PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCHSAAD DAHLAB

BLIDA UNIVERSITY -01-

INSTITUTE OF ARCHITECTURE AND URBAN PLANNING

Department of Architecture

Master's thesis in Architecture.

Workshop theme:

Architecture, Environment and Technology

F.G.P: Optimizing Outdoor Thermal Comfort in Educational Environments :

Redesigning the Outdoor Space of the Institute of Architecture

and Urbanism, University of Blida 1

Presented by:

MEGHERFI sidali (202032038247)

CHEBBOUB mohamed (202032054550)

SUPERVISOR : Dr.SAYAD Bouthaina

JURY COMMITTEE:

Dr.KAOULA dalel

Dr.ABDERRAHIM ZIROUT nabila

2024/2025

Acknowledgment

We would first like to express our gratitude and heartfelt thanks to our beloved parents, brothers, and sisters — may God protect them. You are our inspiration and our greatest support. Your unwavering encouragement, prayers, and strength enabled us to successfully complete this project. Without you, this work could never have been accomplished.

We extend our deep appreciation and special recognition to our supervisor, Dr. Sayyad Bouthayna. We thank you for agreeing to guide us, for your continuous support, and for helping us deepen our knowledge allowing us to produce work that we are truly proud of.

Our thanks also go to the members of the jury who kindly accepted to evaluate our work. We are grateful for their efforts in enriching our research.

A special thank-you is dedicated to our families the best people we have known in our lives and to all our loyal friends, each by name, whose support and encouragement have been a great help throughout this journey.

We also express our gratitude to the staff of the Institute of Architecture and Urbanism (IAU), and especially to the administration of our institute, from the leadership to the simplest employee, for their excellent management from the time of the former director, Dr. Ait Saadi, to the era of the current director, Dr. Mahindad Abderrahim. Their dedication and professionalism have been invaluable.

We would also like to thank our cherished family — the IBDAA Club — for the precious experiences and the positive atmosphere they provided.

Finally, we sincerely thank all the professors under whose guidance we studied during these five years. Their influence and support were essential in enabling us to reach the level we are at today.

Abstract (English)

As global climate conditions continue to change, the need to enhance outdoor thermal comfort in educational settings has become increasingly urgent. Rising temperatures, intensifying urban heat island effects, and the lack of climate-responsive design pose serious challenges to the usability and quality of open spaces in university environments. In hot and semi-arid regions such as Algeria, outdoor thermal discomfort can significantly affect student well-being, learning experiences, and social interaction, especially in exposed courtyards and circulation areas that lack appropriate environmental moderation.

This study focuses on the courtyard of the Institute of Architecture and Urbanism at Saad Dahlab University – Blida 1, which suffers from intense solar exposure, inadequate vegetation, minimal shading, and unoptimized surface materials. Although such courtyards are intended to support movement, relaxation, and informal learning, their design often fails to account for local climatic challenges, resulting in spaces that are underused during periods of high thermal stress and perceived discomfort.

The objective of this research is to assess and improve outdoor thermal comfort through passive design strategies tailored to the site's microclimatic context. The goal is to enhance user experience, increase space utilization, and promote a more comfortable educational environment that supports health, engagement, and academic productivity. The research is grounded in thermal comfort theory, with a particular focus on how vegetation and green infrastructure, shading and passive solar design, urban morphology and wind flow optimization, and water-based cooling strategies influence outdoor microclimates in educational institutions.

The methodology combines a literature review on outdoor thermal comfort parameters and best practices with a detailed analysis of the current conditions of the university courtyard. The study utilizes digital microclimate simulations using ENVI-met software. Various design scenarios are modeled to test the thermal impact of different interventions, including increased vegetation coverage, the addition of shading devices, the introduction of water features, and the use of reflective or permeable materials. Thermal comfort is evaluated through key indices such as PET (Physiological Equivalent Temperature), PMV (Predicted Mean Vote), SET* (Standard Effective

Temperature), and UTCI (Universal Thermal Climate Index), which are widely used in environmental design research.

The results demonstrate that combining vegetation, shading structures, water and cooling strategies, and appropriate material choices can lead to a significant reduction in perceived heat stress. The simulations show a clear improvement in thermal comfort levels during peak summer hours, with some areas shifting from extreme heat stress to moderate or comfortable conditions. This study contributes to climate-adaptive campus design by offering a replicable framework that integrates ecological and passive solutions to improve outdoor environments in hot climate universities.

Key words: Outdoor thermal comfort – ENVI-met simulation – Passive design strategies – Hot climate adaptation – Educational environments

Résumé (Français)

Avec l'évolution constante du climat mondial, l'amélioration du confort thermique extérieur dans les établissements d'enseignement devient une priorité croissante. L'élévation des températures, l'intensification de l'effet d'îlot de chaleur urbain et l'absence de conception adaptée au climat posent des défis majeurs à l'utilisation et à la qualité des espaces ouverts dans les environnements universitaires. Dans les régions chaudes et semi-arides comme l'Algérie, l'inconfort thermique extérieur peut fortement impacter le bien-être des étudiants, leur expérience d'apprentissage et leurs interactions sociales, en particulier dans les cours et les zones de circulation exposées, mal modérées sur le plan climatique.

Cette étude porte sur la cour de l'Institut d'Architecture et d'Urbanisme de l'Université Saad Dahlab – Blida 1, caractérisée par une forte exposition solaire, une végétation insuffisante, peu d'ombrage et des matériaux de surface mal adaptés. Bien que ces cours soient censées faciliter la circulation, la détente et l'apprentissage informel, leur conception ne tient souvent pas compte des contraintes climatiques locales, rendant ces espaces peu fréquentés lors des périodes de stress thermique élevé.

L'objectif de cette recherche est d'évaluer et d'améliorer le confort thermique extérieur à travers des stratégies de conception passive adaptées au contexte microclimatique du site. Elle vise à améliorer l'expérience des usagers, optimiser l'utilisation des espaces et offrir un environnement éducatif plus confortable, propice à la santé, à l'engagement et à la productivité académique. La recherche s'appuie sur la théorie du confort thermique, en mettant l'accent sur l'influence de l'infrastructure verte, de l'ombrage, de la morphologie urbaine et de la ventilation, ainsi que des stratégies de refroidissement par l'eau.

La méthodologie repose sur une revue de littérature des paramètres du confort thermique extérieur et des meilleures pratiques, ainsi qu'une analyse détaillée de l'état actuel de la cour universitaire. L'étude utilise des simulations numériques du microclimat via le logiciel ENVI-met. Divers scénarios sont modélisés afin de tester l'impact thermique d'interventions telles que l'augmentation de la végétation, l'ajout de structures d'ombrage, l'introduction d'éléments d'eau et l'utilisation de matériaux réfléchissants ou perméables. Le confort thermique est évalué à l'aide d'indices clés tels que le PET, le PMV, le SET* et l'UTCI.

Les résultats montrent que la combinaison de végétation, de structures d’ombrage, de stratégies de refroidissement par l’eau et de matériaux adaptés permet une réduction significative du stress thermique perçu. Les simulations révèlent une nette amélioration du confort thermique pendant les heures de forte chaleur, avec des zones passant d’un stress thermique extrême à des conditions modérées ou confortables. Cette étude propose un cadre reproductible pour la conception climatique des campus dans les régions chaudes.

Mots-clés : Confort thermique extérieur – Simulation ENVI-met – Stratégies de conception passive – Adaptation au climat chaud – Environnements éducatifs

الملخص (عربي)

مع التغير المستمر في المناخ العالمي، أصبحت الحاجة إلى تحسين الراحة الحرارية الخارجية في المؤسسات التعليمية أكثر إلحاحًا من أي وقت مضى. تؤدي درجات الحرارة المرتفعة، وتأثير جزيرة الحرارة الحضرية، وغياب التصميم المتكيف مع المناخ إلى تحديات كبيرة في جودة واستخدام الفضاءات المفتوحة داخل الجامعات. وفي المناطق الحارة وشبه الجافة مثل الجزائر، يمكن لعدم الراحة الحرارية الخارجية أن يؤثر بشكل كبير على رفاهية الطلبة، وتجربتهم التعليمية، وتفاعلهم الاجتماعي، خصوصًا في الساحات المكشوفة ومسارات الحركة التي تفتقر إلى المعالجات المناخية المناسبة.

تركز هذه الدراسة على ساحة معهد الهندسة المعمارية والتعمير بجامعة سعد دحلب – البليدة 1، والتي تعاني من تعرض شديد لأشعة الشمس، نقص في الغطاء النباتي، قلة في الظلال، وسوء في اختيار المواد السطحية. ورغم أن هذه الساحات مخصصة للحركة والاستراحة والتعلم غير الرسمي، إلا أن تصميمها لا يأخذ بعين الاعتبار التحديات المناخية المحلية، مما يجعل استخدامها محدودًا خلال فترات الحرارة المرتفعة والإجهاد الحراري.

تهدف هذه الدراسة إلى تقييم وتحسين الراحة الحرارية الخارجية من خلال استراتيجيات تصميمية سلبية تتوافق مع السياق المناخي المحلي. وتتمثل الغاية في تعزيز تجربة المستخدم، وزيادة استغلال الفضاء، وتوفير بيئة تعليمية أكثر راحة تدعم الصحة والمشاركة والإنتاجية الأكاديمية. وتستند الدراسة إلى نظرية الراحة الحرارية، مع التركيز على دور البنية الخضراء، والظل، والمورفولوجيا الحضرية، وتحسين تدفق الرياح، واستراتيجيات التبريد بالماء في تحسين المناخ المحلي الخارجي.

تعتمد المنهجية على مراجعة الأدبيات المتعلقة بمعايير الراحة الحرارية الخارجية والممارسات الدولية الناجحة، إلى جانب لمحاكاة السيناريوهات المناخية. وتم اختبار ENVI-met تحليل مفصل للحالة الحالية للساحة الجامعية. وقد تم استخدام برنامج تأثير تدخلات مختلفة مثل زيادة الغطاء النباتي، تركيب مظلات، إدخال عناصر مائية، واستخدام مواد عاكسة أو نفاذة. وتم تقييم الراحة الحرارية من خلال مؤشرات معتمدة تشمل PET وPMV وSET* وUTCI.

تُظهر النتائج أن الجمع بين الغطاء النباتي، وهياكل التظليل، واستراتيجيات التبريد بالمياه، واختيار المواد المناسبة يمكن أن يؤدي إلى تقليل كبير في الشعور بالإجهاد الحراري. وتكشف المحاكاة عن تحسن ملحوظ في مستويات الراحة الحرارية خلال ساعات الذروة، حيث تتحول بعض المناطق من الإجهاد الحراري الشديد إلى حالات أكثر اعتدالًا أو راحة. تقدم هذه الدراسة إطارًا قابلاً للتكرار في تصميم الجامعات المتكيفة مناخيًا في المناطق الحارة.

الكلمات المفتاحية

استراتيجيات التصميم السلبي – التكيف مع المناخ الحار – البيئات – ENVI-met الراحة الحرارية الخارجية –محاكاة التعليمية

Table of contents

Table of Contents

CHAPTER I

General Introduction

1. Background

Climate change has emerged as one of the most critical global threats, profoundly impacting urban environments and their outdoor spaces. The rising global temperatures, primarily driven by greenhouse gas emissions, have intensified heatwaves, altered precipitation patterns, and caused extreme climate events (IPCC, *Climate Change 2021: The Physical Science Basis*, 2021). Urban areas face these effects more acutely due to the urban heat island (UHI) effect, which leads to significantly higher temperatures than surrounding rural zones (Oke, *Boundary Layer Climates*, 1987). Consequently, outdoor spaces are becoming increasingly uncomfortable, reducing their usability and affecting public health and well-being (World Health Organization, *WHO Guidance for Climate-Resilient and Environmentally Sustainable Health Care Facilities*, 2021).

The altered climatic conditions compromise biodiversity and reduce the efficacy of natural cooling systems such as trees and water bodies. Prolonged heat exposure discourages outdoor activities, weakening social engagement and community life. As highlighted by Kabisch et al., "urban green spaces play a critical role in promoting social interaction and physical activity, yet are vulnerable to climate extremes" (*Human–Environment Interactions in Urban Green Spaces*, 2015, p. 26). Additionally, increased reliance on artificial cooling systems due to rising temperatures leads to higher energy consumption and worsens air pollution (International Energy Agency, *The Future of Cooling*, 2022).

The effects of climate change are also evident in rising sea levels, flooding, and the degradation of natural environments, which necessitate innovative and adaptive urban design. Effective approaches include expanding green infrastructure, employing sustainable water management, and selecting climate-resilient materials (International Union for Conservation of Nature, *Nature-Based Solutions and Climate Change*, 2020). Regulatory frameworks must support the integration of sustainable solutions and environmental protection in urban planning (UN-Habitat, *Planning for Climate Change: A Strategic Values-Based Approach*, 2014).

