats, hyenas, and wolves, along with diverse bird species like eagles, falcons, and hawks.

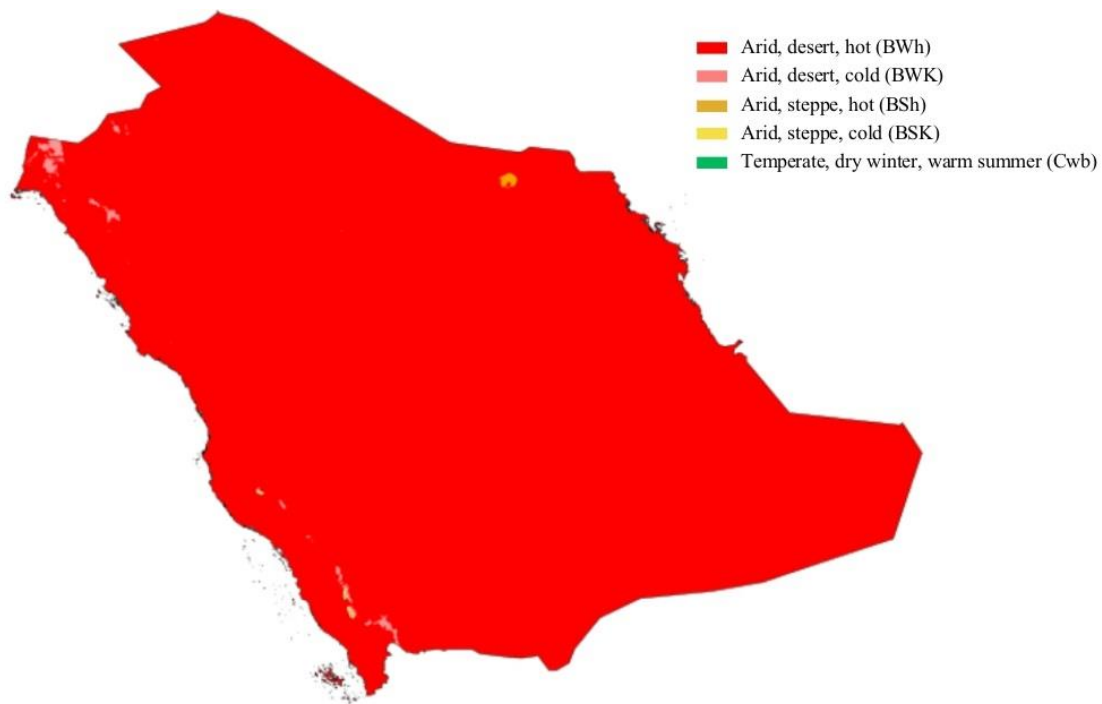


Figure 4: Köppen–Geiger climate classification map for Saudi Arabia.

Source; (Beck et al., 2018).

1.2.3 Dammam Metropolitan Area

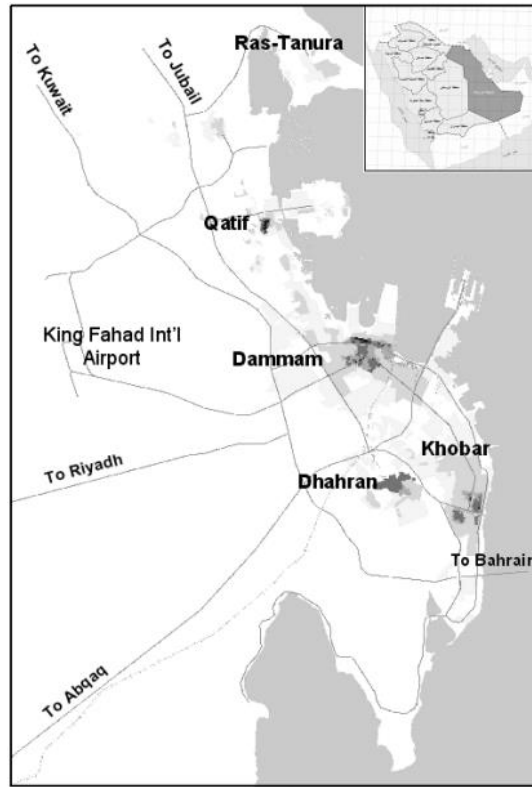


Figure 5: Dammam Metropolitan Area: Components and external connections.

Source; (Aboukorin et al., 2015).

The Dammam Metropolitan Area (DMA), situated in the Eastern Province of Saudi Arabia, stands as one of the pivotal urban centers within the Kingdom. Renowned for its strategic location along the Arabian Gulf coast, DMA serves as a vital hub for commerce, industry, and culture. With rapid urbanization and development initiatives underway, DMA has witnessed significant growth, both in population and infrastructure, in recent years. This metropolitan area encompasses not only the city of Dammam but also neighboring cities such as Khobar and Dhahran, collectively forming an interconnected urban network, see Figure 5. As a key driver of economic

activity and innovation, DMA plays a crucial role in shaping the socio-economic landscape of the region.

The population of the Dammam Metropolitan Area (DMA) has shown significant growth over the past few decades. In 1974, the population stood at 0.365 million inhabitants, which increased to 1.3 million in 1993, and further rose to 1.75 million in 2004, reaching 1.8 million by 2010. This represents a doubling of the population five times over a span of 35 years, from 1975 to 2005. Projections indicate that if current population growth rates persist, the population of DMA is anticipated to range between 3.25 and 3.62 million people by 2040. This would entail an increase of approximately 1.5 to 1.9 million people over the next 25 years (Aboukorin et al., 2015). The rapid urbanization observed in DMA has led to significant unsustainable development practices. One of the most pressing issues is the swift depletion of agricultural lands, coupled with the degradation of marine ecosystems along the shores of the Arabian Gulf caused by extensive landfilling activities in the Gulf waters, Figure 6.

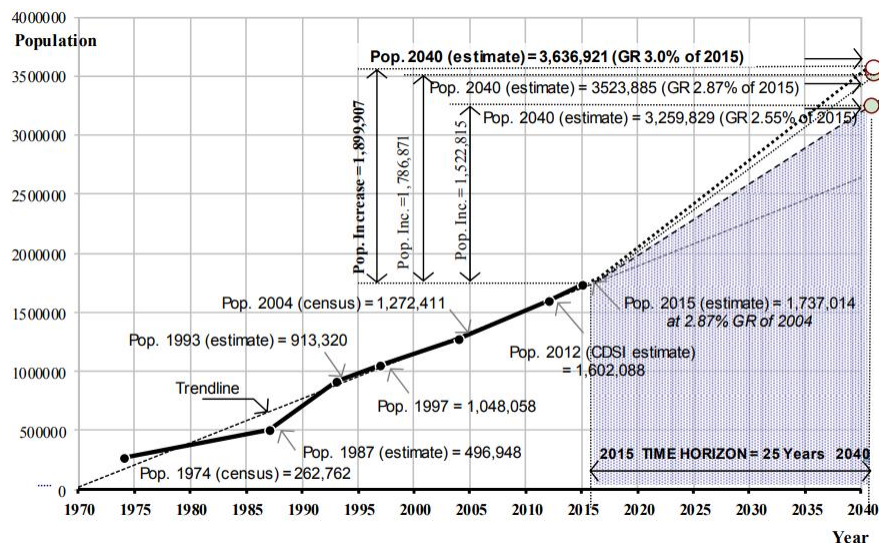


Figure 6: History and projection of population growth in DMA region: 1974-2030.

Source (Aboukorin et al., 2015).

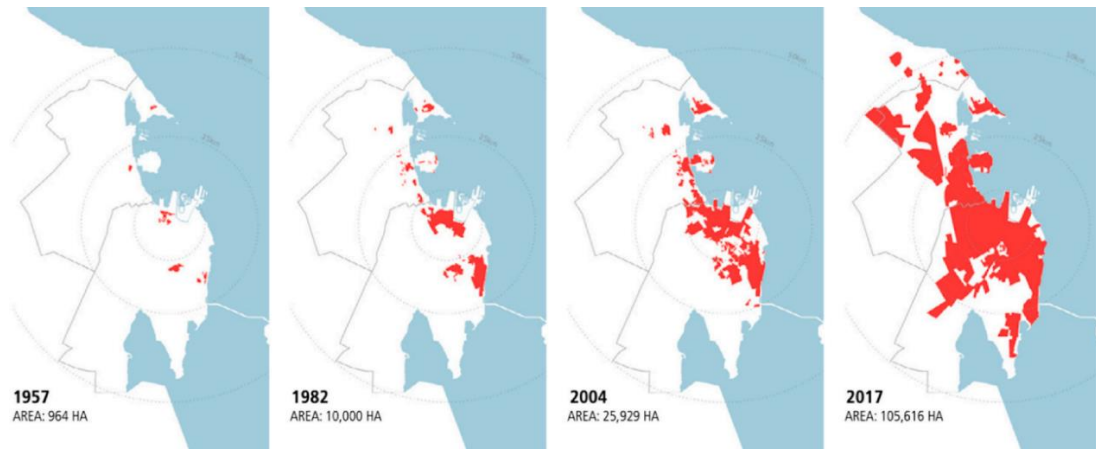


Figure 7: Urban growth stages for Dammam metropolitan area.

Source: (UN-Habitat, 2019).

As shown in Figure 7, the rapid urban growth in Dammam City has led to a myriad of environmental challenges, notably stemming from pollution generated by the oil industry, and increased local consumption (Alhowaish, 2015). The industrial activities associated with oil extraction and processing contribute significantly to air, water, and soil pollution, posing risks to both human health and the surrounding environment. Additionally, the rise in local consumption, driven by urbanization and population growth, has led to increased waste generation and resource depletion, further exacerbating pollution levels and environmental degradation (Alwadei, 2022). Moreover, the urban heat island effect has become increasingly pronounced in Dammam City, with the expansion of built-up areas and reduced green spaces leading to higher temperatures and reduced air quality, particularly during the hot summer months. (Rahman et al., 2017) discovered that the average temperature within the built-up area in Dammam increased from 36.42 °C in 1990 to 44.12 °C in 2014, Figure 8. Addressing these environmental challenges is imperative for promoting sustainable

development and safeguarding the well-being of both current and future generations in Dammam City.



Figure 8: Areas at risk of the UHI effect, DMA.

Source: (UN-Habitat, 2019).

1.3 Problem Statement

Outdoor areas have a vital role in the creation of neighborhoods that are both sustainable and comfortable to live in. They have the ability to enhance the physical and mental well-being of individuals and promote a sense of community. In the first place, outdoor areas like parks, communal gardens, and public squares offer opportunities for community members to gather, socialize, and establish strong relationships with each other. These spaces can also serve as venues for organizing events (Mousavi & Branch, 2016). In addition, outdoor spaces promote physical

activity by providing opportunities for recreational activities like walking, running, cycling, and playing sports, which can improve overall health and well-being (Ward Thompson, 2013). These activities promote a healthy lifestyle and help prevent chronic diseases (Reyes-Riveros et al., 2021). Moreover, well-designed outdoor spaces can attract businesses and visitors to their context, boosting the local economy and creating jobs (Clawson & Knetsch, 2013).

The utilization of the outdoor spaces in the Gulf countries which are located in the Middle East is influenced by two main factors namely: climate, culture (Silva & Akleh, 2018). The climate has a notable influence on shaping the utilization of outdoor areas in the Gulf nations. In the Gulf countries, the climate is characterized by arid and hot desert conditions, with temperatures frequently surpassing 40 °C (104 °F) in the summertime. As a result, outdoor activities are often limited to early morning or late afternoon hours, and air-conditioned indoor spaces are preferred during the hotter parts of the day.

Organizing events at night which are considered outside of formal working hours creates a lot of challenges for all participants and audiences. Outdoor thermal environment during the daytime is considered one of the major factors that determine the success of the outdoor spaces. The phenomenon of the UHI effect has a major impact on the quality of outdoor environments by altering their thermal conditions. During the last ten years, sustainable urban design studies have become increasingly popular, particularly since researchers have linked global warming to UHI due to its greenhouse effect and rise in urban temperatures (Nasrollahi et al., 2020). Most of the international scientific research focused on the physical characteristics of the urban

area (orientation, SVF, H/W ratio, finishing material albedo) and shading from trees as the most effective urban cooling strategies. All these strategies are more feasible to adopt during the design and planning phase of an urban canyon, making it challenging to implement them in an already existing one. On the other hand, outdoor shading devices offer a practical solution as an alternative to urban greenery when planting trees in urban areas is not feasible. Despite the potential benefits of outdoor shading devices for enhancing thermal comfort and reducing energy consumption, they are not widely used in many urban areas. This lack of implementation is leading to uncomfortable conditions for users, particularly in areas with high solar radiation, and contributing to the (UHI) effect. Therefore, it is crucial to study and understand the impact of using shading devices and promote their implementation to improve users' thermal comfort and mitigate the negative effects of urban heat islands.

1.4 Research Aim and Objectives

The study aims to maximize the use of outdoor spaces during non-peak summer months by investigating the effect of outdoor shading devices on enhancing the OTC in the hot desert climate of Saudi Arabia. To achieve this goal, the following objectives will be implemented:

- Review the literature to gain a good understanding of the significance of human thermal comfort in outdoor spaces, different factors affecting thermal comfort in outdoor areas, and potential urban cooling strategies that can be implemented to improve outdoor thermal comfort.

- Evaluate the cooling performance for three covering materials: Cotton Canvas, HDPE, and PVC membrane using field measurement observation setting.
- Develop a simulation model for the existing site setting including the experimental work setup to validate the simulation result with the experimental work.
- Run different shading scenarios covering the hall site. Scenarios includes different materials, four coverage ratios, double roofing scenario with three different sizes of air gap between the two layers and finally simulating the best-case scenario at three different heights.
- Analyze the results and recommend the most effective scenario for future urban development to mitigate the thermal heat stress on the users of outdoor open spaces.

1.5 Significance of the Research

The majority of international research that investigated the (OTC) focused on the Physical attributes of the urban design such as (SVF), buildings (H/W) ratio, and surface materials as key indicators to determine the microclimate of the area (Andreou, 2013; Tan et al., 2016). Other studies examined the effect of street orientation, and urban canyon forms on outdoor thermal comfort (Achour-Younsi & Kharrat, 2016; Johansson et al., 2013). Furthermore, numerous studies have demonstrated the potential of using finishing materials with high albedo to reflect solar radiation, enabling heat to dissipate back into the atmosphere and reducing the UHI effect (Kyriakodis & Santamouris, 2018; Santamouris, 2013).

All these strategies are considered successful approaches to mitigate the UHI effect and maintain the (OTC), however implementing these strategies only can be feasible at the first stage of the urban design process and some of them are suitable for certain climate conditions. It is very difficult to adopt these strategies for existing urban canyons. For this reason, the study will examine other types of urban cooling strategies with a concentration on investigating the effect of artificial shading devices on enhancing the OTC.

This study contributes to the field of environmental design, urban landscape and urban configuration fields, aiming to enhance the outdoor microclimate with the help of simple passive solutions focusing on the aspect of shading strategies and more specifically on the use of artificial shading devices which can be implemented without altering the footprint of existing context. The research findings are expected:

- To have a noticeable impact on enhancing the outdoor thermal environment if implemented in similar urban plazas throughout the city, which consequently optimize and encourage the use of city's urban plazas.
- To Provide insights where improvements need to be made to mitigate the UHI effect and enhance the OTC to get the benefit of using urban plazas for different activities and to design the outdoor urban space not just for now, but also for future climate change.
- To Help policymakers, urban planners, and architects in the professional field in retrofitting outdoor urban spaces and take suitable decisions when designing a responsive and sustainable outdoor landscape in hot-humid regions.

1.6 Research Limitations

The present study has certain limitations that should be noted. The scope of this research is confined to hot desert urban areas, such as Dhahran city, with a specific focus on the climate of the Eastern province in the Kingdom of Saudi Arabia. This climate is characterized as hot humid in summer, and cold humid in winter. Future research can focus on studying other locations in Saudi Arabia, for example, the central province, as well as northern, southern, and western provinces. However, the research will propose a methodology that can be utilized to evaluate the OTC of various cities worldwide. The Research focuses on investigating the potential of artificial shading devices with different materials, different coverage percentages and different heights on mitigating the UHI effect and work to enhance the OTC. Future research can explore the effect of artificial shading devices and their contribution to improve buildings' energy efficiency or improving the visual comfort in outdoor spaces. On the other hand, this study neglected other heat mitigation strategies like changing building orientation, height to street width (H/W), or using finishing material with a high albedo and focused artificial shading strategies as a suitable option that can be applied to the existing urban environment. Maybe future studies can merge outdoor shading devices strategies and other urban cooling strategies.

1.7 Research Structure

As shown in Figure 9, the research is structured into the following sections with the objective of mitigating the UHI effect, enhancing outdoor thermal comfort (OTC), and

devising design strategies for creating sustainable outdoor spaces on the university campus:

Chapter 1: starts with the theoretical section by reviewing the global institutions concerns, research paper and assess the reflection of global issues at the context of the study (Kingdom of Sudi Arabia) to identify the study problem which was determined by: " There is a need to investigate the impact of artificial shading devices patterns on mitigating the UHI effect and assessing the colling performance of it on enhancing the local and microclimate condition as well as thermal comfort of Dhahran City. On the basis of that, the aim and hypothesis of the study are placed. Finally, the study's limitations are presented, outlining the potential boundaries and the structure of the study.

Chapter 2: performs a literature review of scientific papers about the topic of the study. This chapter is divided into five sections which were started by introducing the importance of urban public spaces, then introducing the urban microclimate as one of the main factors that affecting the utilization of outdoor spaces. Furthermore, identifying the major environmental challenges that affect the effectiveness of outdoor space and with focus on the issue of the UHI. Moreover, exploring the topic of outdoor thermal comfort, Finally, discussing in detail the urban cooling strategies with focus on the shading strategies. This chapter reveals broad knowledge of the findings of similar previous research.

Chapter 3: starts by critically assessing different research methodologies employed in prior literature that investigated related topics. This involves a thorough evaluation of the advantages and disadvantages of each methodology to identify the most appropriate

approach for conducting the current study. Additionally, the chapter determines the most suitable simulation program, measurement tools, and resources needed for the research. The study commences with the collection of metrological data for the selected site and establishing additional information about the case study.

Chapter 4: contains Data analyses and result; the data is analyzed using Envi-met software to model the existing baseline scenario, and then starting to run the alternative scenarios, the chapter also contains the results and findings of the different proposed scenarios (statistically and graphically).

Chapter 5: addresses discussion and conclusion, in order to validate the significance of strategies in each scenario, findings from the previous chapter undergoes through systematic analysis and interpretation based on pre-established criteria outlined in the literature review. Furthermore, the comparison between existing and proposed scenarios is performed. Drawing on the findings of the previous chapter, the conclusion of this study offers recommendations for future actions that can be taken to achieve the desired goals.

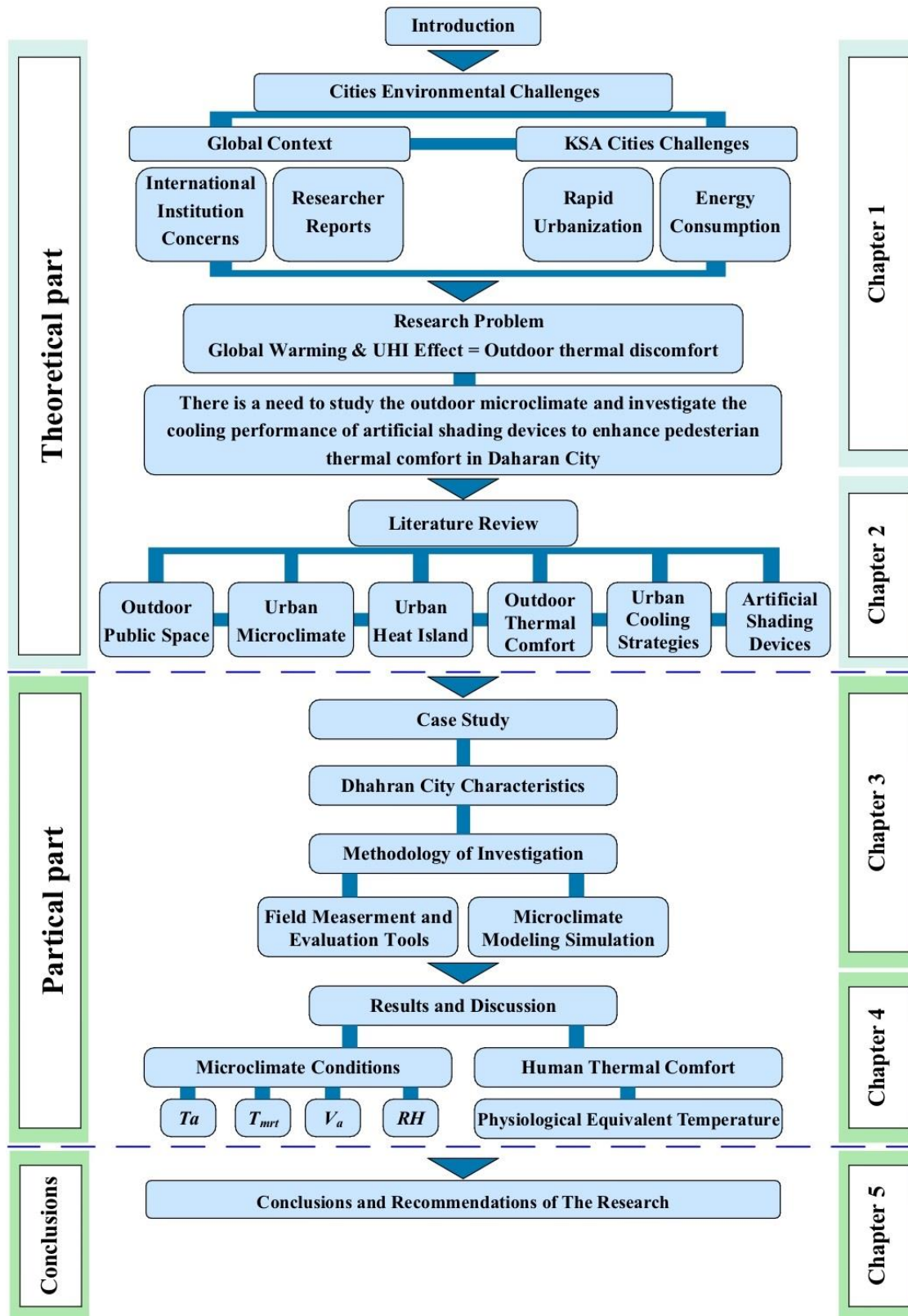


Figure 9: Research Methodology workflow.