Outdoor spaces in educational settings are particularly vulnerable, despite their essential role in student life. They provide venues for socialization, relaxation, and informal learning. Research suggests that well-designed outdoor environments significantly enhance mental well-being,

academic engagement, and cognitive development (Kelz, Evans & Röderer, *The Restorative Effects of Redesigning the Schoolyard*, 2015). Contact with nature on campuses helps lower stress, improve focus, and promote physical health (OECD, *Environment and School Initiatives*, 2006).

Beyond their health benefits, outdoor educational spaces foster collaborative learning and community building. They serve as informal classrooms where students engage in discussions, experiments, and creative activities. According to OECD, "engaging with the natural environment fosters curiosity and experiential learning, particularly in environmental and sustainability education" (*Environment and School Initiatives*, 2006, p. 15).

Nevertheless, ensuring the usability of these spaces throughout the year requires thoughtful climatic adaptation. Effective design strategies must address extreme heat through shading, reflective surfaces, and natural cooling. Features such as pergolas, water elements, and climate-responsive vegetation can extend the comfort and functionality of outdoor spaces. Adaptive measures like seasonal planting and flexible furniture arrangements further enhance their use.

In warm climates, ensuring thermal comfort in outdoor spaces is particularly challenging due to intense solar radiation and limited ventilation. Lack of vegetation, poor material choices, and inadequate shading contribute to heat buildup (Ali-Toudert & Mayer, *Effects of Asymmetry, Galleries, Vegetation, and Materials on Outdoor Thermal Comfort*, 2007). Materials like concrete and asphalt trap heat, worsening thermal discomfort. Likewise, poorly designed shade can obstruct airflow, leading to heat retention rather than relief.

Cooling strategies in such environments must include water-based systems and green infrastructure. While water features provide evaporative cooling, water scarcity demands alternatives like misting systems and permeable pavements. Reflective materials and strategic wind flow management are also critical. Vegetated roofs, vertical gardens, and shaded corridors can reduce surface temperatures while improving aesthetics and ecological quality (Gaitani, Mihalakakou & Santamouris, *On the Use of Bioclimatic Architecture Principles*, 2007).

Urban planning policies should promote climate-resilient designs and encourage community awareness about sustainable practices. Building educational capacity in these areas ensures that

local solutions are aligned with environmental needs. Collectively, these approaches are vital for developing sustainable, comfortable, and livable outdoor spaces in hot climatic regions.

2. Problem Statement

Saad Dahlab Blida 1 University, particularly the Institute of Architecture and Urbanism, presents significant thermal discomfort in its outdoor spaces. The campus features several open areas used for circulation, socializing, and academic activities. However, many of these spaces suffer from extreme heat exposure, lack of shading, and poor microclimate management, leading to decreased usability, particularly during the warmer months. This raises critical questions: What are the key parameters influencing outdoor thermal comfort, and what design strategies can enhance outdoor usability?

3. Hypothesis

Improving the design of outdoor spaces at Saad Dahlab Blida 1 University through the strategic use of shading, vegetation, climate-responsive materials, and passive cooling techniques will significantly enhance thermal comfort, increase space usability, and promote student well-being and engagement in outdoor academic and social activities.

4. Research Objectives

This study aims to explore and address the challenges of outdoor thermal comfort in educational environments, with a specific focus on the Institute of Architecture and Urbanism at Saad Dahlab Blida 1 University. The objectives of this research are as follows:

- To identify the key factors influencing thermal comfort in outdoor educational spaces.
- To analyze the current thermal comfort conditions of outdoor spaces at the Institute of Architecture and Urbanism.
- To propose effective design solutions that enhance the usability and comfort of outdoor spaces in educational settings.

5. Methodology

The methodology adopted in this research combines both theoretical and practical approaches to assess and improve outdoor thermal comfort in the outdoor space of the Architecture Institution at Saad Dahlab University, Blida. The theoretical component involved collecting scientific data and reviewing literature related to thermal comfort indices, climatic parameters, and bioclimatic design principles. In parallel, the practical approach included site analysis, user surveys, and international case studies to identify issues such as heat stress, lack of shade, poor airflow, and low activity in the space. Based on these findings, several design scenarios (such as vegetation, shading strategies, surface materials, and water features) were developed and simulated using ENVI-met software to evaluate their impact on thermal comfort indices. The results of both theoretical and practical research were integrated into a final design proposal aimed at improving the spatial and climatic quality of the space.

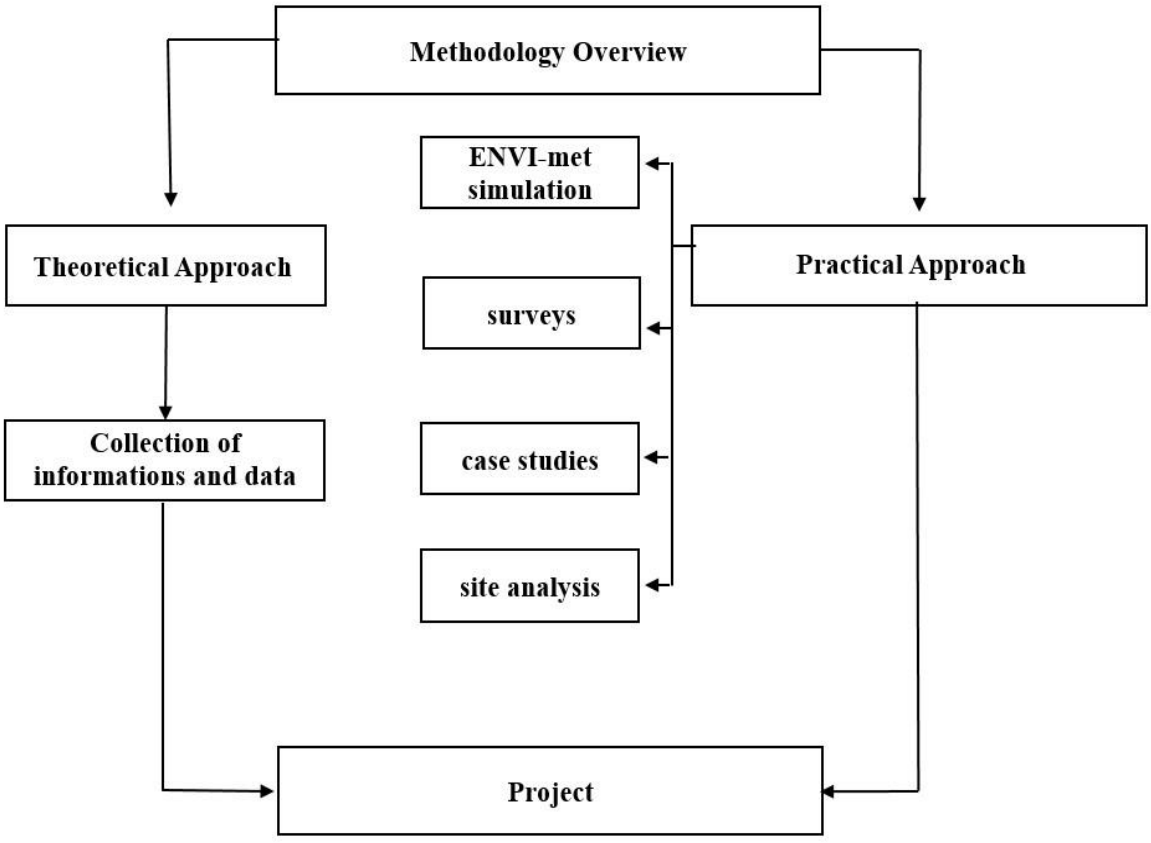


Figure 1 Methodology overview, source : author 2024

6. Thesis structure

Our thesis is structured into four main chapters, each addressing a crucial aspect of optimizing outdoor thermal comfort in educational environments, with a specific focus on the outdoor space of the Institute of Architecture and Urbanism at the University of Blida1.

The General Introduction provides the foundation for the study, outlining the background, problem statement, research objectives, methodology, and overall structure.

The Literature Review and Best Practices chapter explores key concepts related to outdoor thermal comfort, examining influencing factors and successful case studies from around the world.

The Case Study and Design Proposal chapter presents an in-depth analysis of the current conditions at the study site, incorporating site observations, user surveys, and simulation-based validation of proposed interventions aimed at improving thermal comfort. Finally. **The General Conclusion** summarizes the findings, discusses the strengths and limitations of the study, and suggests directions for future research. This structured approach ensures a comprehensive investigation into the role of design strategies in enhancing outdoor thermal comfort in educational settings.

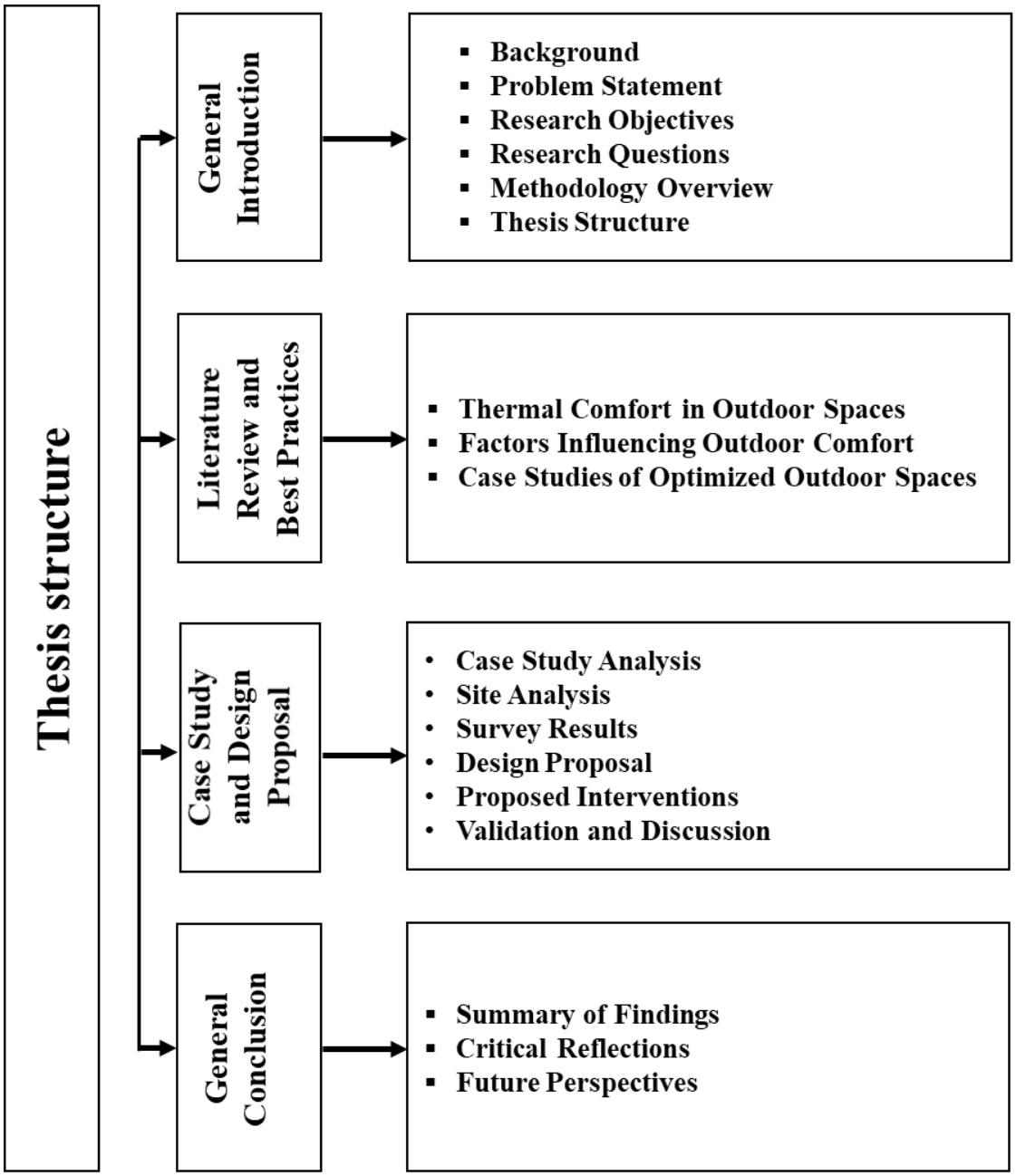


Figure 2 Thesis structure, source : author 2024

Chapter II

Literature Review and Best Practices

Introduction

This chapter explores the concept of thermal comfort in outdoor spaces, a critical factor in designing environments that promote well-being and usability. It begins by defining thermal comfort, detailing its key parameters, and explaining its relevance in outdoor settings. The methods used to measure outdoor thermal comfort, both objective and subjective, are examined to provide a foundational understanding of its evaluation. The chapter also delves into the factors that influence outdoor thermal comfort, highlighting environmental, climatic, and human-related elements. To illustrate these concepts, case studies of optimized outdoor spaces are analysed, offering insights into best practices and strategies for enhancing thermal comfort in similar contexts.

1. Thermal comfort in outdoor spaces

1.1.Thermal Comfort: Definitions and Theoretical Frameworks

Thermal comfort refers to "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2020, p. 5). This definition emphasizes the **subjective nature** of thermal perception, which is influenced by environmental parameters such as air temperature, humidity, and wind, as well as individual factors like clothing and metabolic rate (Fanger, 1970). The sensation of thermal comfort is complex, shaped by both **physiological responses** and **psychological expectations** (Nicol et al., 2012).

Fanger's Predicted Mean Vote (PMV) model was one of the earliest attempts to quantify thermal comfort. Based on steady-state heat balance, the PMV model predicts the average vote of a group of individuals on a seven-point scale ranging from cold (-3) to hot (+3) (Fanger, 1970). However, the **adaptive model**, developed in the early 2000s, argues that people adapt their behavior and expectations to the prevailing thermal environment, especially in naturally ventilated or outdoor settings (de Dear and Brager, 1998).

1.2.Outdoor Thermal Comfort

Outdoor environments pose a **unique challenge** for thermal comfort because they are subject to natural variability in temperature, solar radiation, wind, and humidity. Unlike indoor spaces, which

can be actively controlled using HVAC systems, outdoor comfort relies on **passive strategies** such as shading, wind corridors, and vegetation (Johansson et al., 2016).

Outdoor comfort is especially critical in urban areas and university campuses, where **extended use of outdoor spaces** is expected. These areas must be designed to accommodate **daily and seasonal climatic variations**, and to offer **thermal resilience** during extreme weather conditions (Ali-Toudert and Mayer, 2007).

2. Parameters of Thermal Comfort

Thermal comfort is influenced by a combination of environmental and personal variables. These parameters work together to determine the body's thermal exchange with the surrounding environment and ultimately affect human perception of comfort or discomfort in outdoor settings (ASHRAE, 2017).

2.1.Air Temperature

Air temperature is one of the most fundamental parameters influencing thermal comfort, representing the dry-bulb temperature of the air surrounding the human body. It plays a pivotal role in determining sensible heat exchange between the body and the environment through convection and conduction. While air temperature alone cannot comprehensively assess thermal comfort, it strongly affects the thermal sensation of individuals, especially in outdoor environments with high solar radiation. Elevated air temperatures increase the likelihood of thermal discomfort during hot seasons, particularly when coupled with high humidity and limited airflow. In urban microclimates, surfaces that retain and emit heat during the day further intensify air temperature, exacerbating heat stress (Ali-Toudert & Mayer, 2006, p. 97).

2.2.Wind Speed

Wind speed is a critical environmental parameter that affects the convective and evaporative heat loss from the human body, making it a vital factor in outdoor thermal comfort. Increased air movement facilitates heat dissipation by enhancing sweat evaporation, particularly in hot and humid climates. Conversely, in cold environments, high wind speeds can increase heat loss and induce discomfort. Wind speed also plays a role in diluting and dispersing accumulated heat in urban spaces, thereby contributing to the mitigation of urban heat island (UHI) effects. Its impact

is most significant at pedestrian level (1.2–1.5 m), where comfort assessments are typically conducted (Kastner-Klein & Plate, 2004, p. 379).

2.3.Mean Radiant Temperature

Mean Radiant Temperature (Tmrt) is the uniform temperature of an imaginary enclosure in which radiant heat exchange between the human body and surrounding surfaces equals that in the actual environment. It is a dominant factor in outdoor thermal comfort, especially in spaces exposed to direct solar radiation. Tmrt accounts for both long-wave radiation (from surrounding surfaces) and short-wave radiation (primarily from the sun), and its impact becomes more pronounced when shade is absent. Since humans are highly sensitive to radiation heat gains, Tmrt often surpasses air temperature in determining perceived outdoor warmth (Thorsson et al., 2007, p. 198).

2.4.Relative Humidity

Relative humidity (RH) refers to the amount of water vapor present in the air compared to the maximum amount the air can hold at that temperature. In thermal comfort studies, RH is a crucial parameter because it directly affects the body's ability to lose heat through evaporation. High humidity reduces the efficiency of sweat evaporation, leading to increased heat stress and discomfort in warm climates. Conversely, very low humidity levels may lead to skin and respiratory irritation in cold, dry climates. In outdoor environments, RH interacts with other parameters such as wind and radiation, contributing to complex comfort dynamics (de Freitas & Grigorieva, 2015, p. 55).

2.5.Clothing Insulation

Clothing insulation is a measure of how much thermal resistance a person’s clothing provides against heat exchange with the environment. It significantly affects thermal comfort by modifying the body's heat balance. The standard unit of measurement, “clo,” quantifies the insulation of a clothing ensemble; for example, 1 clo approximates a business suit worn in an indoor environment at 21°C. Outdoor thermal comfort assessments must account for seasonal variations in clothing behavior, especially in adaptive models where users can change their attire based on weather fluctuations. Accurate estimation of clothing insulation is necessary for predictive comfort models like PMV (Fanger, 1970, p. 34).

2.6.Metabolic Rate

The metabolic rate describes the rate of energy expenditure by the human body, expressed in met units (1 met = 58.2 W/m²). It represents internal heat generation and varies depending on a person's activity level—e.g., resting (1.0 met), walking (1.7 met), or jogging (4.0 met). In thermal comfort analysis, metabolic rate is vital because it determines how much heat the body needs to dissipate to maintain thermal neutrality. The more physically active an individual is, the higher the internal heat load, which affects comfort perception even under cooler environmental conditions (ISO 7730, 2005, p. 4).

2.7.Interaction of Parameters

Thermal comfort is not determined by a single factor but rather by the interaction of multiple parameters. For example, a high air temperature may feel comfortable if there is sufficient shading and wind movement. Similarly, a lower air temperature in winter can be offset by direct sunlight exposure. Understanding these interactions is critical for designing outdoor spaces that cater to diverse comfort needs across different climates and seasons. Integrated models such as the Universal Thermal Climate Index (UTCI) or the Physiological Equivalent Temperature (PET) account for such interactions to provide a more accurate comfort assessment (Höppe, 1999, p. 72).

Figure 3Parameters of Thermal Comfort

3. Outdoor Thermal Comfort Indices

Thermal comfort indices are composite metrics designed to evaluate and quantify human thermal sensation and comfort in diverse environments. Unlike single-variable indicators, such as air temperature or humidity, these indices integrate multiple environmental and personal parameters—namely air temperature, humidity, wind velocity, radiant temperature, clothing insulation, and metabolic rate—providing a comprehensive assessment of thermal conditions. These indices are indispensable in the domains of climate-sensitive architecture, urban planning, and environmental design, offering critical insights for optimizing human comfort in outdoor and semi-outdoor spaces (Höppe, 1999; ASHRAE, 2017). The selection of a specific index often depends on contextual factors such as spatial environment (indoor vs. outdoor), the demographic group studied, and the availability of input data (Matzarakis et al., 1999).

3.1.PET – Physiological Equivalent Temperature

The Physiological Equivalent Temperature (PET) is a widely adopted index for outdoor thermal comfort assessment. It translates complex outdoor environmental conditions into an equivalent air temperature in a typical indoor setting, thus offering intuitive comprehension by both experts and laypersons (Matzarakis et al., 1999). PET is grounded in the Munich Energy Balance Model for Individuals (MEMI), which models human thermal regulation based on environmental factors (air temperature, mean radiant temperature, wind speed, humidity) and standardized physiological parameters such as metabolic rate and clothing insulation. Expressed in degrees Celsius (°C), PET is extensively applied in urban microclimate studies and is particularly useful for evaluating the impacts of design interventions like shading, vegetation, or urban geometry (Matzarakis, Mayer & Iziomon, 1999).

Table 1 Physiological Equivalent Temperature souce : (Matzarakis, Mayer & Iziomon, 1999).

PET (°C)	Thermal ensation
≤4°	Very cold
Between 4 and 8° C	cold
Between 13 and 18° C	slightly cold
Between 18 and 23 ° C	Comfortable
Between 23 and 29° C	Slightly hot
Between 29 and 35°C	hot
Between 35 and 41°C	Very hot
≥ 41° C	extremely hot

3.2.PMV – Predicted Mean Vote

The Predicted Mean Vote (PMV) index, developed by Fanger (1970), is a predictive model estimating the average thermal sensation of a large group of people using a 7-point ASHRAE scale, ranging from –3 (cold) to +3 (hot). Based on the steady-state heat balance between the human body and its environment, the PMV considers air temperature, mean radiant temperature, air velocity, humidity, metabolic rate, and clothing insulation (Fanger, 1970; ASHRAE, 2017). Though initially designed for controlled indoor settings, PMV is occasionally used in semi-outdoor environments like atriums or courtyards. However, its application in fully dynamic outdoor environments is limited due to its assumption of steady-state conditions and fixed clothing and activity levels (Nikolopoulou & Steemers, 2003).

Table 2Predicted Mean Vote, source: (Nikolopoulou & Steemers, 2003).

pmv	description
-3	cold
-2	cool
-1	Slightly cold
0	comfortable
1	Slightly warm
2	warm
3	Very warm

3.3.UTCI – Universal Thermal Climate Index

The Universal Thermal Climate Index (UTCI) is a sophisticated metric developed to assess outdoor thermal environments across varying climates and levels of physical activity. It is based on a multi-node thermoregulation model and simulates human physiological responses under transient outdoor conditions (Bröde et al., 2012). UTCI accounts for air temperature, mean radiant temperature, humidity, and wind speed, expressing the result as an equivalent temperature in degrees Celsius. This allows for intuitive interpretation while offering high sensitivity to both environmental and physiological variability. UTCI is endorsed by the International Society of Biometeorology and has become a standard tool in urban climatology and public health research, especially in the context of climate change adaptation and heat stress mitigation (Jendritzky et al., 2012).

Table 3 Universal Thermal Climate Index, source : (Jendritzky et al., 2012).

UTCI (°C)	Stress category
	Extreme heat stress
46	
	Very strong heat stress
38	
	Strong heat stress
32	
	Moderate heat stress
26	
	No thermal stress
9	
	Slight cold stress
0	
	Moderate cold stress
−13	
	Strong cold stress
−27	
	Very strong cold stress
−40	
	Extreme cold stress

3.4.SET – Standard Effective Temperature

The Standard Effective Temperature (SET) is a comprehensive thermal comfort index that estimates the equivalent temperature of an environment in which an average person would experience the same thermal stress as in the actual environment, assuming uniform conditions of humidity, temperature, air speed, and mean radiant temperature. SET is based on the two-node model of human thermoregulation developed by Gagge et al. (1986), which accounts for both skin and core temperatures to evaluate the body's thermal balance. SET differs from other indices in that it explicitly incorporates the influence of humidity and air velocity on evaporative cooling, making it particularly valuable in humid climates or settings with strong wind flow. It also accounts for time-dependent thermal response, clothing insulation, and activity level, making it more adaptable to semi-outdoor and outdoor conditions compared to steady-state models like PMV (ASHRAE, 2017). Expressed in degrees Celsius (°C), SET allows for direct comparison between real environmental conditions and standardized indoor comfort thresholds. While SET is predominantly used in building science and HVAC engineering, its role in microclimate studies and outdoor comfort analysis has increased due to its dynamic modeling capabilities.

Table 4 Standard Effective Temperature, source : (ASHRAE, 2017).

SET (4)	Sensation
>37,5	Very hot, uncomfortable
34,5-37,5	Hot, very unacceptable
30,0-34,5	Hot, uncomfortable, unacceptable
25,6-30,0	Slightly hot, slightly unacceptable
22,2-25,6	Comfortable and acceptable
17,5-22,2	Slightly cool, slightly unacceptable
14,5-17,5	Cool and unacceptable
10,0-14,5	Cold and very unacceptable

4. Factors Influencing Outdoor Thermal Comfort

4.1.Vegetation and Green Infrastructure

Vegetation plays a crucial role in enhancing outdoor thermal comfort by providing shade, reducing surface and air temperatures, and promoting evapotranspiration. Trees, green walls, and green roofs act as natural cooling systems by intercepting solar radiation and releasing moisture into the air, which mitigates the urban heat island effect and improves microclimatic conditions. According to Bowler et al. (2010), vegetated areas can be significantly cooler than surrounding built-up zones, with temperature reductions ranging from 1°C to 5°C, depending on species, canopy density, and layout. Additionally, vegetation improves thermal comfort by increasing sky view factor obstruction, lowering radiant temperature, and dampening wind turbulence. Integrating green infrastructure into urban design not only contributes to thermal regulation but also improves air quality and promotes psychological well-being (Norton et al., 2015).