CHAPTER 2

LITERATURE REVIEW

The chapter provides an extensive examination of literature concerning outdoor thermal stress and users comfort, structured into five key sections. It begins by elucidating the significance of outdoor public spaces before delving into an exploration of the urban microclimate. Next, it highlights the primary environmental challenge in urban areas, focusing on the Urban Heat Island (UHI) phenomenon. Subsequently, it discusses the importance of outdoor thermal comfort and investigates various urban cooling strategies. Additionally, it covers thermal indices for both indoor and outdoor comfort, with particular emphasis on the physiological equivalent temperature (PET) as a crucial metric for assessing outdoor thermal comfort.

2.1 Outdoor Public Spaces

Outdoor public spaces refer to the open areas within urban environments that are accessible to the public and intended for outdoor activities, recreation, and social interaction (Gehl, 2013). These spaces can vary widely in size, design, and purpose, ranging from small neighborhood parks and plazas to large urban parks, waterfronts, and green corridors. Urban outdoor spaces serve as vital components of the urban fabric, providing opportunities for relaxation, exercise, and leisure, as well as fostering community engagement and connection with nature (Reyes-Riveros et al., 2021). These spaces play a crucial role in promoting physical and mental well-being among urban residents by offering opportunities for outdoor exercise, relaxation, and socialization (Lestan et al.,

2014). They also contribute to environmental sustainability by providing green infrastructure that helps mitigate urban heat island effects, reduce air pollution, and support biodiversity (Dover, 2015; Menon & Sharma, 2021).

The design and management of urban outdoor spaces are important considerations in urban planning and development, as they influence the overall livability and quality of life in cities (Tsitoura et al., 2017). Well-designed outdoor spaces incorporate elements such as seating, lighting, landscaping, and amenities to enhance usability, safety, and aesthetic appeal. Moreover, they are often designed to be inclusive and accessible to people of all ages, abilities, and backgrounds. In recent years, there has been growing recognition of the importance of urban outdoor spaces in promoting public health, social equity, and environmental sustainability. As cities continue to grow and densify, the preservation and enhancement of urban outdoor spaces become increasingly critical for creating vibrant, healthy, and resilient urban communities.

Due to rapid urbanization, population growth, and climate change, outdoor public spaces face various challenges that can hinder their effectiveness and inclusivity (Gehl, 2013). The main challenges facing outdoor urban spaces encompass various aspects, including environmental, social, and infrastructural factors (Orsetti et al., 2022). One significant challenge is the limited availability and accessibility of green spaces within urban areas, often resulting from rapid urbanization, land use changes, and competing demands for space. Social challenges, including safety concerns, perceptions of crime, and lack of inclusive design features, can deter individuals from utilizing outdoor spaces, particularly vulnerable and marginalized communities (Valentine, 2017). Environmental challenges such as air and noise pollution, as well as extreme weather events exacerbated by climate

change, pose significant threats to outdoor urban spaces, and impact the health and well-being of users (Nouri et al., 2018).

To overcome these obstacles, holistic approaches that integrate environmental sustainability, community engagement, equitable access, and proactive urban planning are essential for creating vibrant, inclusive, and resilient outdoor urban spaces. The research addressing the environmental challenges facing outdoor public spaces, with focus on studying the urban microclimate and the issue of the outdoor thermal comfort to create resilient, inclusive, and environmentally sustainable outdoor public spaces that enhance the quality of life for all residents.

2.2 Urban Microclimate

Urban areas are characterized by unique climatic conditions known as urban climates, which are influenced by various factors such as human activities, infrastructure, and the built environment (Oke et al., 2017). Meteorologists developed the concept of microclimate during the first half of the twentieth century. Subsequently, architects and urban planners began to embrace this concept more widely in the latter half of the same century. Urban climatic studies are frequently conducted at three scales: mesoscale, local scale and microscale in descending order (Oke, 1997), see Figure 10.

A. Micro Scale:

The micro scale of urban microclimate refers to the smallest level of spatial analysis, typically focusing on phenomena occurring within a few meters to tens of meters. At this scale, microclimatic conditions are influenced by factors such as individual buildings,

vegetation, and surface materials. Examples of microclimatic phenomena at this scale include localized temperature variations around buildings, wind patterns in street canyons, and variations in solar radiation exposure on different surfaces.

B. Meso-Scale:

The meso-scale of urban microclimate encompasses a larger spatial range, typically ranging from tens of meters to several kilometers. At this scale, the interactions between various microclimatic elements and the broader urban environment are examined. Meso-scale phenomena include the formation of urban heat islands, air pollution dispersion patterns, and the influence of land use on regional climate conditions. Understanding meso-scale dynamics is crucial for addressing urban climate challenges and implementing effective mitigation strategies.

C. Canyon Scale:

The canyon scale of urban microclimate focuses specifically on the microclimatic conditions within street canyons formed by tall buildings on either side of a street. At this scale, factors such as building height, width-to-height ratio, and orientation influence solar radiation exposure, wind flow patterns, and thermal comfort levels within the canyon. Canyon-scale studies aim to optimize urban design and planning to enhance comfort, mitigate heat stress, and improve air quality within urban environments.

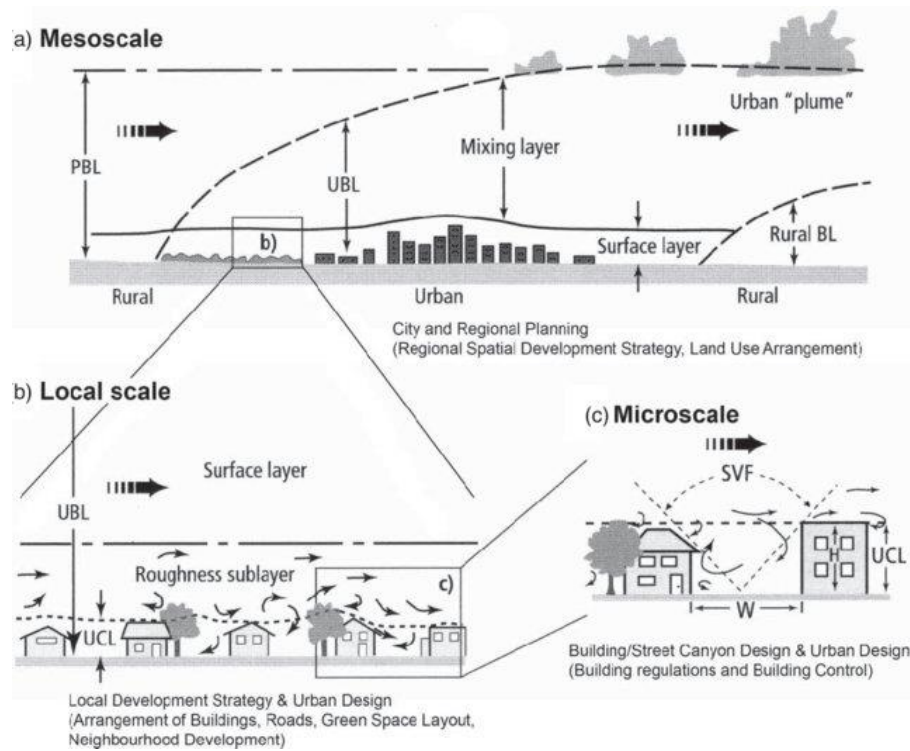


Figure 10: The different dimensions of urban climate and their associations with architectural and urban planning dimensions. Source: Modified from (Oke, 1997).

Microclimates refer to the climatic conditions occurring at lowest layer of the Earth, contrasting with the larger scales of macroscale and mesoscale (Williams, 2007), Figure 10. Urban microclimate has a direct impact on the quality of life of urban residents (Li et al., 2022). Urban microclimate studies play a pivotal role in contemporary urban planning and design due to their multifaceted importance and wide-ranging applications. By understanding the microclimatic intricacies, professionals can optimize urban layouts, green spaces, and building configurations to enhance thermal comfort and mitigate heat stress (Erell et al., 2012). Additionally, urban microclimate studies play a vital role in safeguarding public health and well-being, particularly in the context of rising temperatures and more frequent heatwaves attributed to climate change. Through targeted interventions such as the creation of shaded spaces and cooling zones, these studies contribute to the

reduction of heat-related illnesses and fatalities, thereby promoting overall community resilience (Salata et al., 2017). Furthermore, urban microclimate knowledge informs the design of energy-efficient buildings and infrastructure, facilitating progress towards environmental sustainability and the reduction of greenhouse gas emissions (S. Liu et al., 2023).

Investigating urban microclimates involves employing various methodologies to understand their dynamics and implications for urban planning and management. Historically, the study of urban microclimates relied heavily on observational methods (Blocken, 2015). There are four main methods for studying urban microclimates: field measurements and meteorological observations (Bernard et al., 2017), wind tunnel experiments (Uehara et al., 2000), computational fluid dynamics (CFD) simulations (Antoniou et al., 2019), and finally the new emerging techniques that are relying on analyzing data through artificial intelligence and machine learning (Paper Middel et al., 2016). Figure 11 provides a timeline illustrating the evolution of methods used in urban microclimate research.

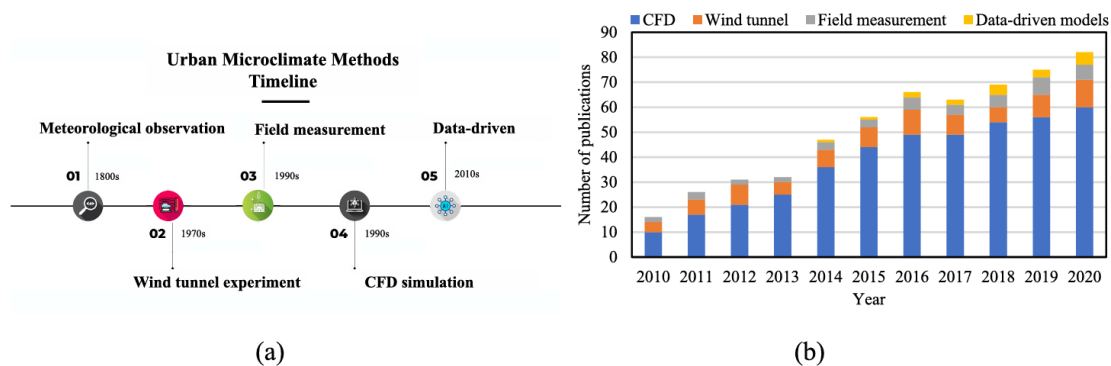


Figure 11: (a) Timeline for urban microclimate methods (b) Number of publications from 2010 to 2020 by the methods.

Source: (S. Yang et al., 2023).

Four primary areas are associated with urban microclimate: urban wind environment, urban thermal environment, building energy consumption, and pollutant dispersion. Figure 12 illustrates a rising trend in research articles on urban microclimate topics from 2010 to 2020. Many studies prioritize isothermal conditions when investigating urban wind comfort, wind comfort, and wind-driven rain. Notably, urban thermal comfort and urban heat islands emerge as prominent subjects in urban microclimate research (S. Yang et al., 2023).

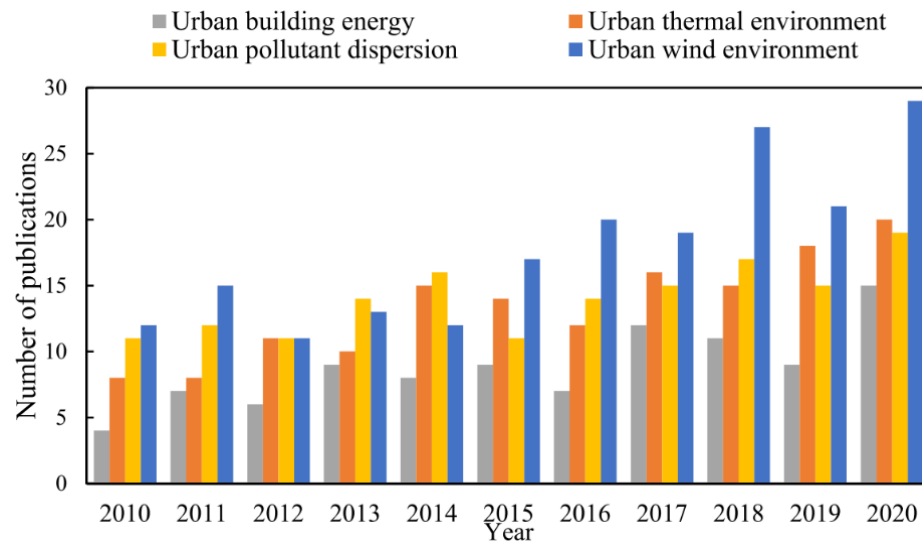


Figure 12: Studies related to urban microclimate classified by different issues.

Source: (S. Yang et al., 2023).

2.3 Urban Heat Island Effect

In 1833, Luke Howard was the first environmental scientist to present proof that cities had higher air temperatures than their surrounding areas. Studies have shown that metropolitan centers can have higher air temperatures than suburbs by up to 3 °C (Howard, 1833), Figure 13. One of the biggest environmental challenges facing metropolitan areas is the Urban

Heat Island (UHI) Effect which refers to the phenomenon in urban climatology characterized by higher temperatures in urban areas compared to their rural surroundings.

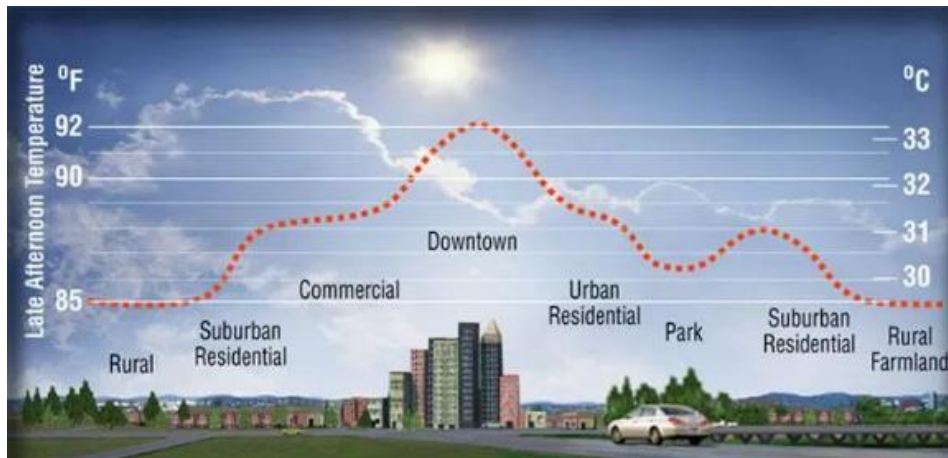


Figure 13: The temperature profile in different areas, with the formation of the UHI.

Source (R.Met.S, 2013).

The intensity of the UHI effect is depends on a) The gradual loss of green cover b) Urban morphology (Dimoudi et al., 2013), c) Thermal characteristics of the materials that were used in pavements and on the facade of buildings (Santamouris & Yun, 2020; Senevirathne et al., 2021), and d) Anthropogenic heat emitted by burning processes, such as road traffic, space heating & cooling, and industries (Du et al., 2016).

The UHI effect has far-reaching implications for environmental quality, public health, energy consumption, and urban sustainability (Gonzalez-Trevizo et al., 2021). Studies have shown that UHI can exacerbate heat-related illnesses, increase energy demands for cooling, and elevate air pollution levels. Additionally, UHI can disrupt local weather patterns, exacerbate extreme heat events, and amplify the effects of climate change through the

occurrence of increasingly extreme summertime heat waves (Farhadi et al., 2019), Figure 14.

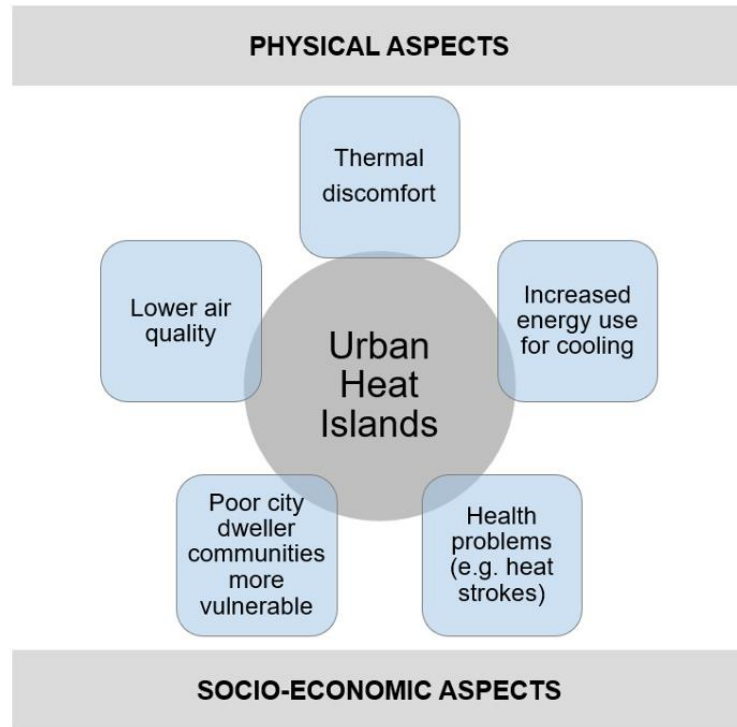


Figure 14: Aspects and Impacts of the UHI effects.

Source: (Filho et al., 2021).

Understanding the mechanisms driving the UHI effect and its impacts is crucial for developing effective mitigation strategies and promoting resilient urban planning and design practices. By integrating insights from multidisciplinary research, including climatology, urban planning, and public health, policymakers and urban planners can implement strategies to mitigate the UHI effect and create more livable and sustainable urban environments.

2.4 Outdoor Thermal Comfort

The Urban Heat Island (UHI) effect is a microclimatic phenomenon predominantly impacting urban areas. It results in notable temperature rises within the local microclimate and has the potential to exacerbate heat waves. The intensity of UHI not only leads to thermal discomfort but also diminishes overall quality of life. In the era of climate change, the significance of thermal comfort has risen substantially, emerging as a critical consideration in design decisions for both outdoor and indoor environments. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), defines thermal comfort as ‘the state of mind, which expresses satisfaction with the thermal environment’ (ASHRAE, 2017). The imperative for conducting an outdoor thermal comfort assessment arises from the significant statistic that 90% of individuals' time is typically spent indoors and this can sometimes be due to uncomfortable outdoor thermal conditions (D. Lai et al., 2020). The difference between indoor and outdoor thermal comfort lies primarily in the environmental conditions and the factors influencing human comfort in each setting (S. Liu et al., 2022). Outdoor Thermal Comfort (OTC) is a relatively new area of research compared to thermal comfort studies for interior spaces. Outdoor thermal comfort refers to the subjective sensation of comfort or discomfort experienced by individuals in outdoor environments based on prevailing weather conditions (Dzyuban et al., 2022). The OTC is influenced by various factors including ambient air temperature, humidity levels, wind speed, solar radiation (including direct sunlight and shade), the presence of natural elements (e.g., vegetation, water bodies), and the urban form (e.g., building density, layout, and orientation) (Khan & Azari, 2021). Furthermore, Personal factors including activity level and metabolic rate are considered as a critical factor in

determining both indoor and outdoor thermal comfort (Amindeldar et al., 2017). Outdoor open spaces with thermal discomfort and less livable setting, can lead to decrease the utilization of outdoor spaces, which can have a serious impact on community health and well-being. Therefore, mitigating the UHI effect and improving OTC have become critical priorities for urban planning and sustainability.

2.5 Relationship Between Outdoor Climate and Thermal Comfort in Outdoor Environments

In recent years, there has been a notable focus on investigating the impact of outdoor climatic parameters, particularly air temperature (T_a), wind speed (V_a), and mean radiant temperature (T_{mrt}), on outdoor human thermal comfort. These studies aim to improve comfort levels in outdoor environments by understanding how these climatic factors influence human perception and comfort (Aljawabra, 2014; Andreou, 2013; Banerjee et al., 2020). While air temperature (T_a) has been recognized as the primary determinant of outdoor thermal comfort, it is crucial to consider other influential factors such as RH, V_a , T_{mrt} as well (D. Lai et al., 2020). Therefore, recognizing the significance of various outdoor climatic parameters has become essential, as no single thermal climatic indicator can fully capture the complexity of outdoor thermal comfort (T. P. Lin, 2009).

Considering urban morphology, factors such as wind speed (V_a) and solar radiation (SR) also play crucial roles in influencing human thermal comfort and adaptation (Herrmann et al., 2011). Several studies have highlighted solar radiation (SR) as the most significant factor influencing human thermal sensation in outdoor spaces, as demonstrated by research

conducted by (Elnabawi & Hamza, 2020; W. Yang, Wong, & Jusuf, 2013) when compared to variables such as wind speed and relative humidity. (Yin et al., 2012) observed that excessive (SR) during summer months led to a decrease in the thermal comfort levels of individuals, prompting them to adjust their adaptation strategies in response to intense solar radiation.

The wind also plays a significant role in enhancing thermal sensation and comfort, particularly during heat-stressed seasons (Abreu-Harbich et al., 2014). However, the impact of wind speed on thermal comfort varies depending on the climatic characteristics of different regions. For instance, increasing (V_a) may lead to discomfort in regions with strong winds and low temperatures, such as northern climates, as noted by (Roshan et al., 2020). Conversely, in environments characterized by intense sunshine during cold seasons, a decrease in wind speed can result in an improvement in thermal sensation outdoors, as observed by (K. Liu et al., 2022). Relative humidity (RH) is another important factor influencing thermal comfort outdoors. High humidity levels can impede the body's ability to cool itself through sweating, leading to feelings of discomfort and perceived heat stress. On the other hand, low humidity levels can exacerbate dryness and discomfort, particularly in arid environments (Djamila et al., 2014).

The mean radiant temperature (T_{mrt}) is recognized as a primary factor influencing the thermal response of individuals to their surrounding environment. This parameter is integral not only in indoor settings but also in outdoor contexts, as emphasized by numerous studies (Guo et al., 2020; A. Lai et al., 2017). These investigations have highlighted the significant impact of T_{mrt} on outdoor thermal comfort, emphasizing the importance of both short-wave and long-wave radiation fluxes from the surrounding

environment. High T_{mrt} values, often associated with exposure to direct sunlight and the absorption of heat by surrounding surfaces, can contribute to discomfort and thermal stress, particularly during hot weather conditions. Conversely, low T_{mrt} values, resulting from shaded areas or reflective surfaces, may enhance thermal comfort by reducing the amount of heat absorbed by individuals. Researchers employ various methodologies, including field measurements, numerical simulations, and thermal comfort surveys, to assess the impact of T_{mrt} on human well-being and develop effective strategies for mitigating thermal discomfort in outdoor spaces (Gál & Kántor, 2020; Naboni et al., 2017). By integrating insights from these studies, designers and planners can create outdoor environments that prioritize thermal comfort and promote the health and satisfaction of individuals.

2.6 Development of Outdoor Thermal Comfort Indices

Given that "comfort" is inherently subjective and reliant on human sensation, numerous studies, encompassing both qualitative and quantitative approaches, have been conducted to comprehensively evaluate thermal comfort levels. In terms of qualitative approaches, (Gehl, 2011) conducted a study on the influence of microclimate by observing the distribution of people in both shaded and sunny areas. His findings underscored the significant impact of local sunny conditions on people's decisions to remain in a particular space or not. (Whyte, 1980) employed time-lapse photography to observe people's utilization of public spaces, revealing that shading plays a pivotal role in shaping usage patterns. Both studies adopt a behavioral perspective, employing straightforward measurement techniques and observation methodologies. On the other hand, advancements in technology and the availability of sophisticated analysis methods have prompted a surge

in studies aimed at assessing comfort levels and developing indicators to quantitatively measure comfort. These indicators often concentrate on the thermo-physiological aspect of comfort sensation, analyzing human perception of the environment. Going beyond mere temperature considerations, these thermal indicators typically incorporate various environmental parameters, including relative humidity, wind conditions, and the thermal exchange between individuals and their surroundings. Table 1 displays a summary of the predictive models that are used to predict thermal stress in outdoor environments that are commonly used in literature.

Table 1: Outdoor thermal comfort indices.

Source: Author.

Thermal Comfort Index	Abbreviation	Parameters Considered	Application	Author
Discomfort Index	(DI)	Air temperature, humidity	Outdoor activities, urban planning	Thom, E.C.1959
Man-Environment Heat Exchange Model	M-ENHEM	Air temperature, humidity, wind speed, metabolic rate	Occupational health, indoor environments	Fanger, P.O. 1970
Outdoor Neutral Temperature	ONT	Air temperature	Urban planning, outdoor design	Gagge, A.P. et al. 1971
Required Sweat Rate	RSR	Air temperature, humidity, metabolic rate	Occupational health, outdoor activities	Parsons, K.C. 1974
Humidex	HI	Air temperature, dew point temperature	Outdoor activities, urban planning	Masterton, J.M. et al. 1979
Effective Temperature	CET	Air temperature, humidity, wind speed, solar radiation	Outdoor activities, occupational health	Krüger, E.L. 1982
Potential Storage Index	PSI	Air temperature, humidity	Occupational health, indoor environments	Holmer, I. 1981

Physiological Equivalent Temperature	PET	Air temperature, humidity, wind speed, solar radiation	Urban planning, outdoor design, occupational health	Höppe, P. 1999
Thermal Sensation Index	TSI	Air temperature, humidity	Urban planning, indoor environments	de Freitas, C.R. et al. 1998
New Wind Chill Temperature	NWCT	Air temperature, wind speed	Outdoor activities, occupational health (cold environments)	NOAA 2001
Actual Sensation Vote	ASV	Air temperature, humidity	Urban planning, indoor environments	Humphreys, M. et al. 2002
Klima Michel Model	KMM	Air temperature, humidity, wind speed, solar radiation	Urban planning, outdoor design, occupational health	Michel, R. et al. 2006
Universal Thermal Climate Index	UTCI	Air temperature, humidity, wind speed, solar radiation	Urban planning, outdoor design, occupational health	Bröde, P. et al. 2012
Heat Stress Index	NSET	Air temperature, humidity, wind speed, solar radiation, clothing insulation, metabolic rate	Occupational health, outdoor activities	Błazejczyk, K. et al. 2017
Index of Thermal Stress	ITS	Air temperature, humidity, wind speed	Occupational health, outdoor activities	Kalkstein, A.J. et al. 2020

The physiologically equivalent temperature (PET) index was selected for this study due to its effectiveness in assessing thermal stress in hot arid climates. The original PET scale was chosen without calibration, considering the limited literature on calibrating PET for such climates. Given the study's focus on evaluating the impact of urban elements on thermal comfort in educational settings like schools and university campuses in a hot arid climate, the original scale was deemed appropriate. Since the study primarily addresses high thermal stress levels, the question revolves around how these urban elements mitigate PET levels compared to the original design. The subsequent section will outline key parameters

related to the PET index, encompassing environmental factors such as mean radiant temperature, wind speed, air temperature, and air relative humidity. However, personal factors like clothing insulation levels and activity levels, set at 0.9 clo and 80 W, respectively, are excluded from the PET model (Höppe, 1999).

2.7 The Physiologically Equivalent Temperature Microclimate Factors

2.7.1 Air Temperature

Air temperature refers to the temperature of the surrounding air, which directly influences the heat exchange between the human body and the environment (Parsons, 2007). The air temperature within a specific environment varies based on the heat exchange dynamics within that environment. Thus, the temperature directly surrounding the human body is more influential for heat flow than a mass of air at a greater distance. In PET calculations, air temperature plays a crucial role as it represents the thermal condition of the surrounding air. The air temperature serves as one of the main input parameters for determining the human body's thermal comfort level. It influences the rate of heat exchange between the human body and the surrounding environment, affecting the perceived thermal sensation. Higher air temperatures typically result in greater heat absorption by the body, leading to thermal discomfort in warm environments. Conversely, lower air temperatures can induce sensations of cold and discomfort. Therefore, accurate measurement and consideration of air temperature are essential in PET calculations to assess thermal comfort accurately.

2.7.2 Mean Radiant Temperature

The mean radiant temperature (MRT) refers to the uniform temperature of an imaginary enclosure, within which the radiant heat transfer from a person's body is equivalent to that in the actual non-uniform enclosure (ASHRAE, 2017). It is a crucial factor in evaluating thermal comfort, playing a significant role in how individuals perceive the surrounding thermal environment. (Zhang et al., 2022) highlight that the mean radiant temperature is closely linked to the materials composing the surfaces emitting it. Consequently, the mean radiant temperature (T_{mrt}) can be computed by summing up the radiation emitted by all surrounding surfaces, considering the temperature of each material.

2.7.3 Wind Speed

Wind flow impacts human comfort and discomfort, influenced by factors such as activity level and duration spent in windy conditions (Tsichritzis & Nikolopoulou, 2019). Research indicates that discomfort levels may vary even at the same wind speed, depending on climatic and personal variables. For instance, during colder seasons, wind speed tends to have a greater impact on discomfort compared to milder seasons (Roshan et al., 2020). Moreover, human activities significantly contribute to the perception of wind comfort. While a certain wind speed might be tolerable during activities like walking or exercising for short durations, it may fall outside the comfort range for individuals who are sitting or waiting for extended periods (Tsichritzis & Nikolopoulou, 2019).

In urban environments, wind flow is predominantly influenced by the layout of the built environment at street level rather than the upper layers above buildings (Zeng et al., 2024).

The wind speed ratio, which compares the wind speed at users level to that in open spaces unaffected by buildings, is a key metric in assessing urban wind conditions (Ikegaya et al., 2017). Factors such as building heights, orientations, and arrangements play crucial roles in shaping wind patterns within urban areas (Mittal et al., 2018; Zahid Iqbal & Chan, 2016). Additionally, elements like vegetation and street orientation can also impact wind flow dynamics. Street orientation, in particular, influences wind behavior, determining whether wind flows in a helical or channeling manner, which has implications for thermal comfort and overall urban health by regulating the distribution of wind speed values within cities or specific areas (Oke et al., 2017).

2.7.4 Relative Humidity

Relative humidity (RH) significantly influences thermal comfort and the calculation of physiological thermal comfort indices such as the Physiological Equivalent Temperature (PET). RH reflects the amount of moisture present in the air relative to the maximum amount it can hold at a specific temperature. High RH levels can impede the body's ability to evaporate sweat effectively, reducing the efficiency of evaporative cooling, and leading to a perceived increase in thermal discomfort. Conversely, low RH levels enhance evaporative cooling, promoting a more comfortable thermal sensation. In PET calculations, RH is considered alongside other meteorological parameters like air temperature, mean radiant temperature, and wind speed to quantify the overall thermal environment experienced by users. Understanding the impact of RH on thermal comfort is crucial for designing urban spaces that prioritize human well-being, particularly in regions characterized by varying climatic conditions. By accounting for RH in thermal comfort

assessments, urban planners and designers can develop strategies to optimize outdoor environments and enhance the comfort and livability of urban spaces for users.

2.8 Sustainable Development Goals (SDGs) & Urban Cooling Strategies

Urban areas around the world face a myriad of environmental challenges driven by rapid urbanization, population growth, and unsustainable development practices. These challenges encompass various dimensions, ranging from air and water pollution to the loss of green spaces and biodiversity and the global issue of the UHI effect. Addressing these challenges requires comprehensive strategies that integrate environmental protection, urban planning, and community engagement to foster sustainable and resilient urban development.

The Sustainable Development Goals (SDGs) established by the United Nations provide a framework for addressing global challenges and achieving sustainable development by 2030, see Figure 15. Urban areas worldwide are grappling with rising temperatures and the adverse effects of the urban heat island (UHI) phenomenon. In response to this challenge, urban cooling strategies have emerged as crucial interventions to mitigate the UHI effect and enhance the resilience of cities to climate change. Urban cooling strategies directly contribute to several SDGs by addressing environmental, social, and economic aspects of sustainable development. Firstly, Urban cooling strategies align closely with Goal 11 (Sustainable Cities and Communities), which aims to make cities inclusive, safe, resilient, and sustainable. By mitigating the urban heat island effect and improving thermal comfort in urban areas, these strategies contribute to creating healthier and more livable cities.

Secondly, they align with Goal 13: Climate Action, as they help reduce energy consumption for cooling purposes and mitigate greenhouse gas emissions associated with urban heat islands. Moreover, by safeguarding public health and well-being through the reduction of heat-related illnesses and improved air quality, urban cooling strategies support Goal 3: Good Health and Well-being. Additionally, certain cooling strategies, such as green roofs and smart shading systems, contribute to Goal 7: Affordable and Clean Energy by promoting energy efficiency and the utilization of renewable energy sources. Finally, by incorporating nature-based solutions like urban forests and green spaces, these strategies also advance Goal 15: Life on Land by preserving biodiversity and ecosystem services within urban environments. Therefore, integrating urban cooling strategies into urban planning and development processes is essential for achieving multiple SDGs and creating sustainable, resilient cities.



Figure 15: Sustainable development goals (SDGs).

Source; (United Nations, 2015).

2.9 Urban Cooling Strategies

Urban areas face the challenge of excessive heat due to the urban heat island (UHI) effect, which exacerbates climate change impacts, compromises human health, and strains energy resources. Urban cooling strategies are pivotal in mitigating these challenges, enhancing urban livability, and fostering sustainable urban development (Anand & Sailor, 2023). Urban cooling strategies encompass a range of interventions aimed at reducing ambient temperatures, enhancing thermal comfort, and mitigating the UHI effect in urban areas. These strategies can be broadly categorized into three main types including urban shading strategies, Cool/High-reflective materials, and interactive water features. Each strategy targets different aspects of the urban environment to counteract heat accumulation and create more resilient and comfortable urban spaces, as shown in Figure 16.

2.9.1 Interactive water features

Urban cooling strategies that utilize interactive water features are effective in reducing temperatures and enhancing thermal comfort in city environments. These strategies include the use of fountains, water pools, ponds, and sprinklers. Fountains and water pools create cool microclimates by evaporative cooling, which lowers the surrounding air temperature. Studies by (Daniel et al., 2018) and (Maciej Serda et al., 2023) emphasize the role of water features in enhancing thermal comfort and mitigating heat stress in urban environments. For narrow spaces like streets or courtyards, mist-spray cooling serves as an effective water-cooling alternative to artificial lakes and fountains. In addition to cooling, mist-spray systems help remove airborne particulates and improve air quality.

2.9.2 Cool / High-reflective materials

Cool roof and cool pavement technologies involve the use of reflective materials to reduce solar heat absorption and lower surface temperatures. Research by (Santamouris, 2014) and (Sen et al., 2019) demonstrates the effectiveness of these strategies in reducing building and pavement temperatures, thereby mitigating the UHI effect and decreasing energy consumption for cooling.

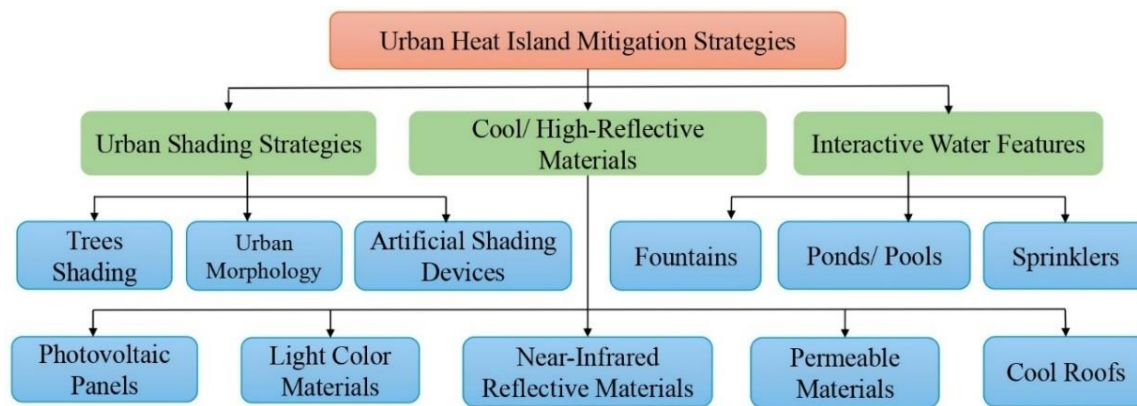


Figure 16: Urban cooling Strategies to enhance thermal performance in urban plazas.

Sources; (Elgheznawy & Eltarabily, 2021).

2.9.3 Urban Shading Strategies

The impact of shading strategies on thermal comfort represents a critical aspect of urban design and environmental planning in the context of climate change. With the world witnessing rising temperatures and more frequent heatwaves, the importance of creating comfortable outdoor environments has become paramount. Shading strategies offer a versatile solution to mitigate the adverse effects of solar radiation and excessive heat, thereby enhancing the thermal comfort of individuals in outdoor spaces.

Shading effects, derived from architectural elements, vegetation, and other landscape amenities, play a crucial role in mitigating the incidence of solar radiation (SR) and sunlight. By providing shade, these elements contribute to lowering ground surface temperatures and reducing the impacts of both long and short-wave radiation (Lindberg et al., 2016; Rodríguez Algeciras et al., 2016). A multitude of studies have explored outdoor thermal comfort and adaptation, investigating the diverse shading effects on human thermal comfort across university campuses, urban parks, and streets. These studies employ a combination of microclimatic measurements and questionnaire surveys to gather comprehensive information about the impact of shading strategies on enhancing human thermal comfort. Several researchers have highlighted that high temperatures in outdoor open spaces often result in thermal discomfort for students, primarily due to inadequate shading coverage (Abdallah et al., 2020; Y. Y. Lee et al., 2021). A number of studies have investigated the cooling effect of green infrastructure (GI), and they proved that the effective usage of GI can significantly enhance the OTC of users by tackling the climate induced UHIs in the air temperature through evapotranspiration and shading (Jungman et al., 2023; Jang et al., 2024; Mohammed et al., 2023). Moreover, the urban form of the city affects the formation of the urban heat island since the smart arrangement of urban configuration can determine the absorption of longwave radiation and the formation of wind streams. Optimizing the geometry of these canyons can effectively enhance thermal comfort and reduce UHI effect. (Oke, 1988) suggested optimizing the height-to-width (H/W) or aspect ratios of urban canyons to minimize heat storage while maintaining effective wind flow for natural ventilation. Another study has investigated the capability of various building massing configurations to offer shading (Nugroho et al., 2022).

In the case of an existing nonadjustable urban context, urban microclimate can be improved by using urban textile canopies (Garcia-Nevado et al., 2020). The effectiveness of outdoor shading systems is influenced by their optical attributes, including material, color, and openness of the shade, as well as their spatial distribution, such as coverage ratio, location, orientation, and the height of the shade (Lam et al., 2023). These factors can have an impact on the amount of solar radiation received and the exchange of radiative heat between people and their surroundings, thus affecting the thermal comfort of users (Jafarian et al., 2021). Although artificial shading is a viable alternative to urban greenery when tree planting is impracticable, only a limited number of studies have delved into the thermal conditions and cooling advantages associated with artificial shade structures, encompassing modern ramadas and permanent shelter canopies (Colter et al., 2019). Table 2 summarized the previous effort of research that investigated the role of outdoor shading structures in enhancing the outdoor thermal comfort. While many studies concentrate on individual attributes of shading devices, such as transparency and material composition, there is a scarcity of comprehensive parametric investigations that simultaneously address multiple properties of these devices to enhance thermal comfort at the micro-scale. Also, it has been noted the lack of research interested in studying thermal comfort in open spaces of educational buildings. This gap underscores the need for research endeavors aimed at quantifying the impacts of shading devices on diminishing heat stress and enhancing visual comfort. To address these gaps in knowledge, this study seeks to investigate the influence of shading devices' materials, transparency, coverage percentage, and the height of the shading structure on enhancing the outdoor thermal comfort. The specific research questions are as follows.

- 1) Which shading material between (Cotton Canvas, High-Density Polyethylene (HDPE), and Polyvinyl Chloride (PVC) membranes) offers the best thermal performance relative to cost and structural integrity?
- 2) What is the optimal configuration of shading devices in terms of in terms of percentage coverage and height to improve pedestrians' thermal comfort

To answer these questions, the research conducted on-site observations, followed by ENVI-met simulation modeling during the summer of 2023, using KFUPM Central Square in the Eastern Province of Saudi Arabia as a case study.

Table 2: Paper reviewed, outdoor thermal comfort, outdoor shading devices, urban textile shading (adapted by Author).

APER	AIM	MATERIAL	METHODOLOGY	FINDINGS
(Lam et al. 2023)	To analyze the impact of shading devices on outdoor thermal and visual comfort.	Clear float glass Plexiglass Concrete Aluminum PVC	Simulation model (ENVI-met)	- A noticeable reduction in T_{mrt}, PET, but negligible effect on T_a and V_a". "Opaque materials of shading devices are more effective than transparent materials". "Opaque materials with zero percent light transmission have been found to be more efficient in reducing illuminance compared to transparent materials".
(Mahmoud and Abdallah 2022)	To enhance students' thermal comfort in school courtyards through the implementation of various shading strategies.	Yellow wood	Simulation model (ENVI-met)	The implementation of hybrid orthogonal and diagonal staggered shading with trees in wide canyons resulted in substantial reductions in PET values, achieving decreases of 18.5 °C and 18.6 °C, respectively.
(Jareemit and Srivanit 2022)	To investigate the cooling benefits of typical street market shading structures across different configurations.	HDPE	Experimental	The temperature reductions beneath the artificial shade structure fluctuated throughout the day, with maximum decreases ranging from 1.6 °C to 2.3 °C.
(Middel et al. 2021)	Evaluate the effectiveness of various shade types in mitigating heat stress and promoting active shade management in urban settings.	Urban form shade. Engineered Shade. Tree shade.	Experimental field measurements	- The air temperature was similar across different shade types. - Mean Radiant Temperature ($\Delta TMRT$) varied widely, with a 50 °C range. - Urban form shade most effectively reduced surface temperature (ΔT_s) and TMRT during the day, followed by trees and lightweight structures. - Shade performance varied with orientation and tree species; nonnative trees were more effective than native or palm trees. - All shade types retained heat (positive $\Delta TMRT$) after sunset.

(Chen et al. 2021)	Assess the impact of ground surface materials and shading characteristics on the outdoor thermal environment.	Deciduous trees. Tensioned membrane.	Field Measurements	• In winter, a higher Sky-view Factor (SVF) is positively correlated with Physiological Equivalent Temperature (PET), whereas in summer, it is negatively correlated. • Deciduous trees significantly improved comfort by raising PET by 10.56 °C in winter and lowering it by 9.73 °C in summer, while tensioned membranes were less effective. • High-reflection water-permeable bricks reduced PET by 1.08 °C in summer, while lawns lowered mean radiant temperature (T_{mrt}) by 1.65 °C but could create a microclimate with higher air temperatures.
(Bande et al. 2021)	Identify the most effective strategies for enhancing outdoor thermal comfort (OTC) in cities such as Dubai, Abu Dhabi, and Al Ain.	Wood Shading Devices. Greenery.	ENVI-met Modeling	• Shading devices have a significant positive impact on reducing the Predicted Mean Vote (PMV), a key indicator of outdoor thermal comfort (OTC). • implementing 100% shading coverage, yielded the best OTC values outperforming scenarios that focused on vegetation. • The typology of vegetation determines the cooling effect of it.
(Elghezawy and Eltarabily 2021)	To assess the effectiveness of a sun sail shading strategy on enhancing the outdoor thermal comfort in school courtyards.	Fabric Sun sails	Field Measurements + Microclimate Modeling using Envi-met	• 60% shading coverage is optimal for improving thermal comfort. • An average reduction in air temperature (T_a) of 0.5 °C was observed beneath the shading devices. • An average decrease in Predicted Mean Vote (PMV) values of over 0.6 was observed. • A decrease in mean radiant temperature (T_{mrt}) of approximately 20% was noted at most receptor points.
(Garcia-Nevado et al. 2020)	To examine the cooling potential of sun sails on urban surfaces.	polyester tissue	Experimental	• High-mounted sun sails provide a global cooling effect over the street, irrespective of their orientation. • Temperature reductions of up to 16 °C in ground temperature and up to 6 °C in façade temperature have been observed due to the presence of sun sails.