4.2.Shading and Passive Solar Design

Shading is one of the most effective passive strategies to improve thermal comfort in outdoor spaces, particularly in hot climates such as North Africa. By blocking direct solar radiation, shading devices—whether natural (trees), architectural (canopies, pergolas), or artificial (shade cloths, tensile structures)—reduce surface and mean radiant temperatures, which are critical determinants of thermal sensation. According to Toudert and Mayer (2007), strategic shading can lower PET values by up to 20°C in hot-arid urban environments. Passive solar design complements shading by optimizing building orientation, overhang dimensions, and material reflectance to control solar gain. These design measures not only alleviate thermal stress but also reduce energy demand for adjacent indoor spaces, contributing to holistic thermal performance (Ali-Toudert & Mayer, 2006).

4.3.Urban Morphology and Wind Flow Optimization

Urban morphology—defined by building height, spacing, orientation, and street canyon configuration—has a profound impact on wind flow, solar access, and heat retention in outdoor environments. In climates like that of Blida, Algeria, dense urban fabrics can impede natural ventilation and exacerbate thermal discomfort by trapping heat. Optimizing wind corridors and preserving open spaces improves convective cooling, which is essential for thermal relief, especially during summer. According to Emmanuel and Johansson (2006), urban forms with higher height-to-width (H/W) ratios can limit daytime solar penetration but often reduce airflow,

necessitating a balanced approach to both solar and wind exposure. Integrating morphology-aware design facilitates the dissipation of stored heat at night and supports microclimatic diversity, enhancing the habitability of public outdoor spaces (Oke, 1988).

4.4.Water-Based Cooling Strategies

The inclusion of water features—such as fountains, ponds, and misting systems—in outdoor urban design provides both sensible and latent cooling, especially effective in arid climates. Water bodies moderate microclimates by absorbing solar radiation during the day and releasing it at night, while evaporative cooling reduces air temperature and enhances humidity levels. Givoni (1991) identifies that urban water elements can lead to a localized cooling effect of 1–3°C, which significantly enhances thermal comfort. Furthermore, the aesthetic and psychological appeal of water contributes to perceived comfort, even beyond measurable temperature reductions. Effective integration of water-based strategies requires attention to evaporation rates, placement relative to airflow paths, and maintenance to prevent stagnation or water waste (Shashua-Bar et al., 2011).

5. Case Studies of Optimized Outdoor Spaces:

Thermal comfort in outdoor spaces is a fundamental aspect of designing functional and user-friendly environments, particularly in educational institutions where such spaces play a vital role in supporting social interaction, relaxation, and academic engagement. This chapter presents a series of case studies that analyse various strategies aimed at improving thermal comfort in outdoor areas within different climatic and cultural contexts. By comparing these examples, the study explores how local environmental conditions, spatial configurations, and user needs shape the design and effectiveness of outdoor spaces. The objective is to derive practical insights that can guide the planning and enhancement of thermally comfortable outdoor environments on university campuses.

5.1.Analysis Methodology

The methodology employed in this chapter combines both qualitative and quantitative approaches to ensure a comprehensive evaluation of thermal comfort strategies in outdoor spaces. The process includes the following key steps.

5.2.Case Study Selection

Case studies were selected based on their geographical diversity, distinct climatic classifications, and their direct relevance to thermal comfort issues in academic environments. Priority was given to university campuses where outdoor comfort interventions have been implemented and documented.

5.3.Data Collection

Information for each case was collected through secondary sources, including scientific articles, academic reports, architectural studies, and institutional publications. The data collected covers site-specific climatic conditions, adopted design strategies, and measurable comfort outcomes using established thermal indices (e.g., PET, PMV, UTCI).

5.4.Evaluation Framework

A structured evaluation framework was applied to ensure consistency in analysing and comparing the case studies. This framework includes:

5.4.1. *Background Context:* Description of the case study location, climate classification, and institutional characteristics.

5.4.2. *Climatic and Environmental Analysis*: Identification of the main climatic challenges and their seasonal impacts on thermal comfort.

5.4.3. *Thermal Comfort Strategies: Categorization of interventions such as shading systems, vegetation use, water features, material choices, and spatial organization.*

5.4.4. *Observed Outcomes:* Assessment of thermal performance through environmental data, user surveys, and behavioural observations.

5.4.5. *Key Challenges and Lessons Learned:* Reflection on the difficulties encountered during implementation and the insights gained from each case.

This methodological structure provides a clear and coherent basis for comparing diverse outdoor spaces and identifying transferable strategies that can be adapted to similar university environments, particularly in climates facing comparable thermal comfort challenges.

6. Case Study: Improving Outdoor Thermal Comfort in Masdar City, Abu Dhabi, UAE

6.1.Technical Sheet

Table 5 Technical Sheet of masdar city, abu dhabi, UAE , source : (Fadli et al., 2020).

Parameter	**Description**
Location	Masdar City, Abu Dhabi, United Arab Emirates
Climate Type	Hot desert climate (BWh – Köppen)
Avg. Summer Temp	Often exceeds 45°C
Humidity	Low, typically below 20%
Main Tools Used	ENVI-met, RayMan, field sensors
Objective	Improve outdoor thermal comfort through passive urban design

6.2.Background Context

Masdar City, located in Abu Dhabi, was envisioned as a model for sustainable urbanism in arid climates. With its compact morphology, narrow streets, strategic shading, and wind funneling techniques, Masdar aimed to create thermally comfortable outdoor environments that encourage pedestrian activity even during hot seasons. The city was designed to minimize heat gain, reduce solar exposure, and optimize wind circulation, all of which contribute to better outdoor thermal comfort (OTC) without active cooling systems (Fadli et al., 2020).

Table 6 background and context-abudhabi-, source : (Fadli et al., 2020).

Case Study	Total area of school	Total study area	Percentage of study area to total area of school	Study area dimension
Case Study A	100 m × 60 m 6000 m²	1280 m²	21.3%	32 m × 40 m
Primary school for girls, located in the northern part of Riyadh in the Alyasmin district				
Case Study B	90 m × 50 m 4500 m²	960 m²	21.3%	24 m × 40 m
Primary school for girls, located in the eastern part of Riyadh in the An Nahdah district				
Case Study C	100 m × 100 m 10000 m²	2176 m²	24.7%	32 m × 64 m
Primary school for boys, located in the central part of Riyadh in the Al Malaz district				
Case Study D	120 m × 60 m 7200 m²	1536 m²	21.3%	32 m × 48 m
Primary school for boys, located in the southern part of Riyadh, in the Badr district				

6.3.Climatic and Environmental Analysis

Abu Dhabi experiences **extreme summer heat** with air temperatures frequently exceeding 45°C. The solar radiation levels are very high, often surpassing **900 W/m²**, and relative humidity remains low, typically around **15–25%**. These conditions create **severe heat stress** in open outdoor environments.Using **ENVI-met** and **RayMan**, researchers simulated microclimate conditions

across **various street configurations**, assessing how **urban form, shading**, and **material reflectivity** influenced thermal indices like **UTCI, PET, PMV**, and **mean radiant temperature (Tmrt)**.

6.4.Thermal Comfort Strategies

6.4.1. Shading and Urban Morphology:

Narrow pedestrian alleys, overhangs, arcades, and building projections reduced solar access and minimized sky view factor (SVF).

Wind Funnel Design:

Traditional wind towers were reinterpreted to enhance airflow in pedestrian zones, increasing wind speed at human height.

6.4.2. Vegetation and Reflective Surfaces:

While vegetation was limited due to water constraints, strategic planting and the use of light-colored, high-albedo surfaces were integrated to reflect heat.

Building Orientation:

The city grid is rotated to align with prevailing wind patterns from the northwest, improving natural ventilation.

Table 7 thermal comfort strategies-abudhabi-, source : (Fadli et al., 2020).

	Masdar	SC01	SC02	SC03	SC04	SC05	SC05
% Shading	7	0	100	19	81	38	62
% Trees	93	100	0	81	19	62	38

6.5.Observed Outcomes

Table 8 University of Sharjah, UAE source : author 2025

These improvements led to **greater usability of outdoor spaces**, particularly during morning and late afternoon hours, and helped **extend thermal comfort durations** without active cooling systems (Fadli et al., 2020).

6.6.Key Challenges and Lessons Learned

6.6.1. Challenges:

Parameter	Baseline	Shading Only	Vegetation Only	Combined
PET (July peak hours)	48°C (severe heat)	41°C (-7°C)	38°C (-10°C)	35°C (-13°C)
Mean Radiant Temperature (Tmrt)	55°C	45°C (-10°C)	40°C (-15°C)	37°C (-18°C)
Air Temperature Reduction (°C)	-	1.5°C	2.3°C	3.1°C
Sky View Factor (SVF)	0.75	0.35	0.25	0.12

- Limited vegetation due to water scarcity restricted the use of green strategies.
- Material performance under extreme sun exposure required frequent maintenance.
- Behavioral adaptation (e.g., timing of outdoor use) was not initially integrated into design.

6.6.2. Lessons Learned:

- Passive design significantly improves thermal comfort even in extreme climates.
- Combining compact urban form, wind-enhancing elements, and high-albedo surfaces provides better microclimate conditions.
- Early integration of climatic analysis into the design process yields

7. Case Study: Optimizing Outdoor Thermal Comfort for Educational Buildings in Riyadh, Saudi Arabia

7.1.Technical Sheet

Table 9 Technical Sheet of educational building in riyadh, saudia arabia, source : author 2025

Parameter	Description
Location	Riyadh, Saudi Arabia
Climate Type	Hot desert climate (BWh – Köppen classification)
Institution Type	Four representative public primary schools
Main Objective	Improve outdoor thermal comfort using passive cooling strategies
Simulation Tools	Ladybug Tools + Grasshopper (UTCI, PET) and Galapagos for optimization
Environmental Inputs	Hourly weather data: air temperature, solar radiation, wind speed, humidity
Indices Used	Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET)

7.2.Background Context

Riyadh's climate poses significant challenges to outdoor comfort in educational environments, particularly during extended summer seasons where temperatures regularly exceed 45°C. Public school courtyards, often the main outdoor activity zones for children, become thermally hostile spaces due to lack of shade and vegetation.

This study evaluated four existing school layouts to explore how strategically placed vegetation and shading elements can transform these courtyards into climatically responsive spaces that support students' well-being and use of outdoor areas. (Binabid, J., Alymani, A. & Alammar, A. (2024))

7.3.Climatic and Environmental Analysis

Riyadh features:

- Extremely high summer temperatures (>45°C)
- Intense solar radiation

- Low relative humidity (<15%)

Limited natural ventilation, particularly in enclosed courtyards

The simulations were based on:

Hourly climatic data

Layout-specific variables such as paved surfaces, wall orientations, and circulation zones

These inputs informed the Ladybug–Grasshopper simulations, which assessed thermal indices (UTCI and PET) and helped quantify discomfort levels throughout the day.

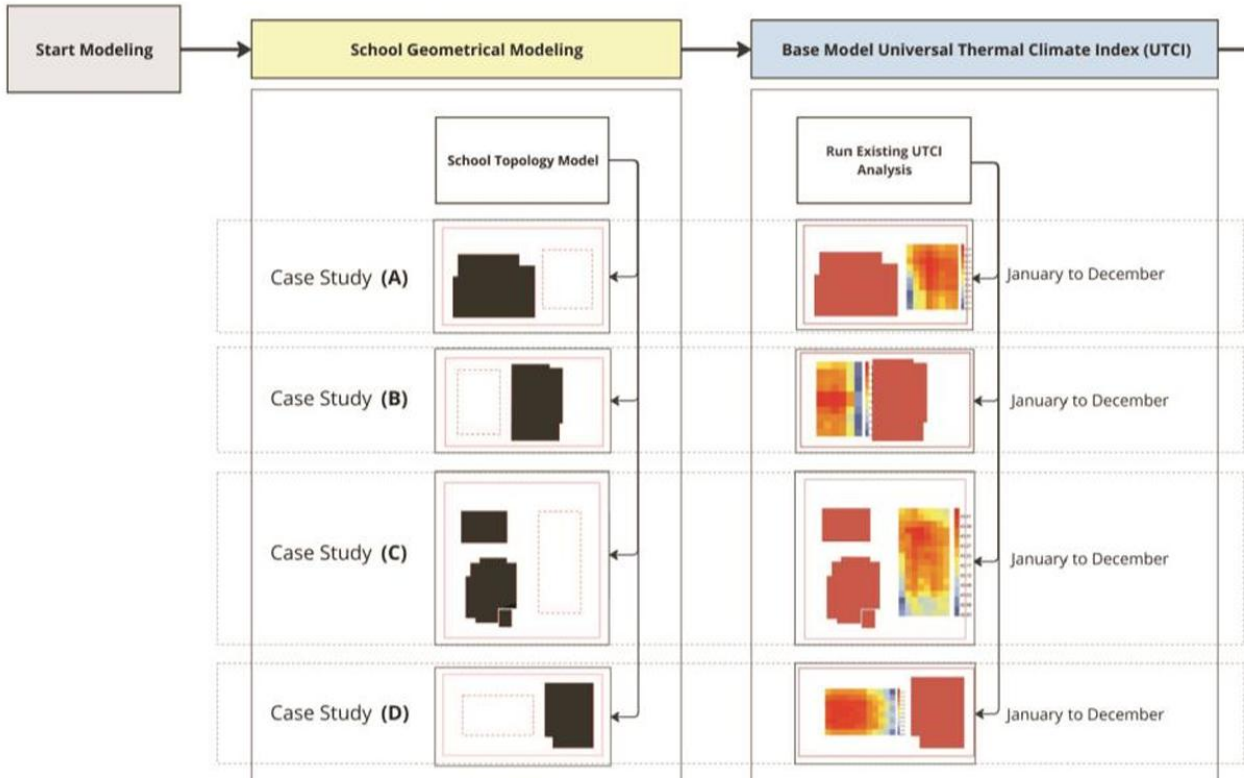


Figure 4 climat and environnement analysis -saudi-, source : (Binabid, J., Alymani, A. & Alammar, A. (2024))

7.4.Thermal Comfort Strategies

The study tested two passive cooling interventions:

7.4.1. Vegetation Implementation:

- Dense tree planting zones near seating and play areas
- Optimized via Galapagos to maximize shade during peak hours
- Species with high transpiration rates were prioritized

7.4.2. Shading Structures:

- Lightweight canopies over pathways and congregation areas
- Aligned with prevailing wind direction to ensure airflow
- Integrated with vegetation to reduce Tmrt and PET
- The combined strategies aimed to reduce heat gain, lower mean radiant temperatures, and improve comfort duration throughout school hours.

Figure 5 thermal comfort strategies -saudi-, source : : (Binabid, J., Alymani, A. & Alammar, A. (2024))

7.5. Observed Outcomes

Table 10 Educational Buildings in Riyadh, Saudi Arabia, source : author 2025

Parameter	Before Intervention	After Intervention	Improvement
UTCI (July – Severe Heat)	43.49°C	39.27°C	↓ 4.22°C
UTCI (February – Mild Conditions)	17.88°C	9.36°C	↓ 8.52°C
Tmrt (Mean Radiant Temperature)	52.9°C	43.5°C	↓ 9.4°C
SVF (Sky View Factor)	0.677	0.117	↓ 82%
Global Solar Radiation	789 W/m²	587 W/m²	↓ 25%
PET Reduction	N/A	↓ 10–15°C	Significant comfort gains

These results showed a **substantial decrease in thermal stress levels**, turning otherwise unusable courtyards into **moderately comfortable zones** during most school hours, especially in spring and early summer.

7.6. Key Challenges and Lessons Learned

7.6.1. Challenges

- Limited irrigation capacity constrained vegetation density.
- Initial designs lacked integration of climatic logic, such as wind flow paths.
- Data for student comfort perception was not included.

7.6.2. Lessons Learned

- Vegetation and shading structures offer high-impact, low-tech solutions.
- Optimization tools (like Galapagos) enhance design efficiency and outcome precision.
- Even small reductions in Tmrt and PET significantly extend outdoor usability.

8. Case Study: Enhancing Outdoor Thermal Comfort with Vegetation – Martyrs Plaza, Ouargla, Algeria

8.1. Technical Sheet

Table 11 Technical sheet martyrs plaza, ouargla, algeria , source : author 2025

Parameter	Description
Location	Martyrs Plaza, Ouargla, Algeria
Climate	Hot desert climate (BWh – Köppen Classification)
Summer Temperatures	Frequently exceed 45°C
Humidity	Very low (arid conditions)
Solar Radiation	High solar radiation year-round
Objective	Assess how strategic vegetation improves outdoor thermal comfort
Simulation Tool Used	RayMan Pro
Thermal Indices Used	PMV (Predicted Mean Vote), PET, SET*, SVF
Field Data Collection	July 2016: Air temperature, humidity, wind speed, solar radiation
Intervention Elements	Vegetation (Acacia Raddiana, Ficus Retusa) in high-use, high-sun zones

8.2. Background Context

Ouargla, located in southern Algeria, experiences extreme desert conditions with peak summer temperatures surpassing 45°C, coupled with intense solar radiation and negligible humidity. Martyrs Plaza, a key public space in the city, was previously exposed and unshaded, making it thermally inhospitable during much of the day, particularly in summer.

This case study sought to explore how introducing adaptive vegetation could meaningfully enhance thermal comfort for plaza users without relying on mechanical solutions. The focus was placed on tree species selection and their spatial deployment to address microclimatic stressors.

Figure 6 background and context-ouargla-, soource : Gherraz, H., Guechi, I. & Benzaoui, A. (2018)

8.3. Climatic and Environmental Analysis

The environmental analysis was conducted during July 2016, a period representative of the harshest thermal conditions in Ouargla. Data collected included:

- Air temperature
- Relative humidity
- Wind speed
- Solar radiation

Simulation using RayMan Pro enabled visualization and quantification of thermal stress based on these inputs. Two configurations were modeled:

Existing Condition: Minimal vegetation (only a few palm trees offering sparse shade)

Intervention Scenario: Strategic addition of Acacia Raddiana and Ficus Retusa

8.4. Thermal Comfort Strategies

8.4.1. Vegetation Selection and Characteristics

Table 12 Vegetation Selection and Characteristics, source : author 2025

Tree	Type	Function
Acacia Raddiana	Deciduous	Seasonal shading, allows winter sun, drought-resistant
Ficus Retusa	Evergreen	Dense canopy for year-round shading, acts as windbreak

8.4.2. Design Implementation

- Vegetation clustered in high-traffic pedestrian zones and around seating areas

- Trees aligned to block peak solar radiation at midday
- Planting pattern optimized to reduce SVF and enhance radiant shielding

This dual approach of seasonally responsive trees and evergreen cover allowed for shading, airflow moderation, and radiation blockage, thereby reducing both Tmrt and PET in key comfort zones.

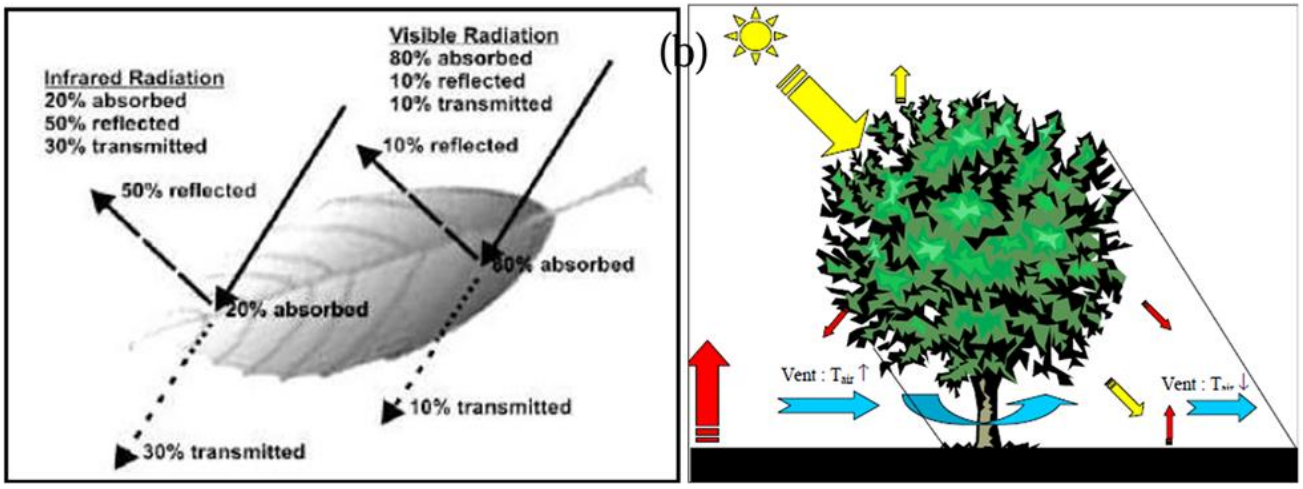


Figure 7 Thermal comfort strategies-ouargla-, source : Gherraz, H., Guechi, I. & Benzaoui, A. (2018) Observed Outcome

Table 13 Martyrs Plaza, Ouargla, Algeria source : author 2025

These results demonstrate **substantial thermal relief** in seating areas and open pathways. PET and

Parameter	Before Intervention	After Intervention	Improvement
Sky View Factor (SVF)	0.637–0.677	0.117	↓ 82%
Global Solar Radiation (W/m²)	789 (peak)	587 (peak)	↓ 25%
Mean Radiant Temp (Tmrt)	52.9°C (noon)	43.5°C (noon)	↓ 9.4°C
PMV (Predicted Mean Vote)	7.9 (unbearable)	4.8 (hot but tolerable)	↓ 39%
PET (Physiological Equivalent Temp)	70°C (extreme heat)	47.1°C (very hot)	↓ 23°C

PMV drops indicate a transformation from **unbearable to tolerable** conditions under the new design.

8.5. Key Challenges and Lessons Learned

8.5.1. Challenges

- Water availability: Critical for sustaining vegetation in arid environments
- Soil conditions: Required specific species tolerant to saline, sandy substrate
- Initial costs: High for sourcing mature trees and maintaining irrigation infrastructure

8.5.2. Lessons Learned

- Strategic vegetation, even in minimal doses, dramatically improves thermal comfort.
- Selecting climate-adaptive species ensures sustainability and minimal water use.
- Focused interventions in targeted zones (seating, crossings) provide maximum impact with minimal resources.

Chapter III

Case Study and Design Proposal

1. Case Study Analysis

1.1. Site Context and Background

1.1.1. Geographical Location

The study was conducted in Ouled Yaich city, Blida province, located in northern Algeria on the southern edge of the Mitidja Plain, at the base of the Tell Atlas Mountains. Situated approximately 48 kilometers southwest of Algiers. Blida have a Mediterranean climate characterized by hot, and dry summers with mostly clear skies, and cold winters with partly cloudy conditions. Annual temperatures typically range from 4°C to 33°C, rarely dropping below -1°C or exceeding 37°C.

1.1.2. Institute Overview

The specific study site is the outdoor space of the Institute of Architecture and Urbanism at the University of Blida 1, located in Ouled Yaich city. This rectangular area, measuring approximately 40 x 50 meters and oriented to the northeast, is situated between three medium-sized buildings, each around 10 meters in height. These include the administrative building, the library, and the main studies building, which is the largest of the three. The studies building features a distinctive cubic architecture, composed of three cubes arranged in an L-shaped configuration. The space is relatively sparse in vegetation, featuring six triangular grassy zones with shrubs that do not exceed 1.2 meters in height and 3 to 4 trees randomly planted across the area. The outdoor space serves as a central hub for student activities and provides an ideal setting for relaxation between learning sessions.

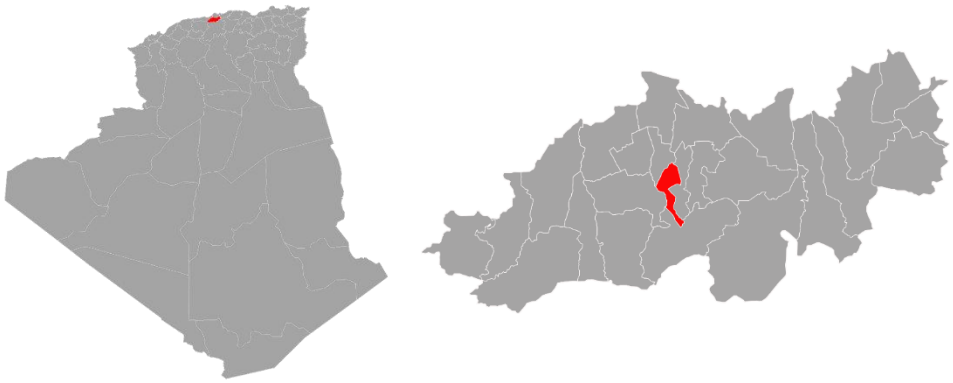


Figure 8 Location of the study site, source : author 2025

1.2. Spatial Analysis

1.2.1. *Spatial Configuration:* Mapping key outdoor spaces, pathways, and gathering areas

1.2.2. *Materials and Surfaces:* Inventory of existing materials (pavements, facades) and their thermal properties.

1.2.3. *Vegetation and Green Coverage:* Tree canopy, plant distribution, and shading potential.

1.2.4. *Built Environment Influence:* Building heights, orientations, and their impact on shading/wind patterns.