(Alnusairat, Al-Shatnawi, and Kakani 2020)	To assess the potential of sun sails in reducing solar loads on streets.	Textile tissues	Simulation (Solar radiation model)	• Sun sails have been shown to effectively reduce solar loads on streets, achieving reductions of 43% to 64%. • The cooling potential of sun sails varies significantly with color, with darker fabrics performing up to 20% better in reducing heat compared to lighter ones. • High-mounted sun sails are always desirable, particularly with light-colored fabrics.
(Elnabawi and Hamza 2020)	To create an integrated interface that links microclimate conditions, outdoor thermal comfort, and design guidelines.	Textile tissues	Field measurements	• According to the study's findings, achieving thermal comfort on an urban scale hinges primarily on the shape and position of openings in shading devices. • According to the findings of the subjective evaluation, people in hot and arid regions have a greater ability to adapt to and tolerate the local climate conditions.
(Lee et al. 2020)	To examine the overhead shading devices in enhancing walkability and to identify biometeorological factors that influence pedestrian behavior.	Light-blue tinted glass	Field measurements	• The shaded zone reduced maximum global solar radiation by 432 W/m², achieving a 90% reduction in solar radiation. • The maximum reductions in air and black-globe temperatures were 0.8 °C and 6.1 °C, respectively. • Maximum differences in physiologically equivalent temperature (PET) and universal thermal climate index (UTCI) between the zones were 8.2 °C and 5.3 °C, respectively.
(Kántor, Chen, and Gál 2018)	Assess the effectiveness of various shading methods, including sails and trees, in alleviating urban heat stress.	Fabric Sun Sail and tree shading	Field measurement	• Trees were more effective in reducing heat stress with an average PET reduction of 9.0 °C between 9:00 and 16:00. • Low-hanging sun sails reduced PET by an average of 5.8 °C, making them less effective than trees. • High sun sails and mature trees were more effective, with PET reductions exceeding 10 °C, demonstrating their strong potential for mitigating heat stress.

(Lee, Voogt, and Gillespie 2018)	Assess and compare the effectiveness of various shading strategies in enhancing thermal comfort in urban environments.	Building shade, tree shade, and umbrella shade	Field measurements	• Building Shade: Found to be the most effective cooling strategy, primarily due to its ability to block incoming shortwave radiation. • Tree Shade: Ranked second in effectiveness, offering significant cooling but less than building shade. • Umbrella Shade: Was the least effective among the three strategies, but still provided a measurable reduction in heat.
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CHAPTER 3

RESEARCH METHODOLOGY

The research methodology chapter serves as a comprehensive guide to the systematic approach undertaken in this study. It begins with an introduction to the study area, providing essential background information necessary for understanding the context of the research. Following this, the chapter outlines the field observation stage, which encompasses various crucial steps such as meteorological measurement, data processing, and thermal comfort index calculation. These processes lay the foundation for acquiring accurate and reliable data for further analysis. Subsequently, the chapter transitions to the simulation stage, where an in-depth exploration of simulation techniques is conducted. This includes an introduction to the simulation program utilized, the setup for numerical simulations, and the rigorous process of model validation. Additionally, the chapter delves into defining the proposed simulation scenarios, outlining the parameters and variables under investigation. By meticulously detailing each stage of the research methodology, this chapter ensures transparency and reproducibility, thereby enhancing the credibility and validity of the study's findings.

3.1 The research workflow of the study

Figure 17 illustrates the research workflow adopted for this study, which integrates on-site meteorological observations with model simulations. This combined approach was

employed to evaluate the effectiveness of shading devices in improving outdoor thermal comfort.

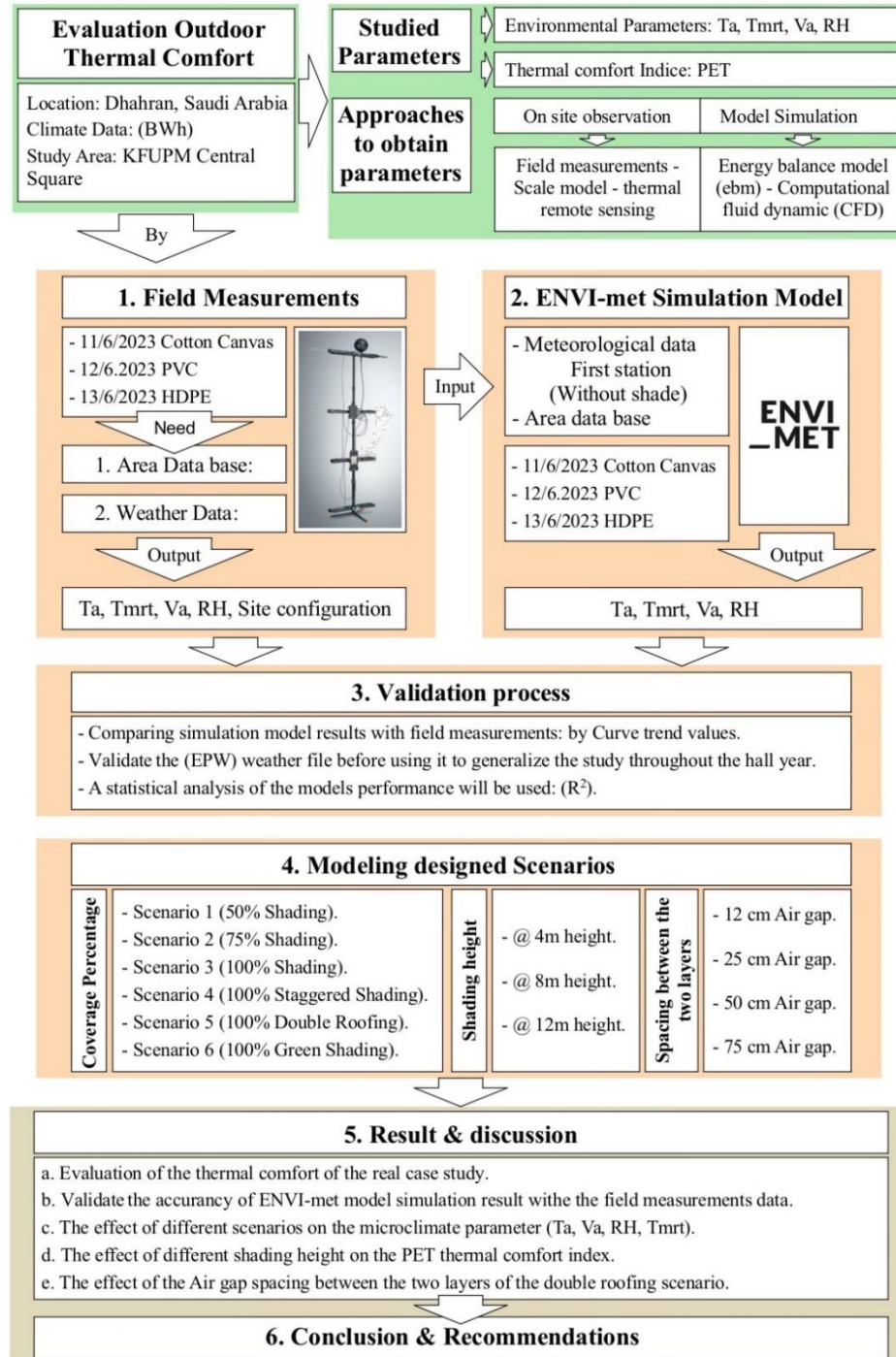


Figure 17: The Research Methodology Workflow.

(Source: Author)

3.2 Description of the Study Area

Dhahran is a city located in the Eastern Province, Saudi Arabia. It is located at latitude 26 East and longitude 50 North. Dhahran's climate is categorized as dry arid climate found in low latitude deserts according to the Köppen-Geiger climate classification system, represented by the code (BWh). Dhahran climate is affected by the Arabian Gulf winds, resulting in hot and humid summers and mild and wet winters. Figure 18 illustrates the range of average air temperatures observed in January, the coldest month, and July, the hottest month. Temperatures fluctuated between 10 °C and 20 °C in January and between 28.9 °C and 43.3 °C in July. The annual average of relative humidity is 54.7% and the average monthly relative humidity ranges from 34% in June to 73% in January (Climate-Data.org, 2021).

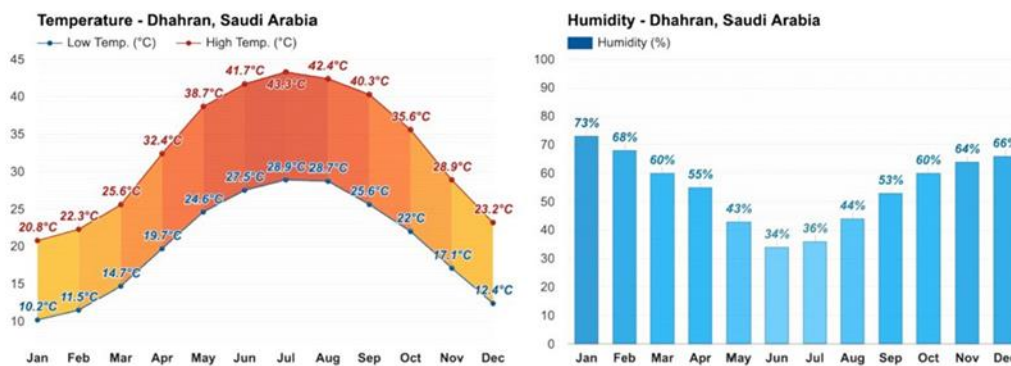


Figure 18: Dhahran Monthly Low & High Average Temperature & Relative Humidity.

Source: (Climate-Data.org, 2021).

The study was performed at the central square of KFUPM campus, the university campus falls within the category of Local Climate Zone (LCZ) 5, characterized as open mid-rise, as shown in Figure 19. This designation encompasses mid-rise buildings typically ranging

from 5 to 6 stories and includes areas with pervious land cover (Stewart & Oke, 2012). The KFUPM central square serves as a vibrant venue for a variety of outdoor activities and student events. However, its usability is constrained by exposure to high air temperatures, intense solar radiation, and varying levels of heat stress throughout the year. These conditions often limit outdoor activities to late afternoon and evening hours, falling outside typical student working hours. Recognizing this challenge, the square was chosen as the focal point for studying the potential cooling effects of artificial shading strategies. The aim is to explore how such interventions can optimize space utilization and expand the range of usable hours for student engagement and events.

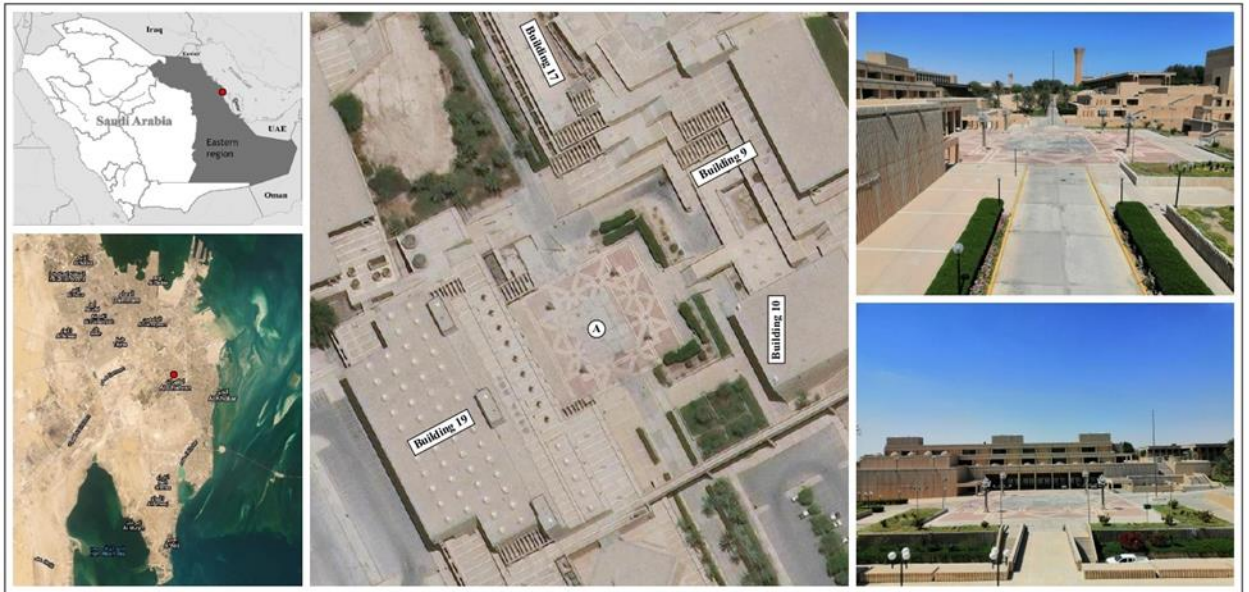


Figure 19: The case study site, KFUPM Campus. Dhahran City, Eastern Province-Saudi Arabia.

3.3 Field observation stage

The study aims to explore the effect of artificial shading devices on the outdoor thermal environment. An experimental setting was employed to assess the outdoor thermal environment and to evaluate and compare the cooling effectiveness of outdoor shading

device with different covering materials against unshaded setting. Therefore, two monitoring stations were used, one under the shading structure and the other exposed without any shade, Figure 20. The study investigated the cooling performance of three different covering materials - Cotton Canvas, Heavy duty polyethylene, and Poly-Vinyl Chloride Membrane which are considered as the most three common covering materials for outdoor shades in Saudi Arabia, Table 3 presents the general thermal properties of these covering materials. The dimension of the structure is $3\text{m} \times 3\text{m}$ with a height of 2.65 m as shown in Figure 21.

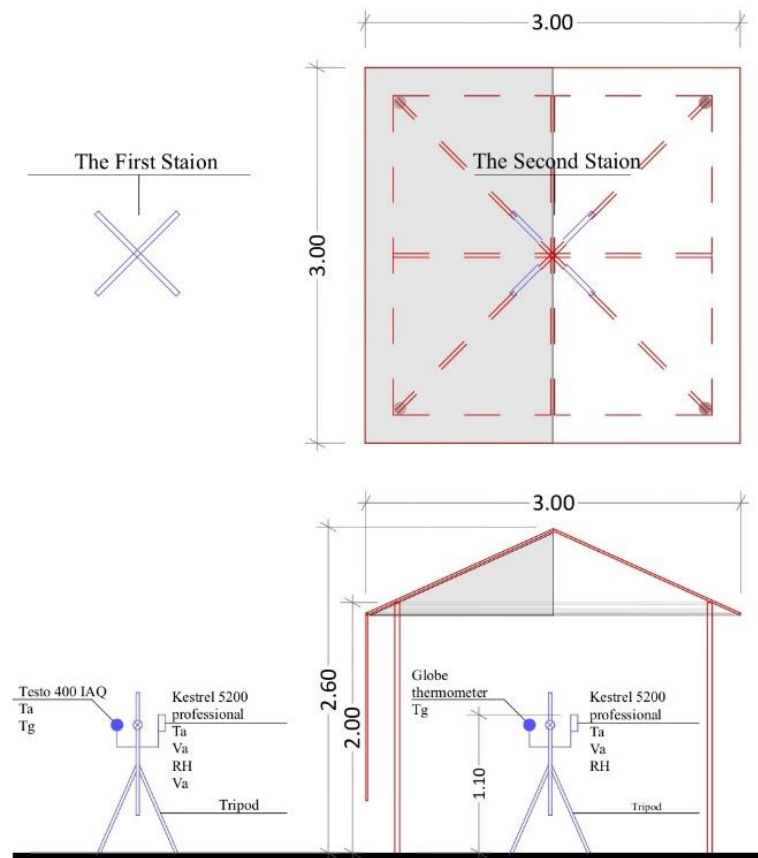


Figure 20: Experimental work setting.

Source: (Author).



Figure 21: The three different covering materials setting of artificial shades.

Source: Author.

Table 3: Thermal properties of the shading device covering materials.

Source: (Haran, 2008).

PARAMETER	COTTON	HDPE	PVC
	CANVAS	MEMBRANE	MEMBRANE
Thickness (m)	0.003	0.003	0.003
Absorption (Frac %)	0.400	0.300	0.110
Transmission (Frac)	0.100	0.100	0.090
Reflection (Frac)	0.500	0.600	0.800
Emissivity (Frac)	0.900	0.950	0.900
Specific heat J/(Kg*k)	1400.00	1950.00	1150.00
Thermal Conductivity W/(m*k)	0.045	0.450	0.175
DENSITY (KG/M ³)	340.00	950.00	1400.00

(Frac %) Fraction of shortwave radiation absorbed, transmitted, or reflected by the material and the emissivity for longwave thermal radiation of the material.

3.3.1 Meteorological measurement

The Field measurements were recorded on 11th, 12th, and 13th of June 2023, which was the beginning of summer season, for three days, from 6:00 a.m. to 5:00 p.m. There were two

observation points, one under the artificial shading structure and the other exposed to the sun without any shade. According to ASHRAE Standard 55, key meteorological parameters including air temperature, wind speed, wind direction, relative humidity, and globe temperature should be measured. These measurements were taken at a height of 1.1 meters above the ground using various meteorological devices listed in Table 4. Data collection occurred at 10-minutes intervals throughout the duration of the study.

Table 4: Devices used in the field measurements. Source: (Author).

Devices name	Variables	Measurement range	3d Model
Kestrel 5200 professional	(Va) (Ta) (RH)	0 to 67 m/s − 54 °C to + 65 °C 0 -100%	
Testo 400 Universal IAQ instrument	Air Flow, Temperature Humidity, Pressure, Illuminance, Radiant heat, Turbulence , CO ₂ and CO		
Globe Probe	Globe temperature (Tg)	0 °C to + 120 °C	
Botsball Wet Globe Temperature	Globe temperature (Tg)	0 °C to 50 °C	

3.3.2 Data processing

Mean Radiant Temperature (MRT) is a measure of the average temperature of all the surfaces surrounding a point or an individual. It represents the combined effect of the radiant heat exchange between a person and their immediate environment. It is considered as an important parameter in thermal comfort analysis (outdoor and indoor) because humans exchange heat with their surroundings not only through the air but also through radiation. The calculation of mean radiant temperature involves the utilization of several key parameters including average air temperature, air velocity, and globe temperature. The globe thermometer method was used to calculate the mean radiant temperature (T_{mrt} °C), which is widely used to evaluate human thermal comfort and calculate heat radiation loss. Equation (1) is used for the calculation of T_{mrt} (ASHRAE 2001).

Equation 1: Calculating the mean radiant temperature using globe thermometer method.

$$T_{mrt} = [(T_g + 273.15)^4 + (1.335 \times 10^8 V_a^{0.6}) / (\epsilon \cdot D^{0.4}) * (T_g - T_a)]^{0.25} - 273.15$$

where T_a is the air temperature (°C), T_g is the globe temperature (°C), ϵ is the globe emissivity (0.95 for a black globe), D is the globe diameter (mm), and $1.335 \times 10^8 V_a^{0.6}$ (m/s) is the globe's mean convection coefficient.

3.3.3 Thermal Comfort Index Calculation

Various measures have been employed to evaluate the degree of thermal comfort experienced by humans in outdoor spaces (Colter et al., 2019; Paper Middel et al., 2016). Previous researchers had utilized a mathematical measurement to calculate human thermal

index. The study used the Physiological Equivalent Temperature (PET) index, which is a thermal comfort indicator for outdoor and semi-outdoor environments. PET is derived from the Munich energy balance model for individuals (MEMI), which is a widely used model (Johansson et al., 2014). The PET index, expressed in degrees Celsius, offers a spectrum of thermal sensation, ranging from extreme heat stress to extreme cold stress, as detailed in Table 5.

According to (Coccolo et al., 2016) the PET index scale varies across different climates and is not standardized. Hence, adjustments to calibrate the PET scale are necessary, involving the utilization of questionnaires and observed meteorological data. A tailored scale was developed for the hot and humid climate of Taiwan, as indicated in Table 5, leading to a shift of the comfort range by 7 °C (T.-P. Lin et al., 2008). In 2016, a separate investigation aimed at calibrating the PET index for a hot arid climate was carried out in Egypt, the findings revealed that, particularly during summer conditions, the comfort range shifted from 18-23 °C to 23-32 °C (Elnabawi et al., 2016).

Table 5: The PET Thermal comfort Scale for different climate conditions. Source: (W. Yang, Wong, & Zhang, 2013).

Thermal perception	PET (°C)	PET – Hot humid climate (°C)	PET – Mediterranean climate (°C)
Very cold	<4	<14	<8
Cold	4 to 8	14 to 18	8 to 12
Cool	8 to 13	18 to 22	12 to 15
Slightly cool	13 to 18	22 to 26	15 to 19
Comfortable	18 to 23	26 to 30	19 to 26
Slightly warm	23 to 29	30 to 34	26 to 28
Warm	29 to 35	34 to 38	28 to 34
Hot	35 to 41	38 to 42	34 to 40
Very hot	>41	>42	>40

3.4 Simulation stage

3.4.1 ENVI-MET: Model overview

The ENVI-met program stands out as a three-dimensional model employing computational fluid dynamics to simulate the dynamic changes occurring in outdoor microclimates over time, diverging from traditional models that assume stationary conditions. It was developed by Dr. Matthias Bruse and is used to analyze thermal and airflow conditions in urban environments (Bruse & Fler, 1998). It is commonly used by urban planners, architects, and environmental scientists to assess and predict the impact of various design and planning decisions on the microclimate. In addition to modeling vegetation and buildings, ENVI-met simulates airflow around buildings and heat exchange between ground and buildings (Huttner, 2012).

3.4.1a Applications

ENVI-met is an essential tool for urban planning and environmental design, providing detailed insights into microclimatic interactions in urban areas. It enhances urban layouts for better thermal comfort and mitigates the urban heat island (UHI) effect by simulating various design choices, including building placement, green space integration, and reflective materials (Müller et al., 2014).

Furthermore, ENVI-met is crucial for evaluating climate resilience, allowing simulations of extreme weather conditions like heatwaves and heavy rainfall to improve urban designs. It is also a powerful educational and research tool, teaching students about urban climatology and the interactions between built environments and natural elements. Overall, ENVI-met supports sustainable and livable city planning, climate resilience assessment,

environmental impact studies, and academic research, aiding informed decision-making amid increasing environmental challenges.

3.4.1b ENVI-met usage workflow

The ENVI-met Headquarter is the core simulation engine of the ENVI-met software suite, designed to perform detailed microclimate simulations by analyzing interactions between urban surfaces, vegetation, and the atmosphere, Figure 22.

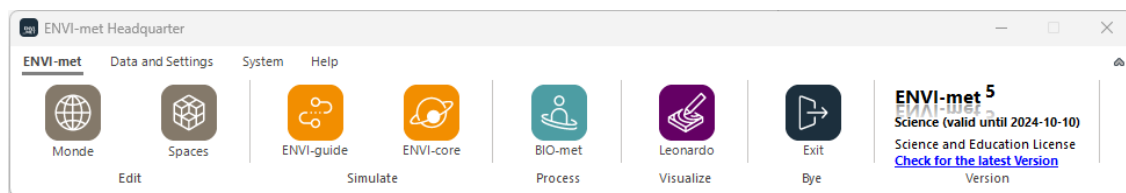


Figure 22: ENVI-met Headquarter.

Setting up a model in ENVI-met involves several key steps to accurately simulate urban microclimates:

Step 1: Define the Simulation Domain

The first step in the model setup process in ENVI-met software is defining the simulation domain. This involves specifying the horizontal and vertical extents of the simulation area to be studied. Users must set the grid layout, including the horizontal and vertical extents (x, y, and z axes), and choose the resolution of the grid cells to balance detail and computational load. Higher resolution provides more detailed results but requires more computational resources. Also, Users have to input the terrain data to represent elevation variations within the simulation area. This is essential for accurately modeling airflow and other microclimatic processes, see Figure 23 and 24.

Change or create model domain settings

Model Location
Model Geometry
Georeference and DEM Level
Default Settings
Nesting Grids
Description and Copyrights

Location on earth
Name of location: Dhahran Saudi Arabia
Find location...
Position on earth:
Latitude (deg. +N, -S): 26.24
Longitude (deg. -W, +E): 50.04
Reference time zone:
Name: Arabian Standard Time
Reference longitude: 45

Create new empty area
Apply changes to existing area
Cancel

Figure 23: Model location setup in ENVI-met.

Change or create model domain settings

Model Location
Model Geometry
Georeference and DEM Level
Default Settings
Nesting Grids
Description and Copyrights

Model Geometry
Model Dimensions:
x-Grids: 92 y-Grids: 74 z-Grids: 90
Size of grid cell in meter:
dx= 3.00 dy= 3.00 dz= 1 (base height)
Method of vertical grid generation:
☒ dz of lowest gridbox is split into 5 subcells
☐ telescoping (dz increases with height)
Telescoping factor (%): 0.00
Start telescoping after height (m): 0.00
Model rotation out of grid north: -27.00
Maximum Model Size is 50x50x40 in ENVI-met LITE
Detailed Design

Create new empty area
Apply changes to existing area
Cancel

Figure 24: Model Geometry setup in ENVI-met.

Step 2: Configure Urban Features

User should perform the followings:

Define the location, height, and materials of buildings within the simulation domain using Space and Monde tools.

Specify the types, locations, and heights of vegetation, such as trees and shrubs using Albero. Vegetation significantly influences microclimate through shading and evapotranspiration.

Detail the characteristics of various surfaces (e.g., roads, pavements, water bodies), as different materials have different thermal properties and albedo values.

Step 3: Set Meteorological and Temporal Parameters

As shown in Figure 25, the setup of meteorological and temporal parameters in ENVI-met is a crucial step in the model setup process, ensuring that the simulation accurately reflects real-world weather conditions and timeframes. Below is a detailed guide to this step:

a. Meteorological Parameters

For the meteorological parameters, the initial weather conditions are paramount. Users must input the initial air temperature at the start of the simulation and provide the initial relative humidity levels. Wind speed and direction are specified, which are critical for accurately simulating airflow and pollutant dispersion. Additionally, data on solar radiation is inputted, as it significantly affects temperature and plant growth.

b. Boundary Conditions

Boundary conditions are equally important, as they set the atmospheric variables like temperature, humidity, and wind at the edges of the simulation domain. This ensures realistic interactions and continuity between the simulation area and its surroundings. Incorporating the diurnal cycle, which includes variations in meteorological conditions over a 24-hour period, is essential to accurately simulate day-night cycles.

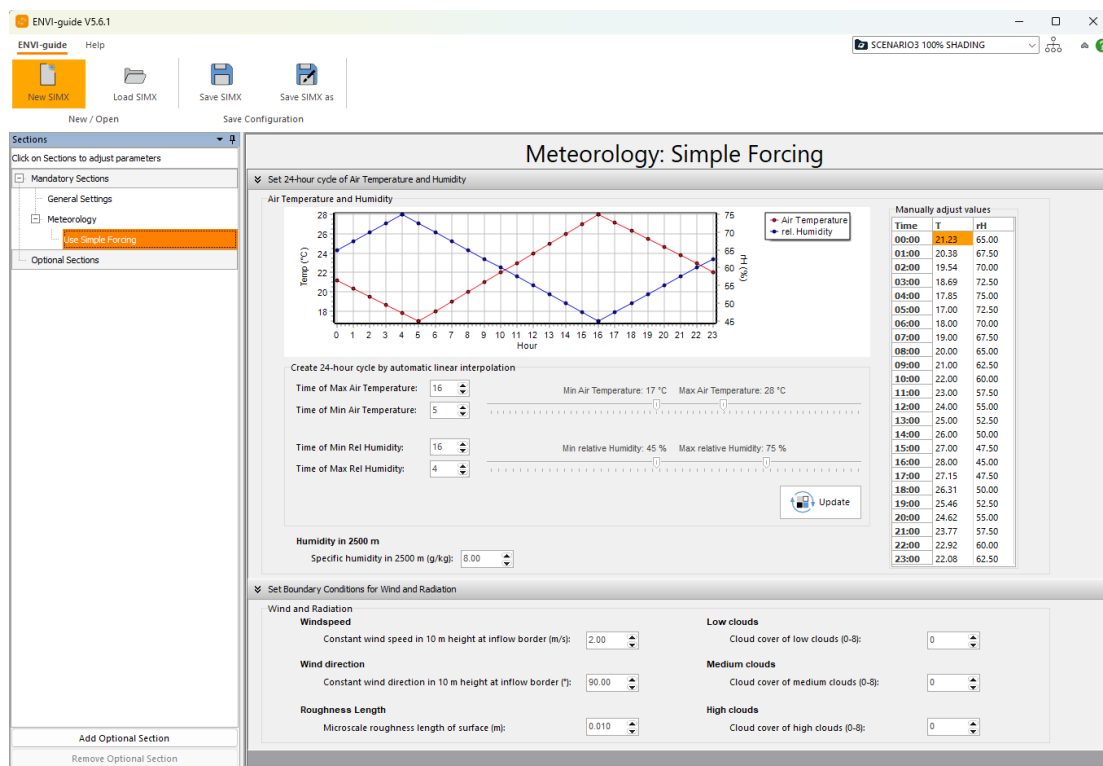


Figure 25: Setup of the meteorological parameters and the boundary conditions.

c. Temporal Parameters

For the temporal parameters, the simulation duration needs careful definition. The total time span must be set, whether for 24 hours, several days, or longer, depending on the study's objectives. Specific start and end times are determined to capture the desired

timeframe precisely. By meticulously setting these meteorological and temporal parameters, users ensure that the ENVI-met simulation provides reliable data that accurately represents real-world conditions, which is essential for urban planning, climate resilience assessment, and environmental impact studies, see Figure 26.

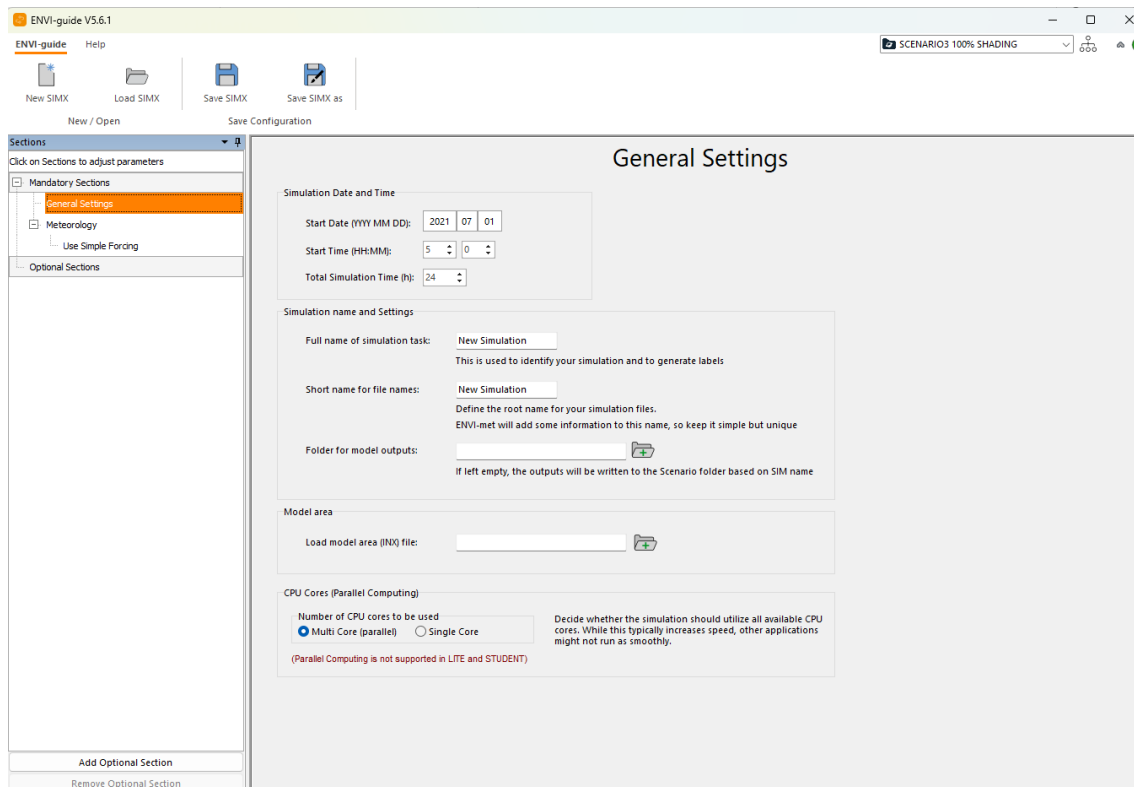


Figure 26: Setup of the Temporal parameters interface.

Step 4: Additional Settings

In addition to the core meteorological and temporal parameters, there are additional settings in ENVI-met that further refine the simulation for greater accuracy and realism, see Figure 27.

Initial soil moisture is a critical parameter that influences heat and moisture fluxes within the simulation area. By inputting accurate data on soil moisture levels, users can ensure that the interactions between the soil, vegetation, and atmosphere are realistically modeled. Precise soil moisture data helps in creating a more accurate representation of the urban microclimate.

Surface roughness is another essential setting that must be defined for different areas within the simulation domain. Surface roughness refers to the texture and irregularities of surfaces, such as buildings, vegetation, and terrain. These features influence wind flow and turbulence, affecting how air moves across and around them. Properly setting surface roughness ensures that the model can simulate realistic wind behaviors, which is vital for urban planning, especially in designing buildings and layouts that optimize airflow and reduce heat islands.

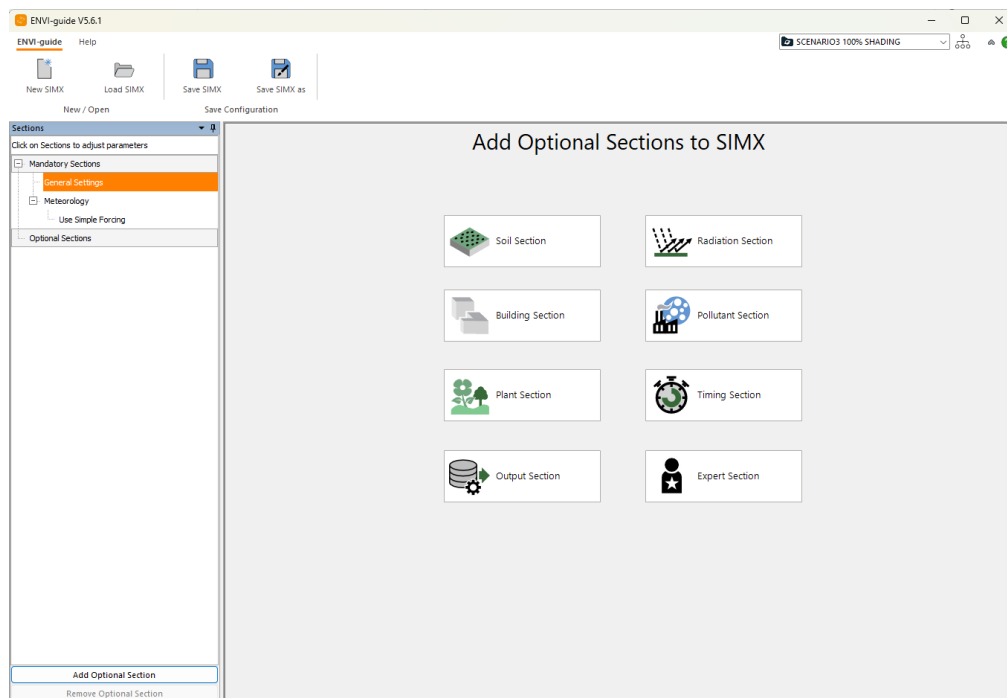


Figure 27: Additional settings interface.

The model comprehensively accounts for the intricate interplay among radiation, turbulence, surface characteristics, vegetation, and air within urban environments. It achieves this by dynamically coupling radiation and turbulence models, ensuring precise simulations of outdoor microclimates (Simon, 2016). This tool has been established as invaluable for urban planners and architects seeking to analyze and assess outdoor urban environments (Müller et al., 2014). For this study, ENVI-met V.5.6.1 and its submodule Bio-Met were utilized for simulation purposes. Specifically, Bio-Met was applied to compute the Physiologically Equivalent Temperature (PET).

3.4.2 Setup for the numerical simulations

Figure 28 illustrates the study area's model domain in ENVI-met, the existing configuration of the university campus was replicated within the ENVI-met environment. The model covered a total area of 276 meters by 222 meters, with a model height extending up to 90 meters, surpassing the height of the tallest building on campus, which stands at 20 meters. To ensure a high level of detail and accuracy, the model utilized a grid unit configuration of 92 by 74 by 90, with a resolution of 3.0 meters in the x and y directions and 1.0 meter in the z direction, Table 5 provide a detailed information about the model area setup in ENVI-met. This configuration aimed to provide ample open space at each boundary of the model area. The components of the study area and the finishing materials are detailed in Table 6. To simulate wind conditions, the model established a distance between the model border and the buildings three times the height of the building.

The simulation was conducted from 6 a.m. to 6 p.m. on the same days of the experiment work, on 11th, 12th, and 13th of June 2023, employing the simple forcing method in ENVI-met for the setup of the weather file. The meteorological inputs (Ta, RH, Va) were based on records from the site that was extracted from the first station (exposed to the Sun) during the experimental days using automatic and manual devices that are shown in Table 4.

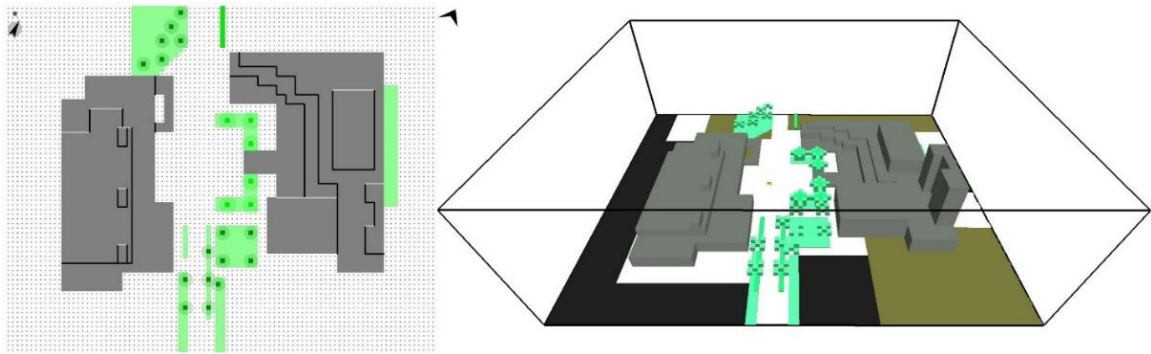


Figure 28: The study area's model domain in ENVI-met V 5.0.0.

Table 6: Input data for configuring the ENVI-met model.

Table	
‘Location on earth’	‘Latitude (°, +N, -S) 24.466667N
	‘Longitude (°, -O, +E)’ ‘Longitude (°, -O, +E)’
‘Reference time zone’	‘Name’ CET / GMT +1
	‘Reference longitude’ 45.00
‘Model geometry’	Total area = 83 m ×65 m ×90 m
	The building is 23 m high
	Building orientation : West
	Boundary condition : Full forcing
Exsisting finishing materials	Wall material = Concrete Cast dense
	Roof material = Concrete Light weight
	Soil and pavement :
	Pavements: [0000GP] Concrete pavement Gray
	Light-colored Asphalt [0000GP]
Vegetation	Soil: [000000] Loamy soil
	Albizia lebbeck Mimosaceae

	Palm Tree
	Plumeria alba
	Cassia javanica tree
	Grass Cover 25 cm
Microclimate Parameters	
Simulation Dates	11 th , 12 th , 13 th June 2023,
Start Time	6:00 a.m.
Total Simulation Time	12 h
Resolution	3.0 m × 3.0 m × 1.0 m
Model rotation out of grid north (°)	-27
Season	Summer
10 m wind speed	2.90 m/s to 6.50 m/s
Wind direction	North west 315°
Roughness length	0.1
Air temperature	Max: 39.97 °C (14:00), Min: 28.3 °C (06:00)
Relative humidity	Max: 28.74 % (06:00), Min: 12.30 % (15:00)
Cloud cover (oktas)	High:0, Medium:0, Low:1

3.4.3 Model validation

Despite ENVI-met being built on a solid physical foundation (Huttner, 2012), it relies on certain approximations as noted by (D. Lai et al., 2020; J. Yang et al., 2021), which means it cannot completely replicate real-time conditions. Consequently, the process of model validation is crucial to evaluate the dependability of simulation outcomes and to prevent any potential misinterpretations as emphasized by (Crank et al., 2020).

Model validation is achieved by comparing multiple meteorological variables observed in the field during the same timeframe as the actual measurements with their respective simulation results. This process can be translated into one or several statistical metrics that quantify the degree of reliability exhibited by the model as discussed by (Jamei et al., 2019; Lam et al., 2021; Shinzato et al., 2019). The coefficients of determination (R^2) were

used as the indicator for the model validation. Air temperature is a frequently employed meteorological parameter for the purpose of validation, followed by relative humidity and mean radiant temperature being as additional variables that are commonly utilized for the same purpose of validation (D. Lai et al., 2020).

3.4.4 Simulation scenarios

The efficacy of sun sail devices is contingent upon a combination of factors, including their optical properties and spatial distribution. Both attributes play integral roles in shaping the overall impact of sun sail devices on the surrounding environment (Elgheznawy & Eltarabily, 2021). To evaluate the outdoor thermal environment, the study first ran a scenario without any shade, referred to as the Base Case scenario. This scenario was then used as a reference to assess the cooling performance of the proposed artificial shading scenarios. Four shading coverage scenarios were simulated using cotton canvas as the covering material: Scenario 1 with 50% coverage, Scenario 2 with 75% coverage, and Scenarios 3 and 4 with 100% coverage, with and without a staggered configuration, respectively. Scenario 5 combined the best two covering materials (cotton canvas and HDPE) to simulate the cooling performance of a double roofing shading scenario. Scenario 6 focused on green shading and using it as a reference to evaluate the effectiveness of artificial shading devices. Furthermore, scenario 5 was modeled and simulated at three different height scenarios (4m, 8m, 12m) to study the impact of the shading height. Finally, the study investigated the effect of the air gap between the two covering layers by simulating three different gap sizes (25 cm, 50 cm, and 75 cm). All meteorological data, including air temperature (T_a), wind speed (V_a), mean radiant temperature (T_{mrt}), and physiological equivalent temperature (PET), were analyzed at 1.5 m above ground,

following ASHRAE 2017 guidelines for all proposed scenarios. Figures 29 and 30 show the simulation scenarios, which tested different coverage ratios and heights of sun sail devices in the central square of the KFUPM campus.



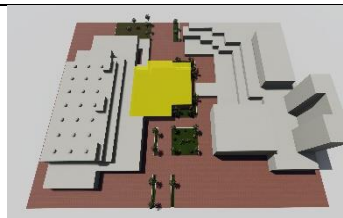
S0: 0% SHADING



S1: 50% STAGGERED SHADING



S2: 75% DOUBLE ROOFING



S3: 100% SHADING



S4: 100% STAGGERED SHADING



S5: 100% DOUBLE ROOFING



S6: 100% GREEN SHADING

Figure 29: Scenarios proposed for improving the outdoor thermal comfort.