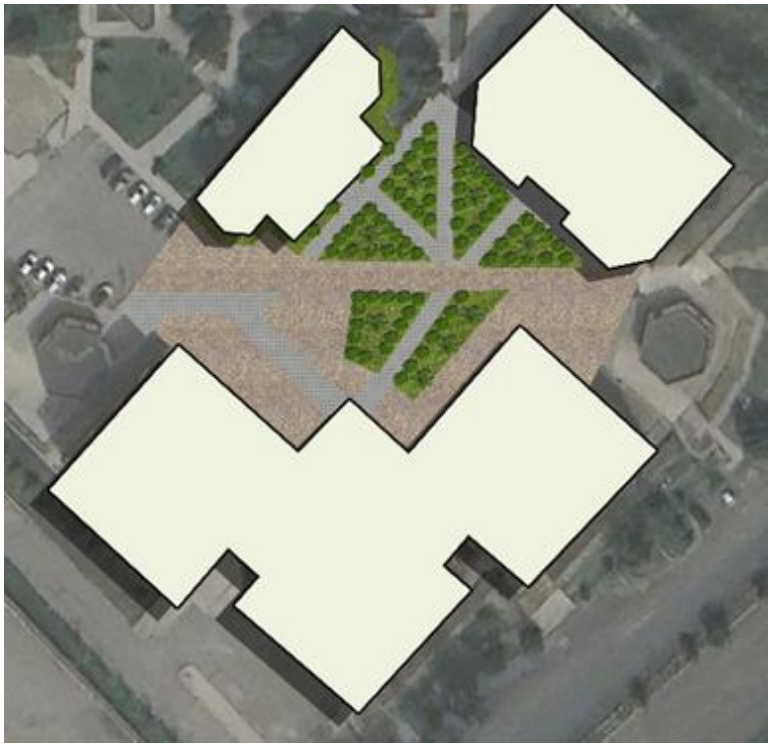


Figure 9 plan showing the pathways of users, source : google earth, edit bu author 2025

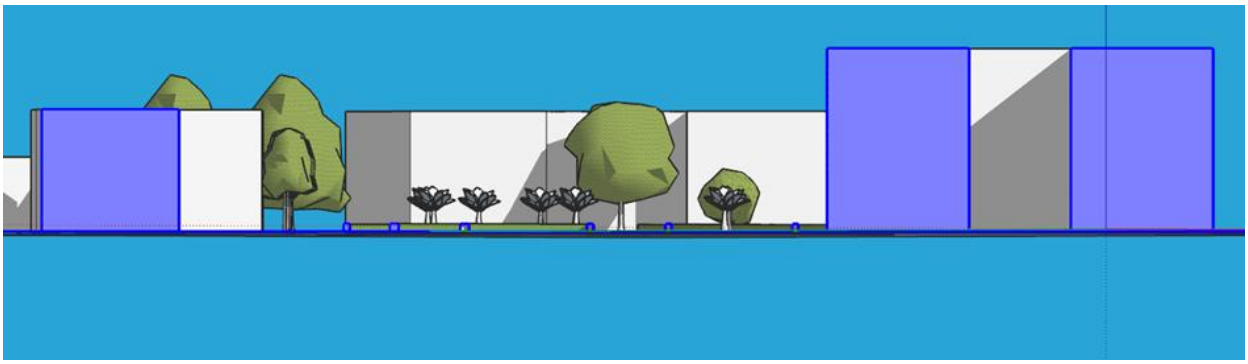


Figure 10 section showing the vegetation, the building heights, source : author 2025

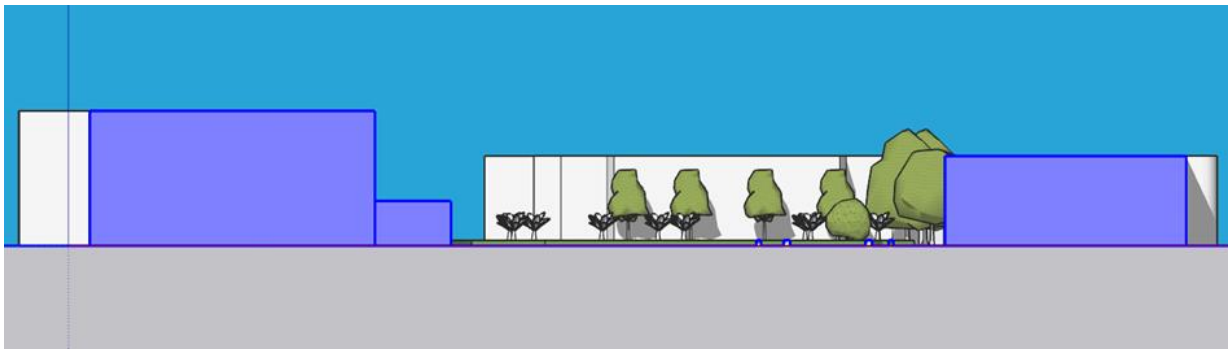
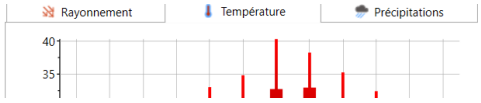
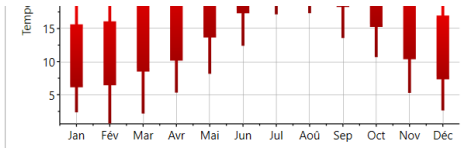
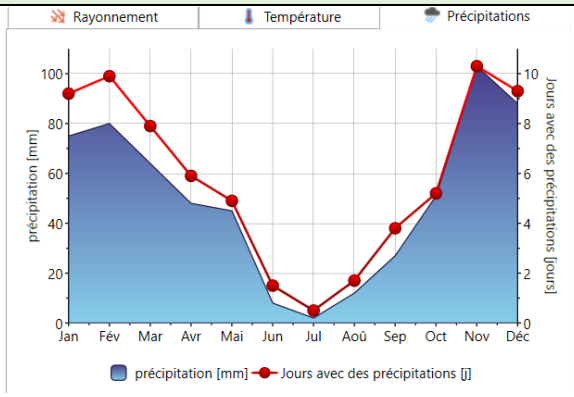


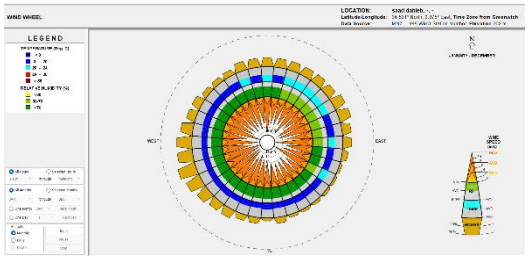
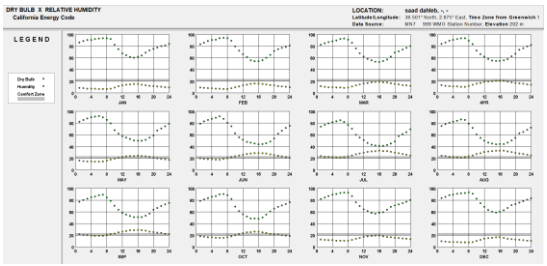
Figure 11 section showing the vegetation, the building heights, source : author 2025

1.3. Microclimate Analysis and Visualization (3 pages)

1.3.1. *Climate Diagrams:* Temperature, humidity, and wind rose diagrams.

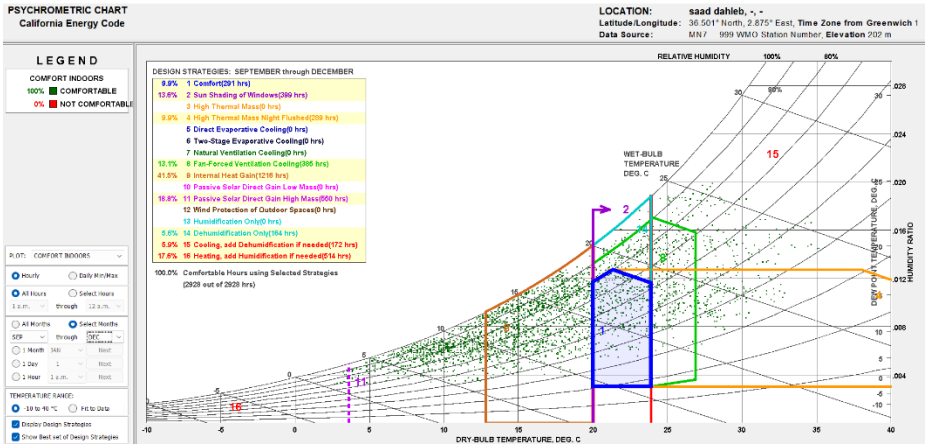
Table 14 climate analysis, source : author 2025

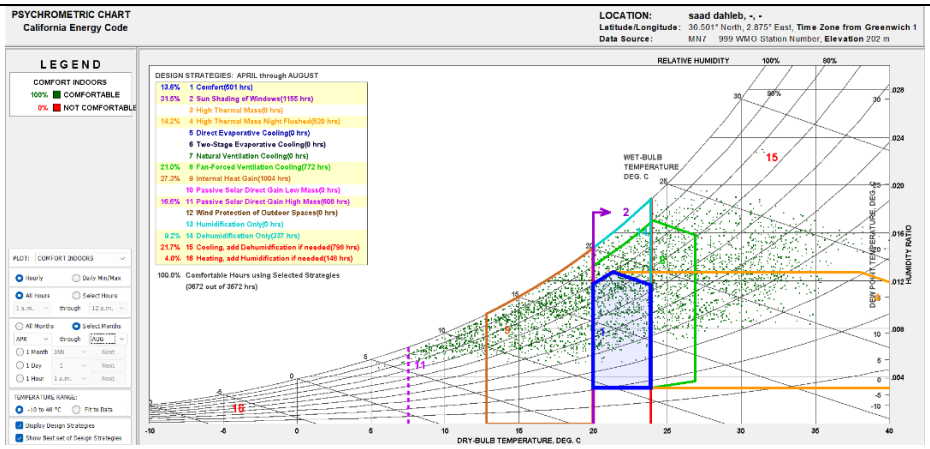
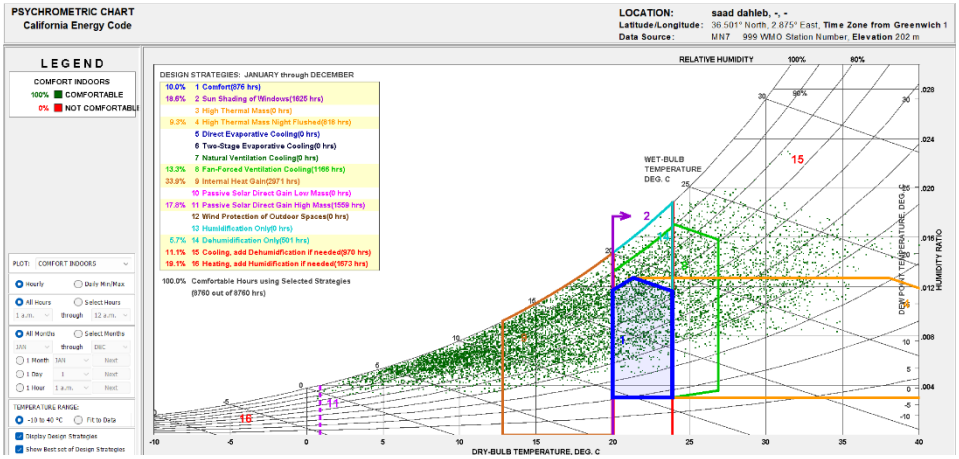
Température mensuelle	Précipitation
 *Figure 12 temperature of the study area. Source: meteonorm* 	 *Figure 13 Precipitation in the study area. Source: meteonorm*
The temperature varies between 16°C and 40°C in the summer season, and between 0°C and 22°C in the winter season.	The average rainfall is approximately nine months per year. The amount of precipitation in winter is between a maximum of 110mm in November and a minimum of 95mm in January, in summer it is between 5mm in July and 40mm in September.

Vitesse du vent	Humidité
 *Figure 14 wind speed of the study area. Source: climate consultant*	 *Figure 15 humidity of the study area. Source: climate consultant*
The prevailing winds blow in a southwest and northeast direction, with a maximum speed of 16m/s, and a minimum speed of 8m/s. The region is characterized by relative humidity which varies between 30% and 70%	Humidity varies between 50% and 95% in the winter month, and between 40% and 90% in the summer month.

Energy analysis

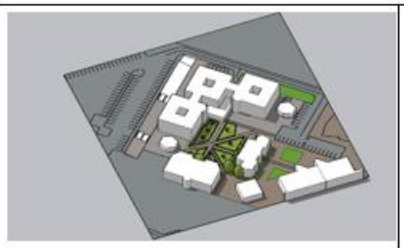
Table 15 energy analysis, source : author 2025

GIVONI diagram of the winter period	During the winter season, passive methods provide only 42% thermal comfort. In order to achieve full comfort at 100%, it is necessary to use active solutions for the remaining 58%, particularly a heating system.
	 *Figure 16 GIVONI diagram of the winter period of the study area.climat cosultant source*

GIVONI diagram of the summer period	During the summer season, passive methods offer 60% comfort, while active methods offer 40% comfort, thanks in particular to an air conditioning system.  *Figure 17 GIVONI diagram of the summer period of the study area. Climat consultant source*
Annual	Taking into account the annual needs in terms of percentage and hours of comfort, we observe that passive techniques only provide 60% comfort. To achieve 100% optimal comfort, it is necessary to use active techniques for the remaining 40%. This includes an air conditioning system as well as a heating system representing.  *Figure 18 Annual GIVONI diagram of the study area. Meteonorm source*

1.3.2. *Sun Path and Shadow Analysis:* Seasonal variations in shading and solar exposure.