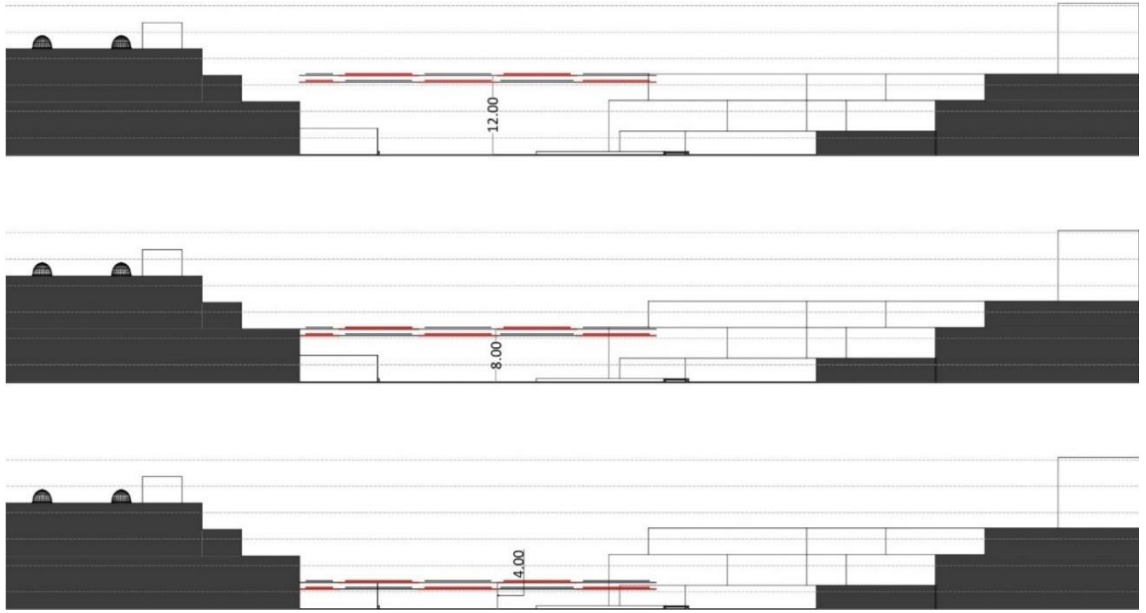


Figure 30: Modeling S5 at three different heights, (@ 4, @ 8, @ 12m).

CHAPTER 4

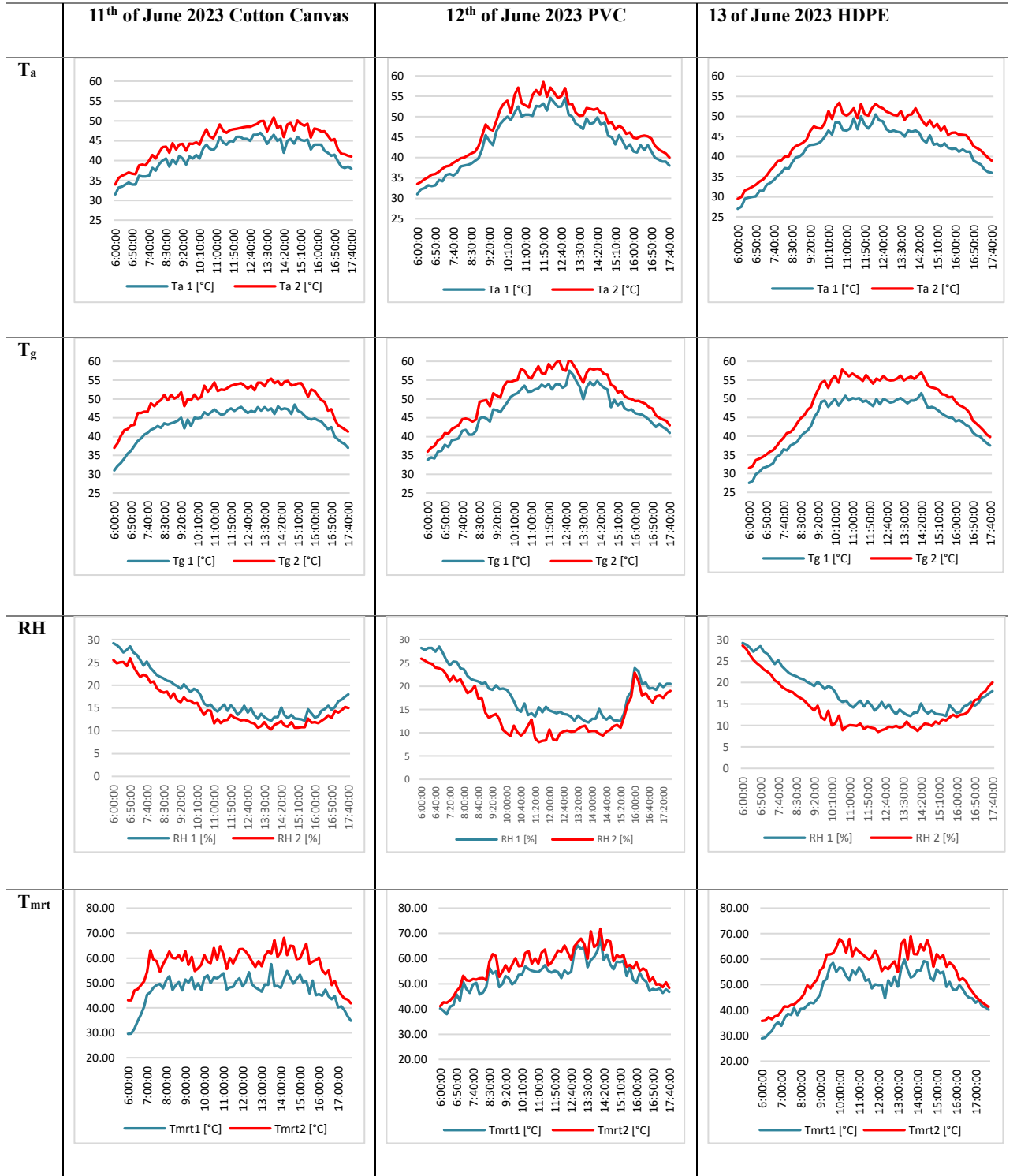
RESULTS AND DISCUSSION

The results and discussion chapter of this study provides a detailed analysis of findings from experimentation and simulation. It begins by examining the impact of various covering materials on urban microclimate and cooling performance. The calculation of the sky view factor (SVF) is then discussed as a crucial parameter for understanding urban microclimate. Validation results of the ENVI-met model are presented, focusing on validation of roof covering materials and weather files. The chapter then presents results from ENVI-met simulation scenarios, assessing the baseline model and the cooling effect of proposed scenarios. Height variation's impact on cooling performance is explored, along with the effect of artificial shading on Physiological Equivalent Temperature (PET). Additionally, the chapter investigates the effect of air gaps between shade layers. Through meticulous analysis, this chapter contributes to knowledge of urban microclimate and thermal comfort.

4.1 The effect of the covering materials on urban microclimate and cooling performance underneath

Table 7 shows the Diurnal pattern of the T_a , T_g , RH, T_{mrt} profile data that was collected from the weather station under the shading structured which was covered by using the three covering materials (Cotton canvas on 11th of June, PVC on 12th of June, HDPE on 13th of June) 2023, from 6 a.m. to 6 p.m. These data are compared with data collected from a station in an unshaded area.

Table 7: The Diurnal pattern of the Ta, Tg, RH, Tmrt profile under the three covering materials of artificial shade compared to the unshaded area.



- The Diurnal pattern of the air temperature profile under the three covering materials:
Table 7 shows that HDPE (High-Density Polyethylene) is generally considered the best choice in reducing the air temperature among the three covering materials; (the reduction reaches more than 5 degrees), and that's refers to two factors; the Breathability and Heat Dissipation of HDPE.
- The Diurnal pattern of the globe temperature profile under the three covering materials:
Table 7 shows that cotton canvas is generally considered the best choice in reducing the globe temperature, and that's refers to two factors; the high heat capacity and low thermal conductivity of the cotton canvas; (the reduction reaches more than 8 degrees).
And between the two-plastic base membrane (HDPE & PVC) one can see that HDPE is the best choice and that's refers to the Breathability and Heat Dissipation of HDPE; (the reduction reaches more than 5 degrees).
- The Diurnal pattern of the Relative humidity profile under the three covering materials:
Table 7 shows that Relative Humidity was observed to be higher than that in unshaded conditions. The increase in relative humidity under the HDPE membrane reached more than 8%.
- The diurnal pattern of the mean radiant temperature profile varies depending on the type of covering material utilized:
Table 7 shows that cotton canvas is generally considered the best choice in reducing the mean radiant temperature, and that's refers to two factors; the high heat capacity and low thermal conductivity of the cotton canvas; (the reduction in the T_{mrt} reaches more than 16 degrees). And between the two-plastic base membrane (HDPE & PVC) one can

see that HDPE is the best choice and that's refers to the Breathability and Heat Dissipation of HDPE; (the reduction reaches more than 5 degrees).

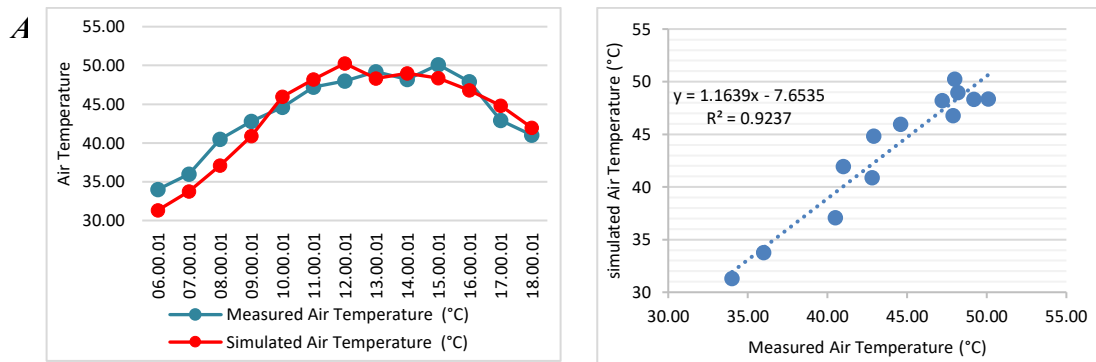
The experimental work resulted in the fact that the cotton canvas considered as the best covering material between the three materials and the HDPE membrane is the second choice between the two-plastic base membrane (HDPE & PVC).

4.2 Validation results of the ENVI-met model with the experimental work

4.2.1 Validation of the roof covering materials using the regression

coefficient (R^2)

To validate the model, a comparison was conducted between various meteorological variables recorded during field measurements and the corresponding simulation results. In particular, during hot summer conditions, researchers commonly prioritize the validation of the model using air temperature (T_a) as a critical parameter. The coefficient of determination (R^2) was employed as a key indicator for assessing the model's validation performance (Tsoka et al., 2018).



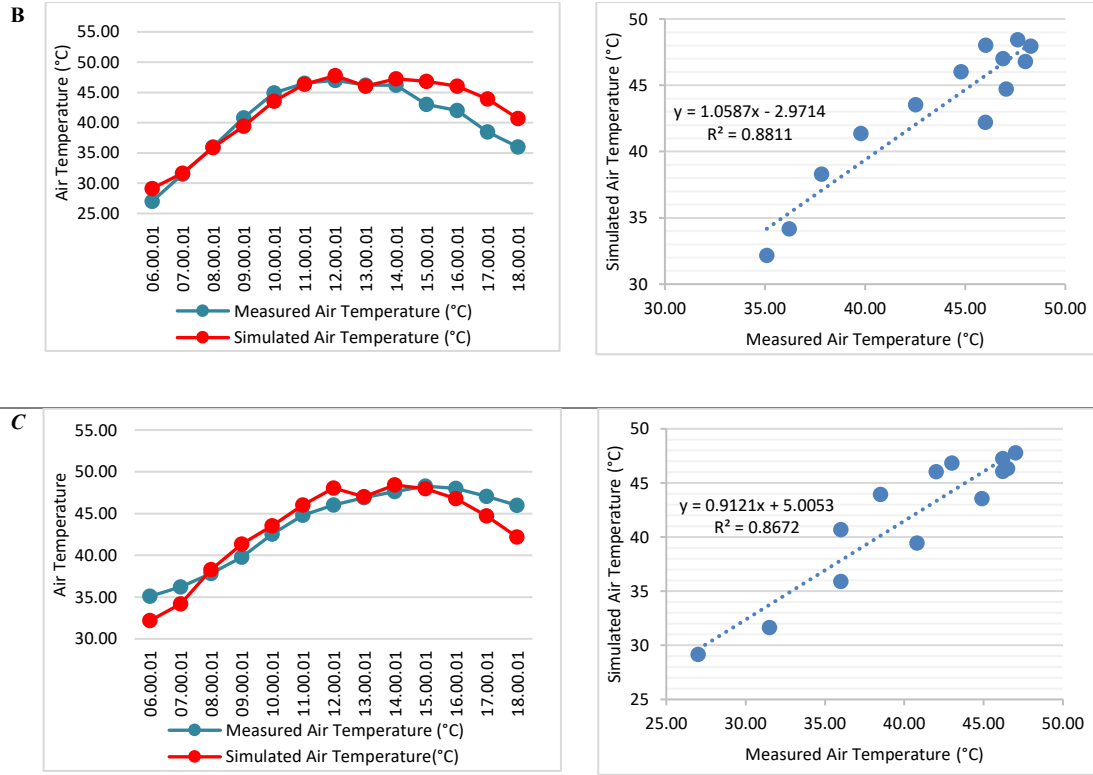


Figure 31: Temporal patterns of measured and simulated (T_a) and coefficient of determination (R^2) graph for (a) Cotton Canvas, (b) PVC, (c) HDPE.

Figure 31 displays the predicted and measured values of air temperature beneath the artificial shading device with the three different covering materials namely, Cotton Canvas (A), HDPE (B), and PVC (C). The datasets exhibit a strong correlation, reflected in the Regression Coefficient values (R^2) ranging between 0.867 and 0.923. Previous research indicates that these values fall within the range considered highly acceptable for model validation (Nasrollahi et al., 2021; Nazarian et al., 2019).

4.2.2 Validation of the weather file (EPW) with ENVI-met

To investigate the impact of the proposed artificial shading devices during the hall non-peak summer months, the study uses the EPW weather file extracted from (Dhahran-Abdulaziz. AB SH SAU 404160) located at King Abdulaziz Air Base (4.5 Kilometers away

from the study site). The validation process was performed by comparing the measured data with numerical results of air temperature and relative humidity of a receptor placed in the same point where the actual measurements were taken. The regression coefficient approaches for the air temperature were ($R^2=0.933$), which indicates a good correlation with the ENVI-met model, see Figure 32.

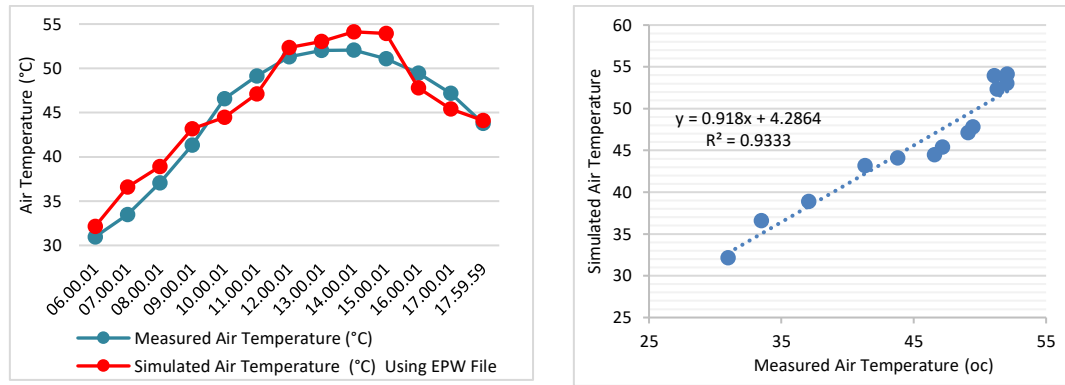


Figure 32: Temporal patterns of measured and simulated (T_a) using EPW file and coefficient of determination (R^2) graph.

4.2.3 Validation of the roof covering materials using Mean Absolute Error

The Mean Absolute Error (MAE) is a metric used to measure the accuracy of a simulation model by comparing its predictions to experimental data. It calculates the average absolute difference between the predicted and observed values. The first step is Calculate Absolute Errors: For each data point.

$$\text{Absolute Error}_i = |\text{Experimental Value}_i - \text{Simulated Value}_i|$$

Secondly, Compute Mean Absolute Error (MAE): Average these absolute errors over all data points. Where n is the number of data points.

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |\text{Experimental Value}_i - \text{Simulated Value}_i|$$

Table 8: Mean Absolute Error (MAE) for the Cotton Canvas.

Time	Measured Air Temperature (°C)	Simulated Air Temperature (°C)	Absolute Error
06.00.01	34.00	31.32	2.68
07.00.01	36.00	33.76	2.24
08.00.01	40.50	37.08	3.42
09.00.01	42.80	40.89	1.91
10.00.01	44.60	45.97	-1.37
11.00.01	47.20	48.21	-1.01
12.00.01	48.00	50.26	-2.26
13.00.01	49.20	48.33	0.87
14.00.01	48.20	48.98	-0.77
15.00.01	50.10	48.36	1.74
16.00.01	47.90	46.79	1.11
17.00.01	42.90	44.83	-1.93
18.00.01	41.00	41.95	-0.95
Average			5.67
MAE			0.44

Table 9: Mean Absolute Error (MAE) for the PVC.

Time	Measured Air Temperature (°C)	Simulated Air Temperature (°C)	Absolute Error
06.00.01	35.09	32.17	2.92
07.00.01	36.21	34.18	2.03
08.00.01	37.82	38.30	-0.47
09.00.01	39.79	41.35	-1.56
10.00.01	42.52	43.54	-1.01
11.00.01	44.80	46.02	-1.22
12.00.01	46.02	48.04	-2.01
13.00.01	46.89	47.02	-0.13
14.00.01	47.62	48.42	-0.80
15.00.01	48.28	47.96	0.32
16.00.01	48.01	46.80	1.21
17.00.01	47.05	44.71	2.33
18.00.01	46.00	42.21	3.79
Average			5.39
MAE			0.41

Table 10: Mean Absolute Error (MAE) for the HDPE.

Time	Measured Air Temperature (°C)	Simulated Air Temperature (°C)	Absolute Error
06.00.01	27	29.14	2.14
07.00.01	31.5	31.65	0.15
08.00.01	36	35.891	-0.109
09.00.01	40.8	39.432	-1.368
10.00.01	44.9	43.538	-1.362
11.00.01	46.5	46.332	-0.168
12.00.01	47	47.769	0.769
13.00.01	46.2	46.052	-0.148
14.00.01	46.2	47.242	1.042
15.00.01	43	46.823	3.823
16.00.01	42	46.021	4.021
17.00.01	38.5	43.921	5.421
18.00.01	36	40.68	4.68
Average			18.891
MAE			1.453153846

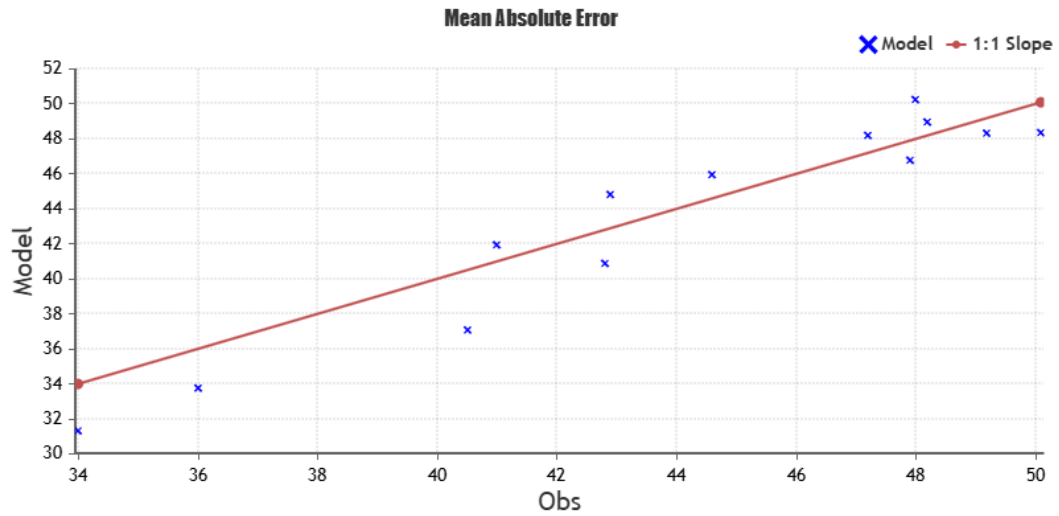


Figure 33: Mean Absolute Error (MAE) graph for the Cotton Canvas.

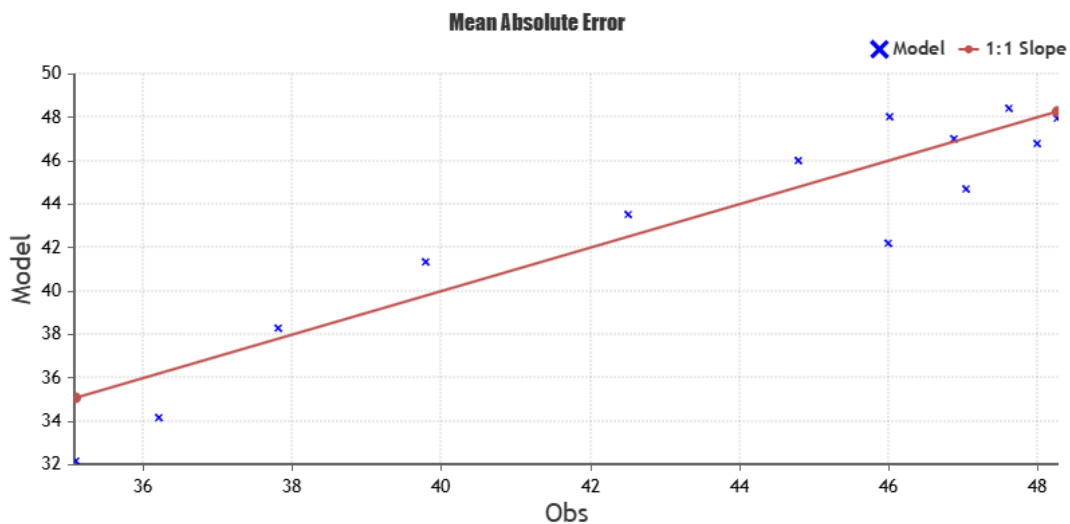


Figure 34: Mean Absolute Error (MAE) graph for the PVC.

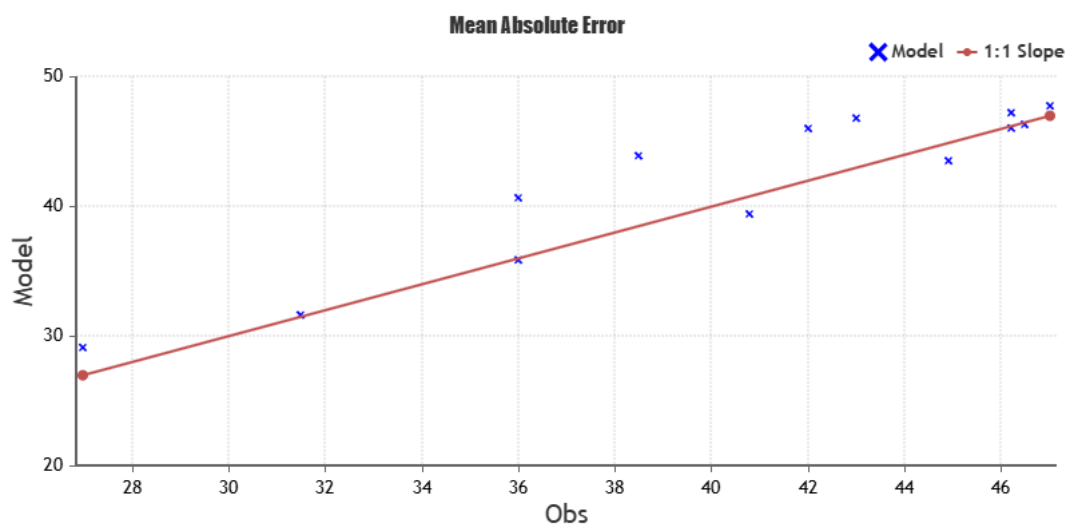


Figure 35: Mean Absolute Error (MAE) graph for the HDPE.

Tables 8, 9, and 10 show MAE values of 0.44, 0.41, and 1.45, respectively. These low MAE values indicate that, on average, the predicted values differ from the experimental values by small values, demonstrating a strong correlation. See Figure 33, 34, 35.

4.3 ENVI-met Simulation scenarios results

Given the notable disparities in T_a , T_{mrt} , and PET index, the study gives particular attention to these parameters. While variations in air velocity (V_a) and relative humidity (RH) are comparatively less pronounced, the analysis underscores the significance of these factors. It's worth noting that all results were collected at 1.5 meters above the ground.

4.3.1 Baseline Model Assessment

In order to evaluate the thermal comfort experienced by occupants at the 'KFUPM central square' across different seasons, the PET index was computed using ENVI-met. This analysis utilized a modified PET scale specifically tailored for arid climates (BWh), as detailed in the study conducted by (Elnabawi et al., 2016). This approach allowed for a comprehensive assessment of thermal conditions throughout the year, considering the unique climatic characteristics of the region. Figure 36 displays the simulated meteorological variables alongside the PET thermal comfort index at 15th of every month in 2023 covering the time span from 6 a.m. to 6 p.m. for the baseline model scenario at the study location. The simulation results depict a gradual increase in both air temperature (T_a) and mean radiant temperature (T_{mrt}) across the study area, commencing from 7 a.m. and peaking around 1 p.m. This trend aligns with the solar radiation profile, ultimately resulting in a corresponding rise in the PET values, which were recorded to be less than 30 °C at 6:00 a.m. The thermal conditions in the middle courtyard vary across a spectrum, ranging from the comfort level to the very hot grade, with intermediate stages including warm and hot levels that denote varying degrees of thermal discomfort. These fluctuations can be attributed to the direct exposure of the courtyard to sunlight throughout the day.

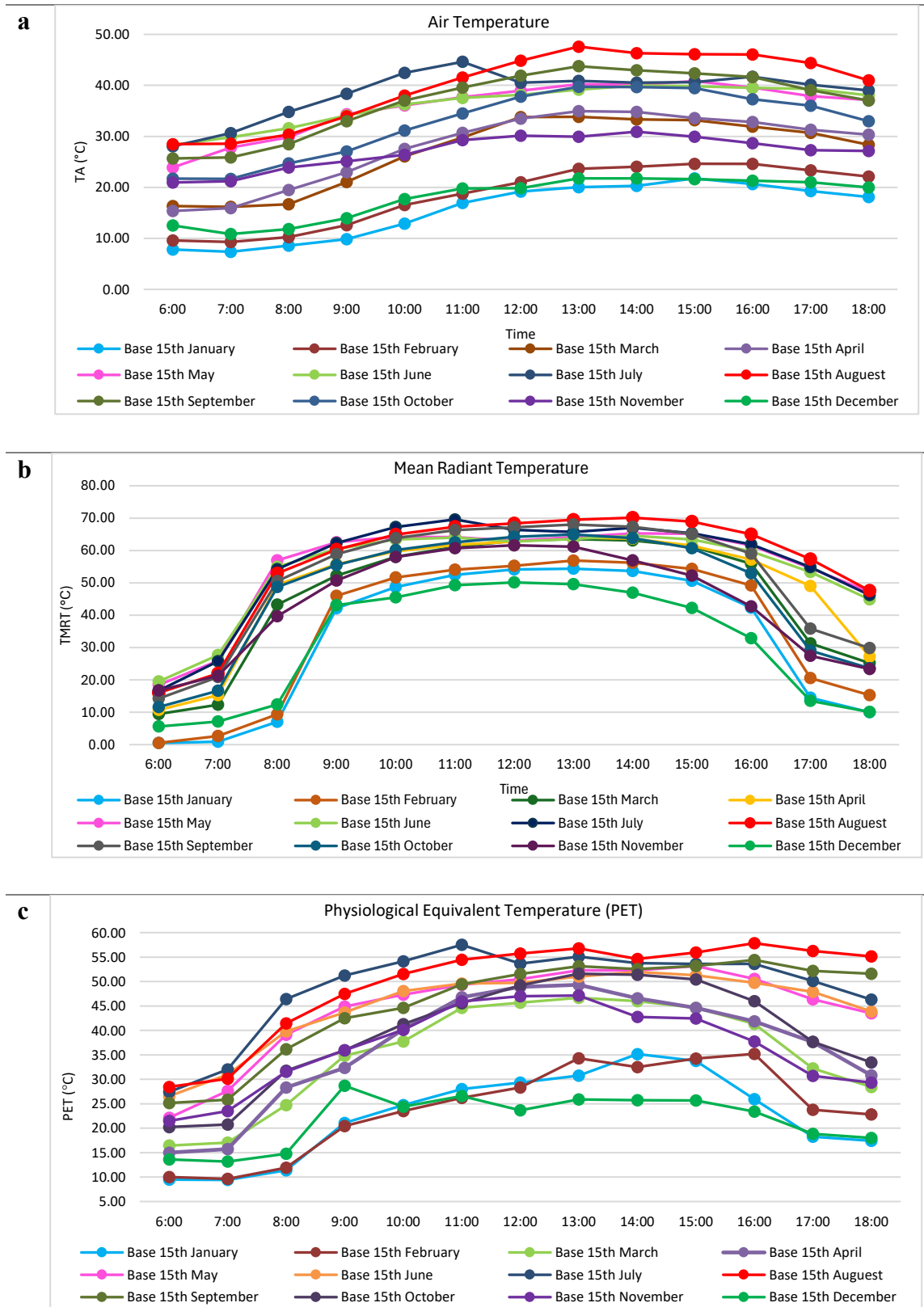


Figure 36: Simulated Ta, Tmrt, and PET values at 1.5 m above the ground for the Baseline Model (6 am.-6pm., for the hall year of 2023).

4.3.2 The cooling Effect of the proposed scenarios

Figure 38 depicts the diurnal variation in various meteorological variables under different simulation scenarios on 15th of March 2023. Throughout the study, it was observed that the impact of sun sails on air temperature (T_a) was minimal. Specifically, at noon, the effect of sun sails on T_a was most pronounced. Among the scenarios studied (S1, S2, S3, S4, and S5), the mean T_a was reduced by 0.57 °C, 0.62 °C, 0.49 °C, 0.29 °C, and 0.35 °C, respectively, at this time. These findings align with those of numerous prior studies, which have consistently demonstrated the cooling efficacy of sun sail shading devices. Specifically, the analysis indicates that HDPE sun sails, canvas sun sails, and PVC shading devices are capable of reducing the mean air temperature by up to 0.59 °C, 0.50 °C, and 0.40 °C, respectively (Elgheznawy & Eltarabily, 2021; Kántor et al., 2018; Lam et al., 2021). On the other hand, it can be observed that planting trees with high density leaf is the most efficient scenario, it can reduce T_a by more than 3 °C. and this results is in agreement with the results of (Armson et al., 2012), they found that the average differences in the air temperature between treeless places and the two street arrangements with trees reach over 1-2 °C.

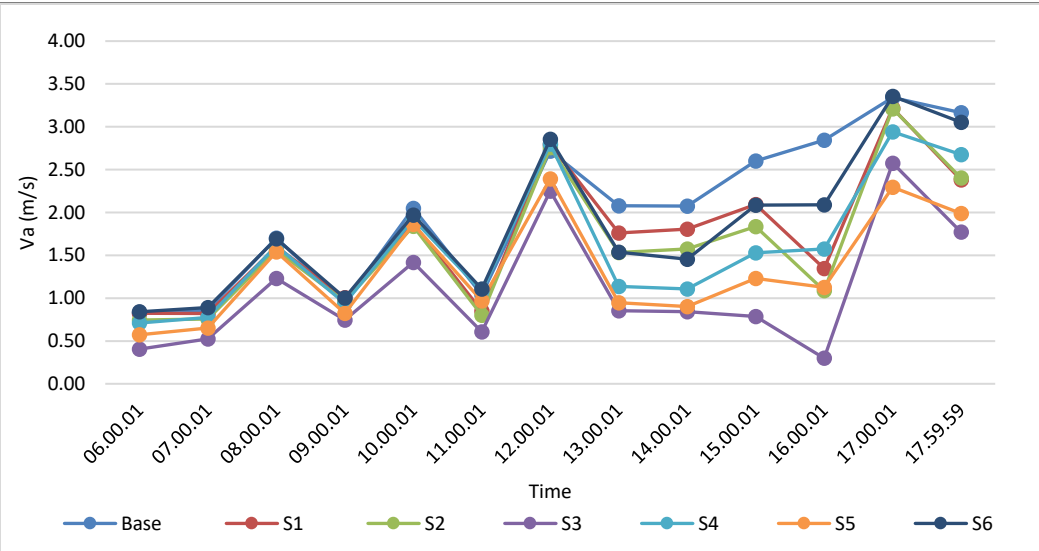
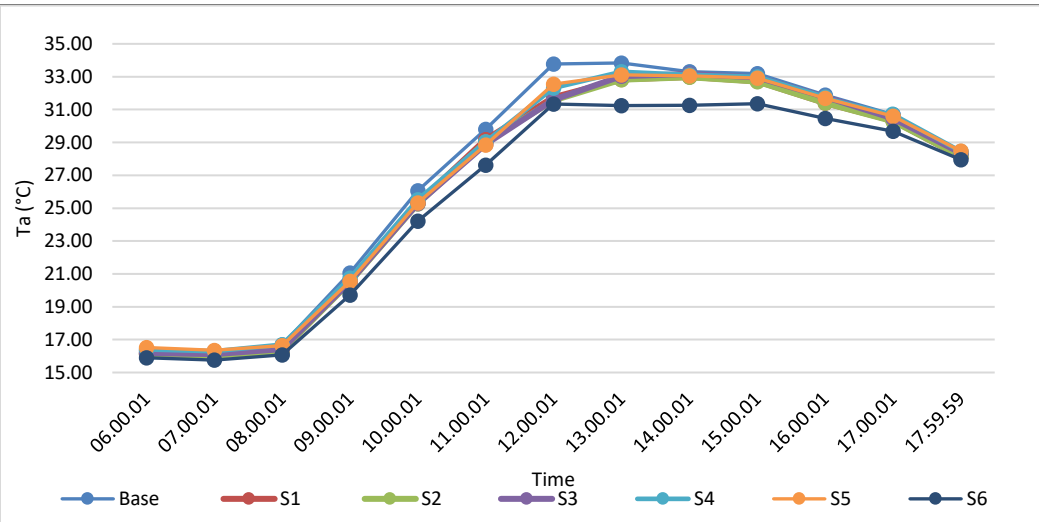
Throughout the study period, wind speeds (V_a) across all scenarios varied between 0.35 m/s and 3.36 m/s, as illustrated in Figure 38. Notably, the wind speed (V_a) exhibited changes ranging from 0.2 m/s to 1.00 m/s across different scenarios, particularly in response to the implementation of the sun sail strategy. Previous studies by (Garcia-Nevado et al., 2020; Zhao et al., 2024) have also confirmed the negligible impact of sun sails on wind speed (V_a). Furthermore, all scenarios have a negligible impact on the relative

humidity except S6; the green trees play a significant role in increasing the relative humidity percentage with more than 4%.

During the study period, there was a notable reduction in T_{mrt} , indicating the cooling performance of sun sails shading. During the morning hours, all scenarios demonstrated their maximum reduction in T_{mrt} . Specifically, the sun sail strategy for S1, S2, S3, S4, and S5 exhibited the highest area average T_{mrt} differences, measuring 18.12°C, 19.15°C, 20.05°C, 14.17°C, and 20.21°C, respectively. The result on T_{mrt} align with previous research conducted by (Elgheznawy & Eltarabily, 2021; Kántor et al., 2018), both of whom observed a reduction in T_{mrt} of 11.4 °C and 13.19 °C, respectively, with the addition of sun sail shading. It is evident that the highest reduction in T_{mrt} during the study period, exceeding 30°C, was achieved by covering the square with trees (Scenario 6).

Regarding PET, it is evident from Figure 37 that all the proposed scenarios notably enhanced the PET values. The cooling effects of all scenarios on PET exhibited a consistent change pattern, mirroring the reduction in the T_{mrt} values. Initially, during the morning hours, the reduction in PET value was significant, exceeding 8 °C, before gradually decreasing over time. This trend could be attributed to the emission of longwave radiation from sun sails towards users after they absorb solar radiation (Garcia-Nevado et al., 2020). Among the artificial shading scenarios, S4 and S5 emerged as the most effective during both morning and afternoon periods, with a maximum reduction of PET values amounting to 8.10 °C and 8.19 °C, respectively, observed at 9:00. These findings align with the conclusions drawn by (Elgheznawy & Eltarabily, 2021), who proposed that sun sail shading has the potential to decrease heat stress levels by 1-2 categories, thus transitioning them from severe to warm or moderate. On the other hand, the green shading strategies

(S6) achieve the optimum reduction in PET reaching more than 13 °C at 12:00. These results agree with the results of (Darvish et al., 2021), who found that tree shading can achieve a reduction in PET value with more than 14 °C. In general, the efficacy of these four scenarios in enhancing thermal comfort throughout the day is closely tied to their capacity to manage direct solar radiation exposure. Figure 38 illustrate the spatial distribution outcomes of both T_{mrt} and PET at 10:00 am on the 15th of March for S5.



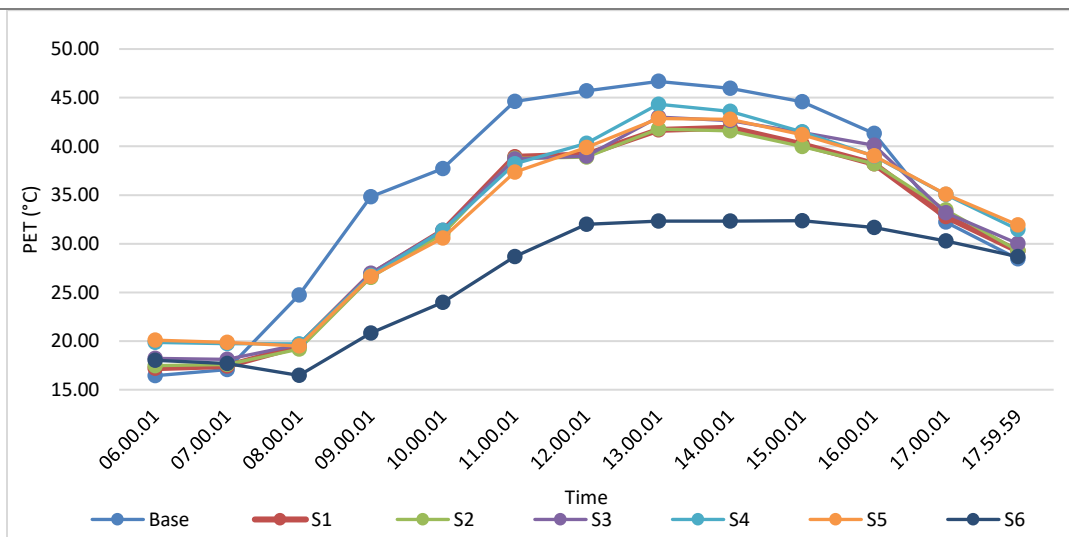
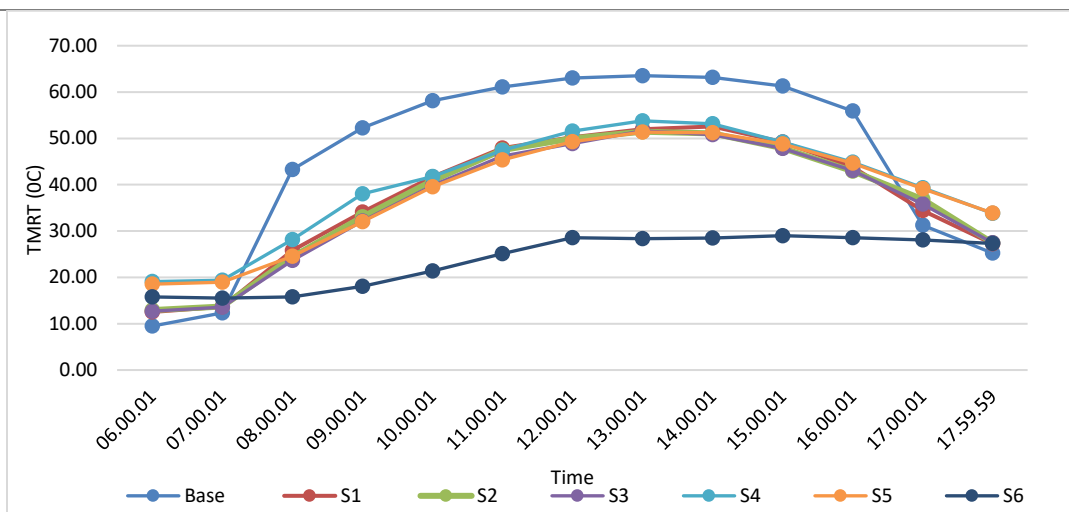
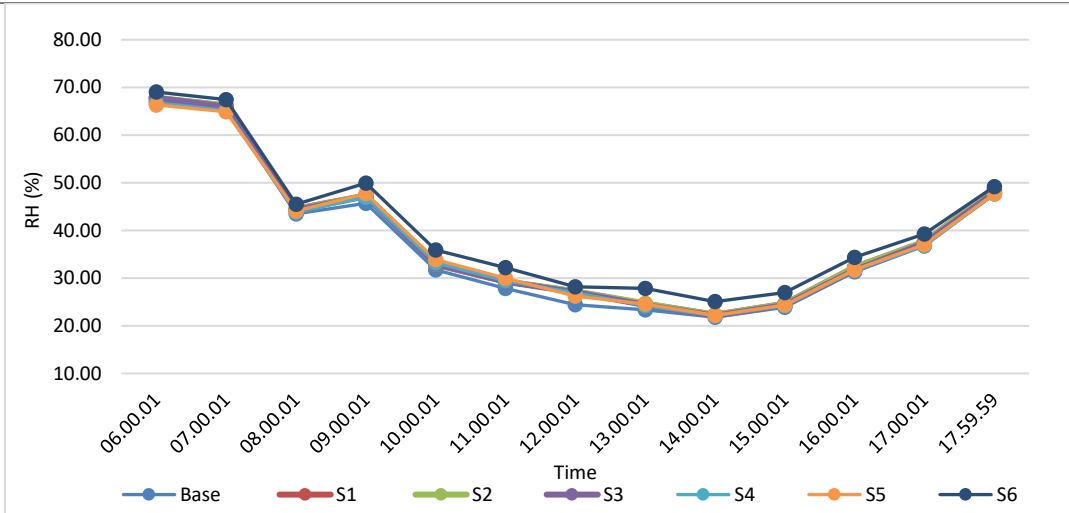


Figure 37: Simulation results of microclimate parameters for the proposed scenarios.



S6= 100% Tree
shading

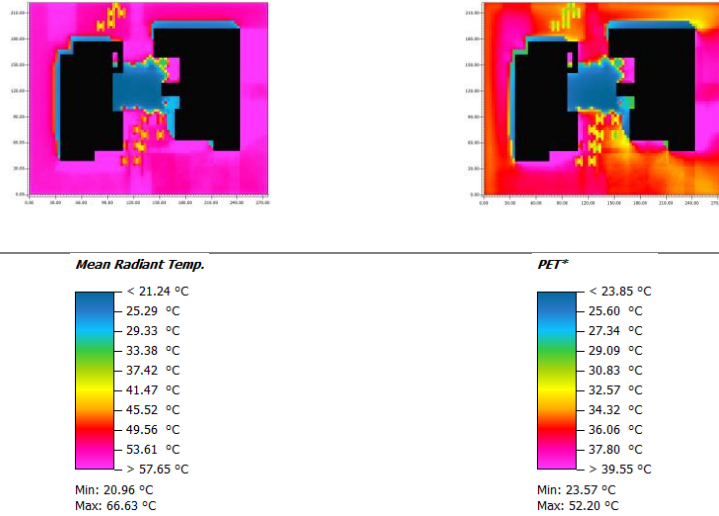


Figure 38: Contour map of Tmrt and PET distribution in the different scenarios at 10:00 A.M.

4.3.3 The effect of shading height

As elaborated in the previous section, the proposed scenarios, which are based on artificial shading, have been modeled at 3 different heights = 4m, 8m, and 12m at the top of the central square. ENVI-met software was used to simulate scenario 5 with the three proposed heights on 15th of March to obtain PET results of the proposed scenarios and compare them. To study the impact of the height we took three measurement points (@ the Center, @ the northern edge, and @ the Southern edge) as shown in Figure 39.

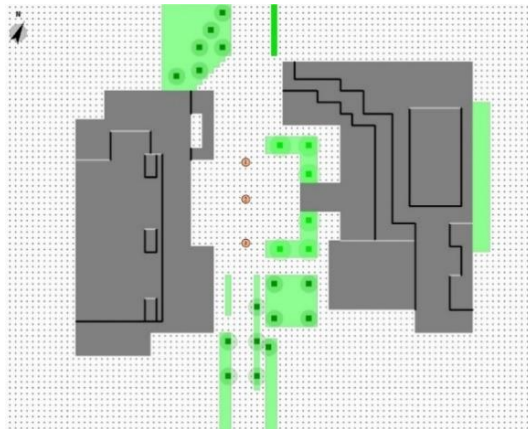


Figure 39: Site Plan defining the three measurement points.