Table 16 sun path and shadow analysis, source : author 2025

Time	Daily shadow path	
10 :00		
12 :00		
14 :00		
16 :00		

2. Methodology and Design Proposals

In our study, to assess the thermal comfort levels in the outdoor spaces of the Institute of Architecture and Urbanism, we adopted a two-step methodology that combines both subjective and objective assessments. This dual approach provides a comprehensive understanding of user perceptions and the actual thermal performance of the outdoor environment.

- **Subjective Assessment:** A questionnaire survey was conducted to gather users' thermal perceptions and comfort preferences.
- **Objective Assessment:** A microclimate simulation of the outdoor spaces was performed to analyze thermal conditions under various environmental scenarios.

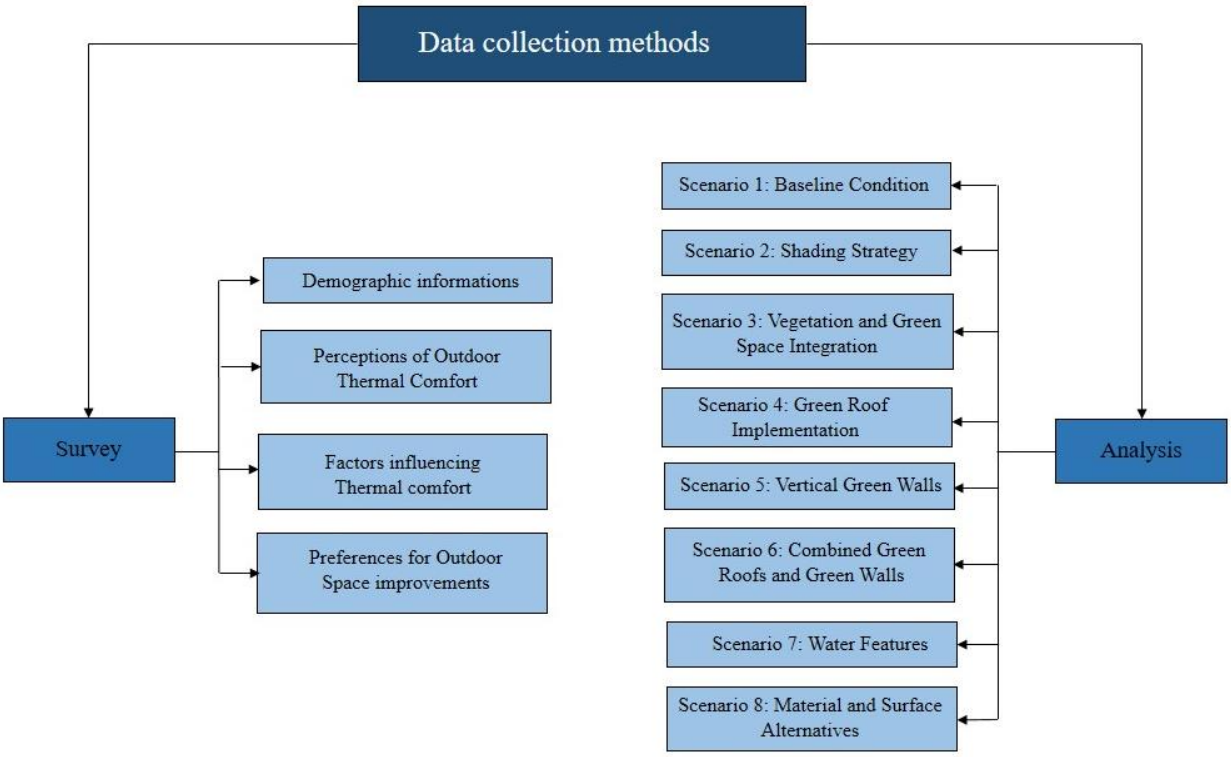


Figure 19 Diagram showing the methodology, source : author 2025

3. Thermal Comfort Surveys

3.1. Questionnaire Protocol

- **Objective:** Users' perceptions of thermal comfort and identify discomfort triggers.
- **Target Population:** Students, faculty, and staff who regularly use the outdoor spaces.
- **Survey Period:** From early October to the mid-November.
- **Distribution Method:** Online forms.
- **Response Rate:** 246.

3.2. Questionnaire Structure

The survey structure was designed to capture thermal comfort variables through a combination of quantitative and qualitative questions. The first section gathered demographic information,

including age, gender, academic year, and outdoor space usage frequency, to understand the diversity of respondents. The second section focused on perceptions of outdoor thermal comfort, measuring comfort levels across seasons and identifying key factors influencing comfort, such as sun exposure, wind, and vegetation. The third section explored factors affecting thermal comfort, assessing the influence of air temperature, humidity, wind, clothing, and physical activity, to help correlate subjective feedback with objective microclimate data. Finally, the fourth section collected insights on preferred improvements, such as increased greenery, shaded areas, and water features, to guide the design scenarios tested in the microclimate simulations.

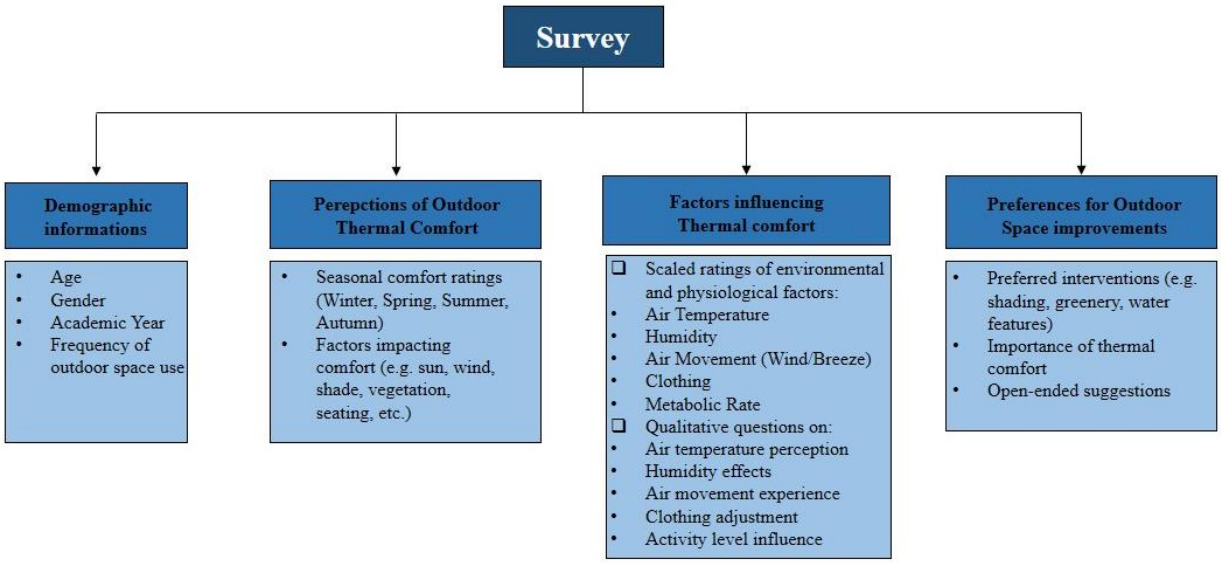


Figure 20 Diagram of the questionnaire structure, source : author 2025

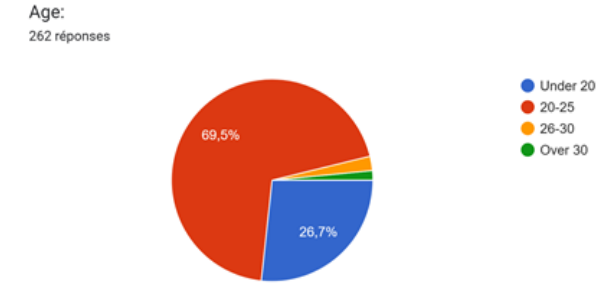
3.3. Questionnaire Results

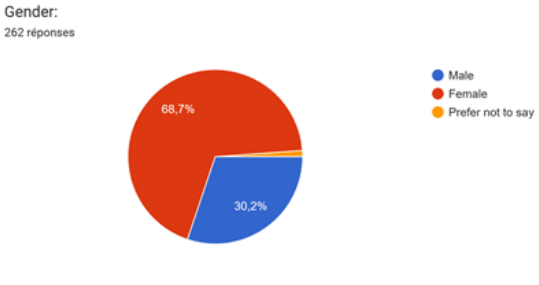
The responses provided valuable data points for the study:

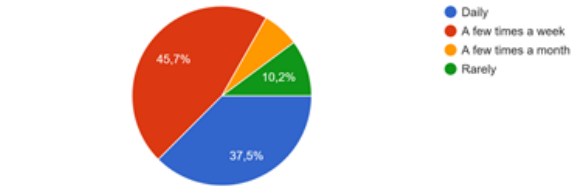
- ✓ **Demography:** The majority of respondents were students aged 20–25, spending time outdoors daily or several times a week.
- ✓ **Seasonal Comfort Patterns:** Participants reported high discomfort during summer, with comfort levels increasing in spring and autumn.
- ✓ **Key Discomfort Factors:** The most cited factors were high temperatures, lack of shade, and limited air movement.
- ✓ **Improvement Preferences:** The most requested interventions included more shaded areas, increased greenery, and water features to cool the environment.

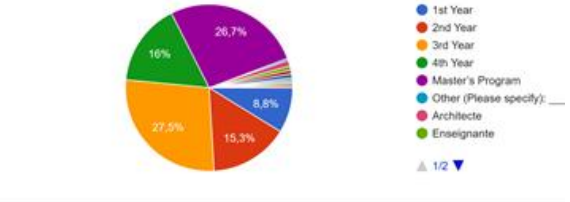
Table 17 Questionnaire result, source : author 2025