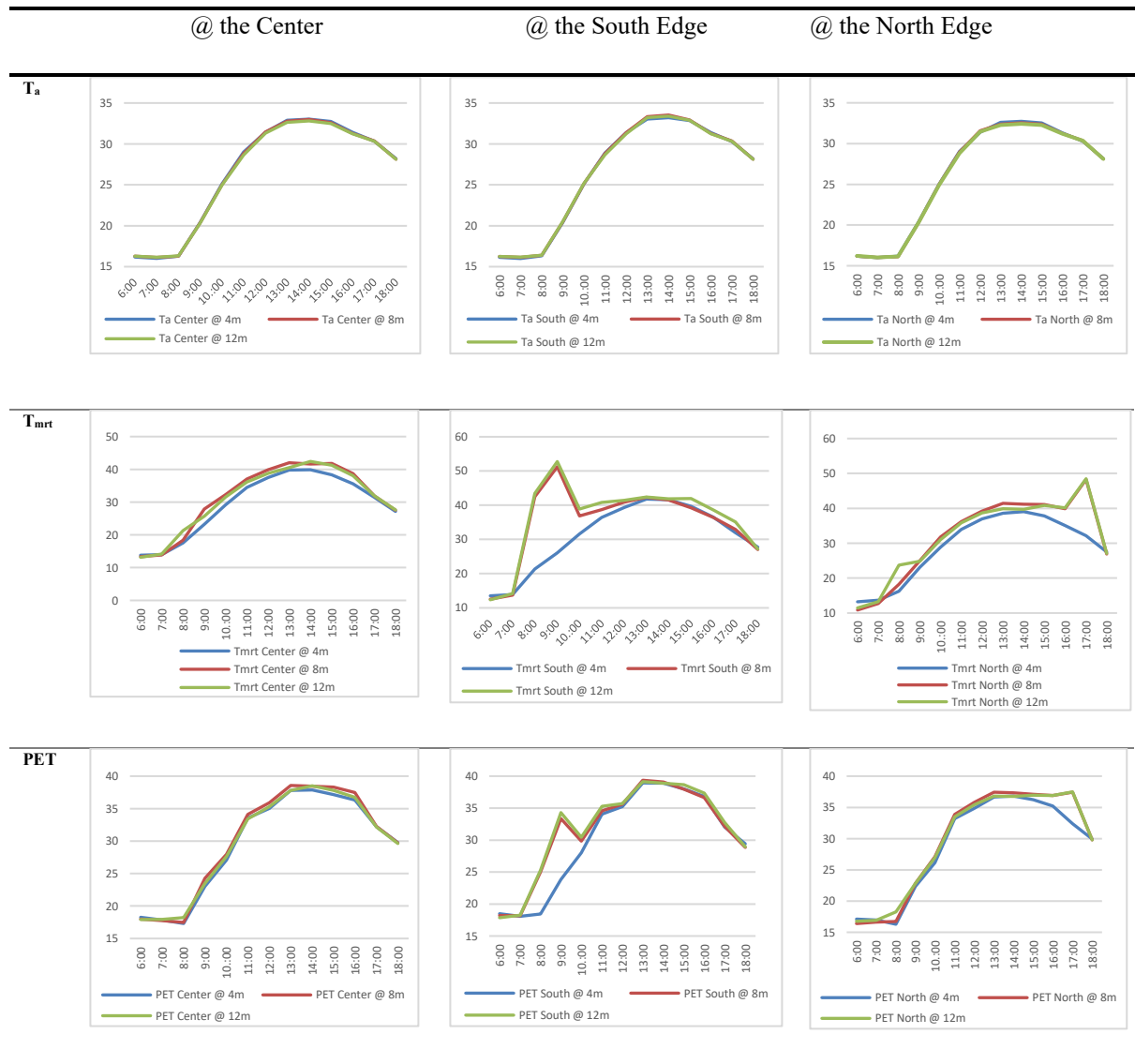


Figure 40: Simulation Result of Ta, Tmrt and PET @ three different height.

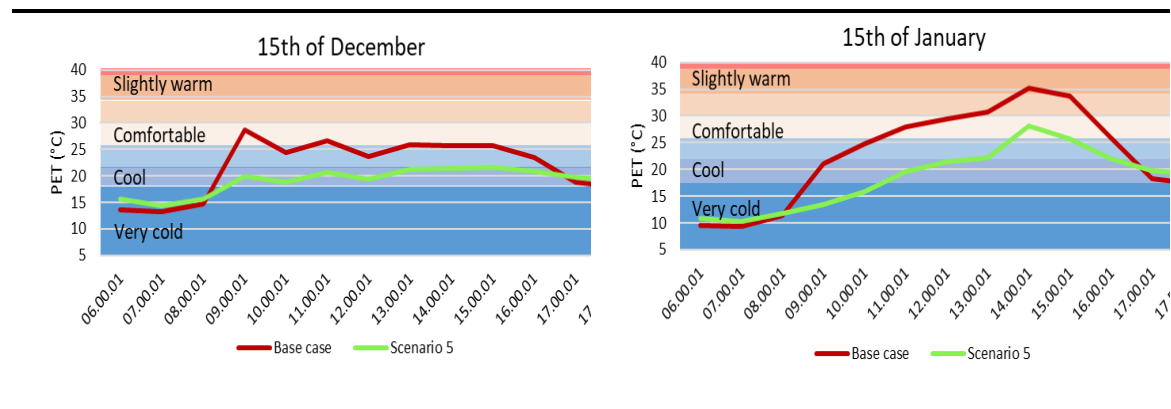
From the result one can observe that the height of the shade had a negligible impact on the T_a . On the other hand, the height of the shade had a notable effect on the T_{mrt} and PET especially at both edges of the shading area and that's refers to Sun angle. As one can see during the morning hours the sun goes deep beneath the shading structure from the south side and the same phenomena recorded at late noon hours from the northern side at the sun set, See Figure 40.

4.4 The effect of artificial shading on the PET throughout the year

As mentioned above, S5 is considered as the best artificial shading scenario, in the next section the study runs S5 throughout the year to see the cooling performance by month using the EPW weather file. The reduction in PET values is measured in reference to scenario S0 (Baseline). The results were divided into three parts representing the results during summer, winter and moderate seasons.

- The Cooling Effect of Scenario 5 during Winter Months

The PET thermal comfort profile for the base case during the winter season was within the comfort zone. On the 15th of December there was no need to shade the plaza unless there is a need to provide visual comfort to the users of the space. However, on January 15th and February 15th, the base case profile moved outside the comfort zone after 11 a.m. In these instances, the shading scenario S5 provided effective cooling, reducing PET values by up to 8 °C, see Figure 41.



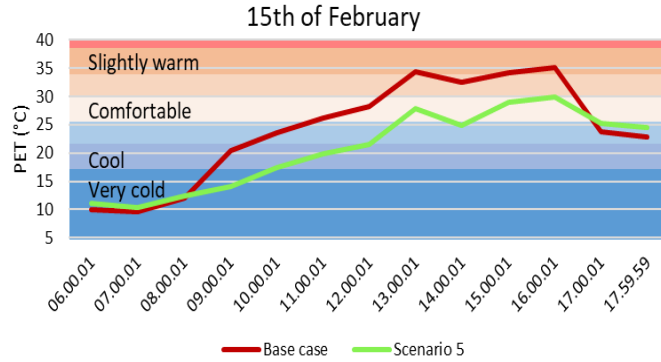


Figure 41: The Cooling Effect of Scenario 5 during Winter Months.

- The Cooling Effect of Scenario 5 during moderate Months

The PET thermal comfort profile for the base case during the moderate season exceeded the comfort zone immediately after 8 am. The shading scenario S5 provided effective cooling performance during the morning hours, reducing the PET values by up to 8 °C, see Figure 42.

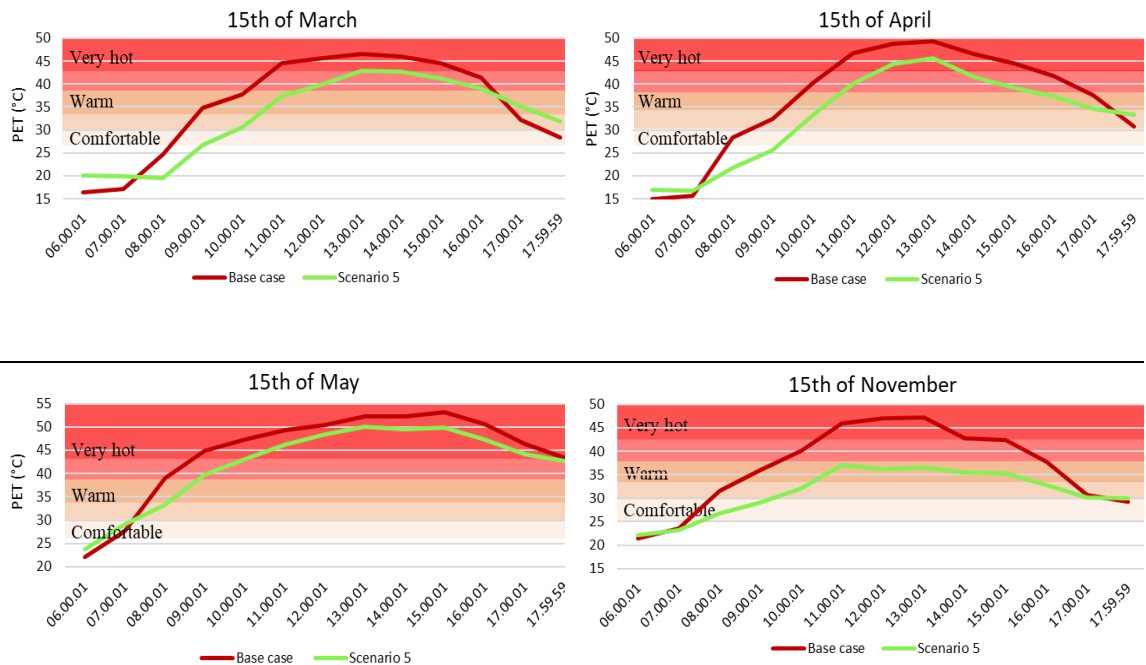


Figure 42: The Cooling performance of Scenario 5 during moderate Months.

- The Cooling Effect of Scenario 5 during summer Months

The PET thermal comfort profile for the base case during the summer season exceeded the comfort zone immediately after 6 am. It can be noted that the cooling performance of the shading device became less during the peak summer months, and that refer to the harsh summer condition in Saudi Arabia in which the PET profile reach more than 55 °C, see Figure 43.

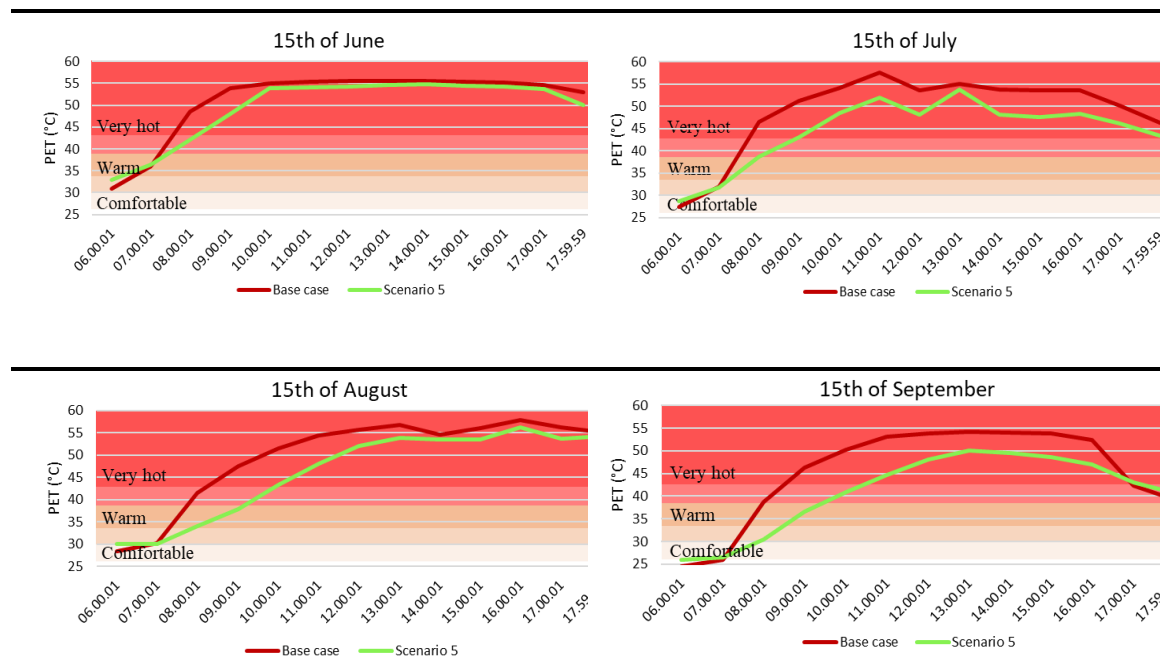
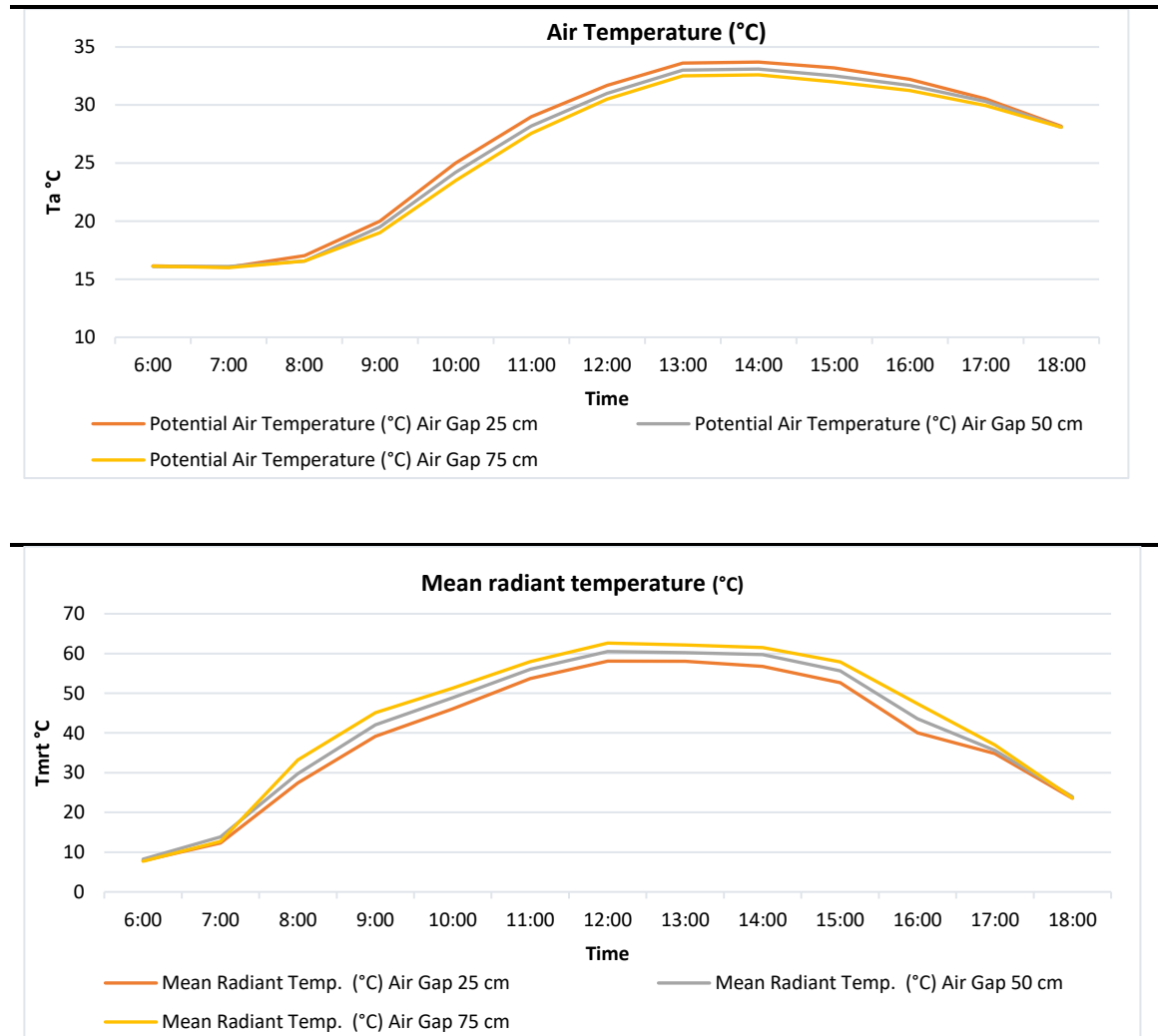


Figure 43: The Cooling Effect of Scenario 5 during summer Months.

4.5 The effect of artificial shading on the PET throughout the year

To investigate the impact of the air gap between the two layers of the shade cover on enhancing the outdoor thermal environment, the study simulated four different spacing sizes: 25 cm, 50 cm, and 75 cm. All scenarios were run on the 15th of March 2023. The

results indicated that the lowest air temperature (T_a) was recorded with a 75 cm air gap, suggesting that increasing the air gap leads to a significant reduction in T_a . Conversely, the lowest values of mean radiant temperature (T_{mrt}) and PET were recorded with a 25 cm air gap. This is because a smaller air gap acts as thermal insulation, see Figure 44.



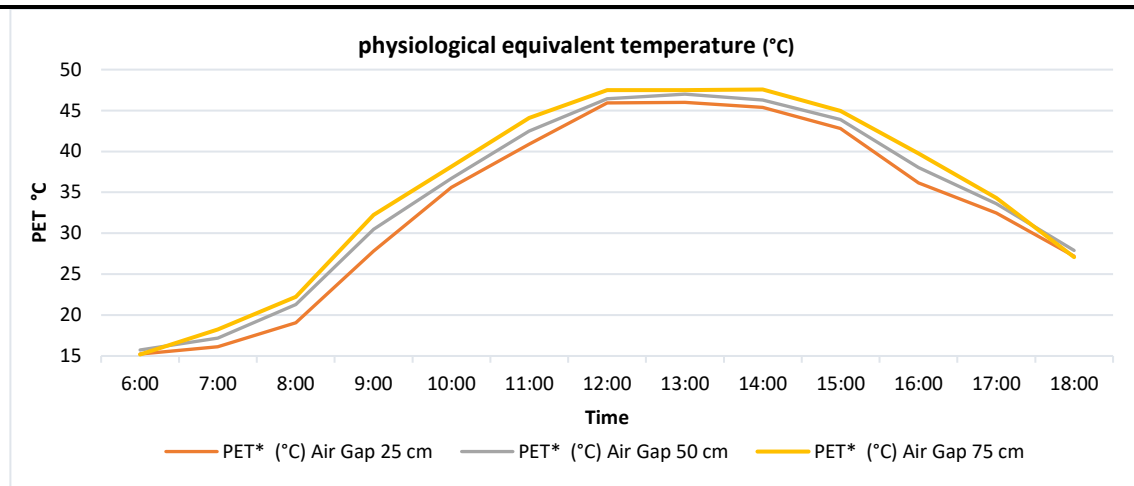


Figure 44: The effect of different sizes of air gap on Ta, Tmrt, and PET.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

The implementation of effective urban cooling strategies in outdoor spaces can significantly decrease urban heat stress, enhance walkability, and improve overall livability in cities. This study seeks to assess the cooling performance of artificial shading devices with different coverage ratios, heights, and vegetation types on enhancing outdoor thermal comfort (OTC) in university squares using the ENVI-met simulation model and to provides essential insights for urban planners and architects in hot-humid climates like Dhahran, offering practical guidance for optimizing outdoor spaces. The findings can be summarized as follows:

1. Notably, shading device height has minimal impact on air temperature but significantly affects mean radiant temperature and PET. A height of 4 meters proved optimal, enhancing thermal comfort while avoiding unnecessary costs. Compared to 8-meter and 12-meter heights, the 4-meter shading height achieved temperature reduction exceeding 20°C in mean radiant temperature and 8°C in PET during morning and late afternoon hours.
2. The study shows that a double roofing system with a 100% coverage ratio and a 4-meter height (Scenario 5) provided the greatest reduction in heat stress, with reductions exceeding 13°C in mean radiant temperature and 8°C in PET. This suggests that, in future designs, the focus should be on maximizing coverage and using materials with high thermal capacity and low thermal conductivity, such as Cotton Canvas and HDPE, while keeping the height moderate. This approach can achieve substantial cooling effects while ensuring cost efficiency.
3. Additionally, the impact of a 25 cm air gap in double roofing, acting as thermal insulation increasing the PET index reduction by an average of 2.2°C. This finding encourages urban planners to consider incorporating air gaps or other thermal

insulation methods in shading devices, enhancing outdoor thermal comfort without the need for more complex or expensive interventions.

4. Overall, the study supports the development of targeted urban cooling strategies that are both effective and economically viable. It underscores the importance of thoughtful material selection and shading configurations to create thermally comfortable environments in hot desert climates. By applying these findings, urban designers can create more livable outdoor spaces while optimizing resource use, offering practical solutions to mitigate heat stress in public spaces.

Recommendations

- Future work should focus on investigating the cooling performance of new covering materials that have a good thermal performance in terms of thermal conductivity and heat thermal capacity like the Teflon membrane (PTFE).
- There is a need to investigate the cooling performance of artificial shading devices combined with other urban cooling strategies from the cool reflective material category or the interactive water feature (sprinklers).
- Future studies can investigate the role of applying an artificial source of wind to increase the air flow under the shading structure.
- Future studies should investigate different shapes of shading devices.
- Finally, more effort should be made to investigate the cooling effect of the air gap of the double roofing shading device.

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Recent Research Topics

1. Evaluating the Performance of Outdoor Shading Devices on Human Thermal Comfort in Hot Humid Climates: A Case Study of Dhahran (Paper under review submitted to Building and Environment Journal)