Section 1: Demographic Information

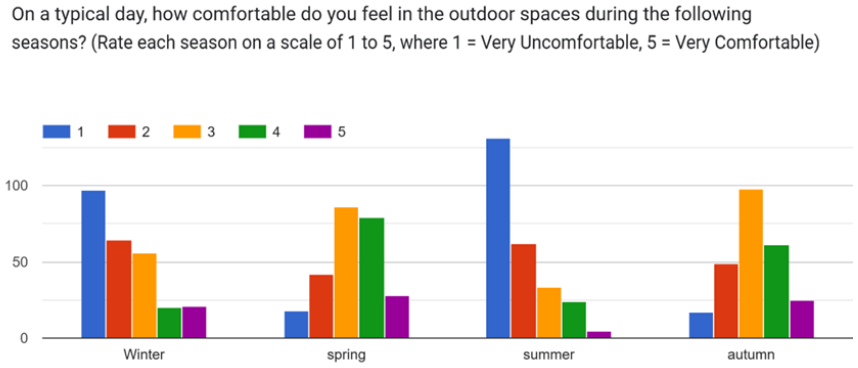


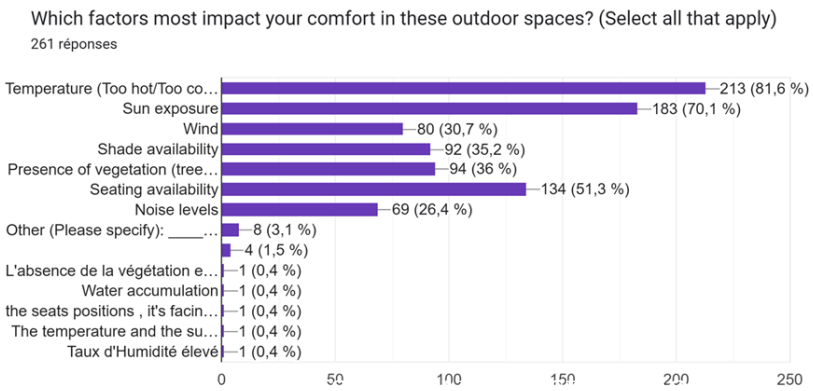




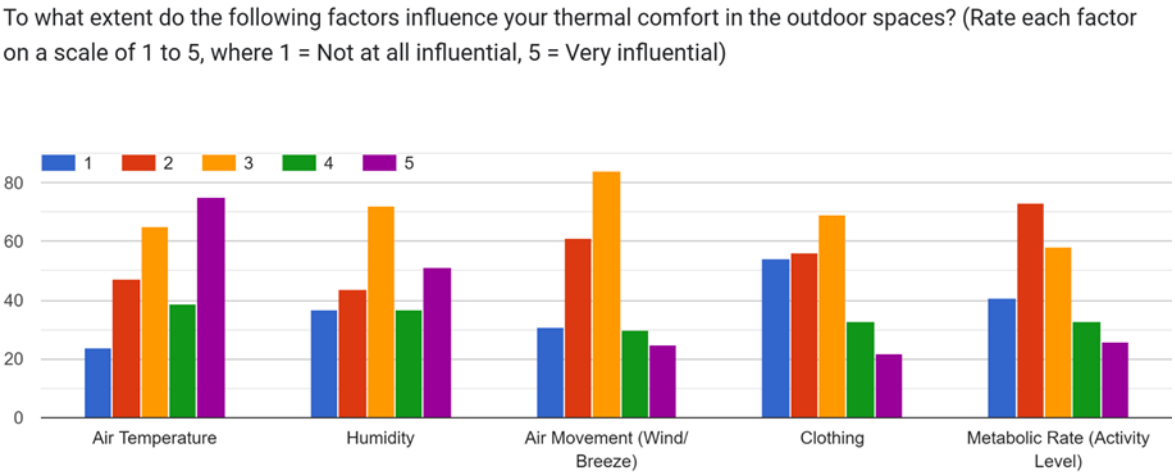


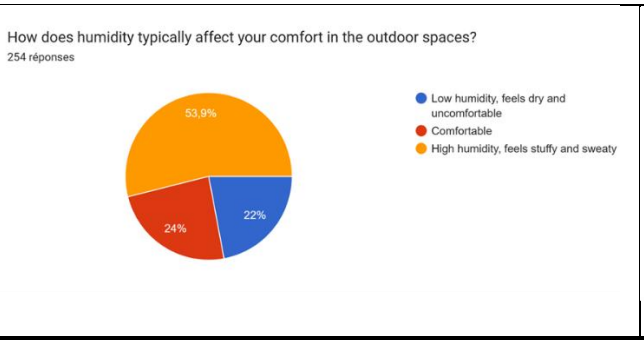
Section 2: Perceptions of Outdoor Thermal Comfort

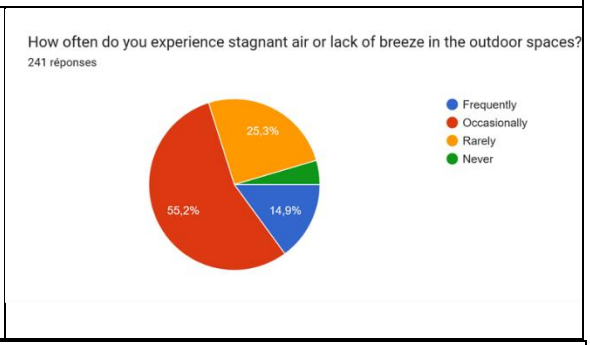




Section 3: Factors Influencing Thermal Comfort



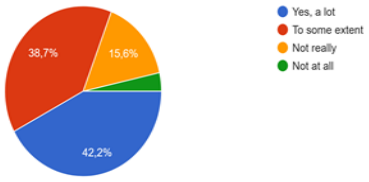




Section 4: Preferences for Outdoor Space Improvements

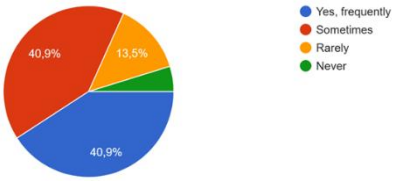
Does physical activity (walking, moving, etc.) significantly impact your comfort in the outdoor spaces?

256 réponses



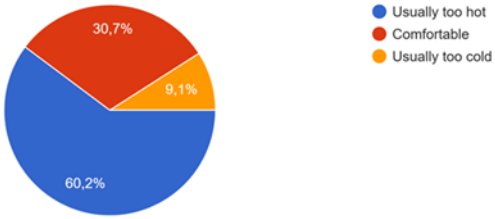
Do you adjust your clothing specifically for spending time outdoors at the Institute?

252 réponses



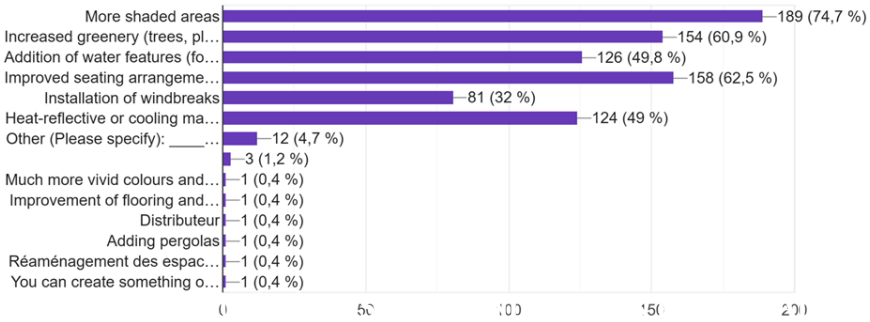
In your experience, how would you describe the air temperature in the outdoor spaces throughout the year?

254 réponses



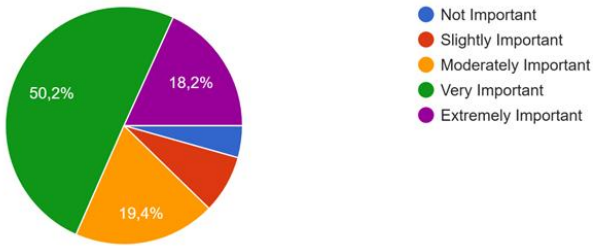
Which of the following changes do you think would improve your thermal comfort in outdoor spaces? (Select all that apply)

253 réponses



How important is thermal comfort to your overall satisfaction with the outdoor spaces?

253 réponses



4. Microclimate Simulation

4.1. Simulation Parameters

The microclimate simulation, conducted with ENVI-met V5.6.1, used Metronom-generated climate data for October 13, 2024, a peak outdoor usage day. Simulated parameters included air temperature, humidity, mean radiant temperature, and wind speed. Thermal comfort was evaluated with PET, UTCI, PMV, and SET indices. (See table below).

4.2. Simulation Scenarios

We tested eight scenarios to assess different design interventions' impact on the site's microclimate and thermal comfort levels:

1) **Scenario 1: Baseline Condition**

Simulate the existing outdoor space and library area without any modifications, capturing factors like temperature, humidity, wind patterns, and solar exposure at different times of the day and across seasons.

2) **Scenario 2: Shading Strategy**

Introduce shading elements such as pergolas, shade sails, and strategically planted trees in high-exposure zones to reduce direct solar radiation and mitigate thermal discomfort.

3) **Scenario 3: Vegetation and Green Space Integration**

Add various plant types (tall trees, shrubs, ground cover) around pathways and seating areas to enhance shading and evapotranspiration, aiming to cool the environment naturally.

4) **Scenario 4: Green Roof Implementation**

Apply green roofs to the library, testing extensive (low-maintenance) and intensive (denser vegetation) systems to measure temperature regulation and their effect on surrounding outdoor comfort.

5) **Scenario 5: Vertical Green Walls**

Place green walls on sun-exposed library facades to reduce direct solar gain, lowering surface temperatures and contributing to local cooling.

6) **Scenario 6: Combined Green Roofs and Green Walls**

Simulate the simultaneous integration of green roofs and vertical gardens to amplify cooling benefits, balancing temperature reduction with aesthetic and ecological value.

7) Scenario 7: Water Features

Introduce water features (fountains, ponds, reflecting pools) near seating areas, varying size and placement to optimize evaporative cooling effects.

8) Scenario 8: Material and Surface Alternatives

Replace conventional hardscapes with cool, reflective, and permeable materials in high-traffic zones to mitigate surface heat accumulation and enhance pedestrian comfort.

Table 18 Simulation Details, including Modelled Scenarios. ENVI_met V5.6.1

Simulation Details

Model : ENVI_met Microclimate

Location: Institute of Architecture and Urbanism, Blida city

Climate: Mediterranean climate

Date: October 13, 2024

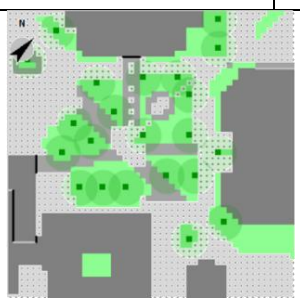
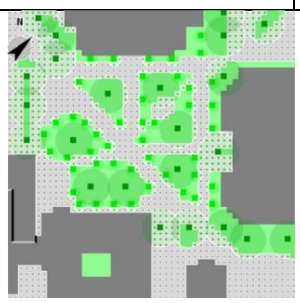
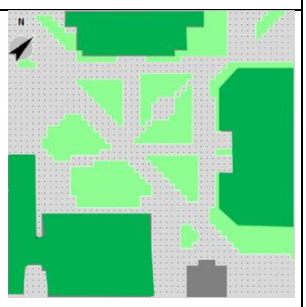
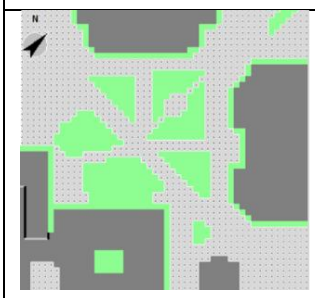
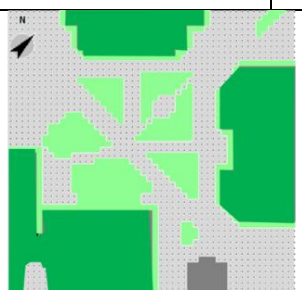
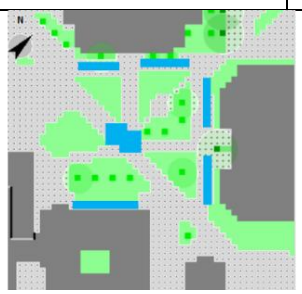
Time: 8 a.m. to 5 p.m. **Inputs:** Full forcing climate file, Meteonorm 8

Scenarios: Eight different scenarios (Figure 3)

Outputs

- Microclimate Parameters: Ta (°C), RH (%), T_{MRT} (°C) and W (m/s)
- Thermal comfort Indices: PET (°C) , UTCI, PMV and SET.

Modelled Scenarios

(1) Baseline Condition	(2) Shading Strategy	(3) Vegetation Integration	(4) Green Roof
			
(5) Vertical Green Walls	**(6) Green Envelope**	**(7) Water Features**	**(8) Surface Alternatives**
			

4.3. Simulation Results

Air Temperature (Ta °C) – Reduction of Ambient Heat

The implementation of various design strategies led to measurable improvements in air temperature across the courtyard. Compared to the baseline condition, all scenarios contributed to temperature mitigation, with the most significant reduction observed in Scenario 2 (Shading

Strategy), which decreased the average air temperature by nearly 0.9°C. Scenario 3 (Vegetation Integration) also performed notably well due to its evaporative cooling effect. These strategies proved most effective in minimizing heat buildup and promoting a more thermally comfortable environment.

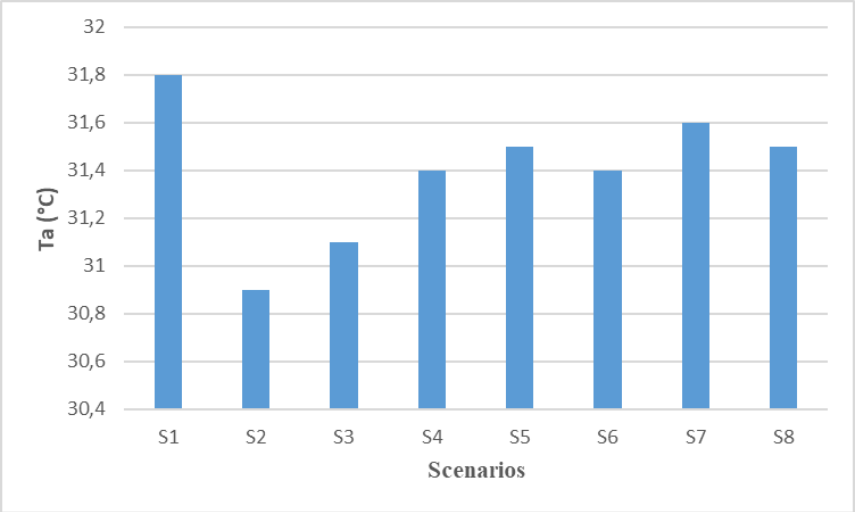


Figure 21 Diagramme Air Temperature (Ta °C) – Reduction of Ambient Heat

Relative Humidity (RH %) – Enhancing Air Moisture Content

The addition of vegetation and water features notably improved relative humidity levels across the courtyard. Scenario 3 (Vegetation Integration) achieved the highest increase in RH, reflecting the role of plants in enhancing atmospheric moisture through evapotranspiration. Scenario 6 (Combined Green Roofs and Walls) and Scenario 7 (Water Features) also contributed significantly, supporting a more humid and comfortable microclimate in a hot-dry context.

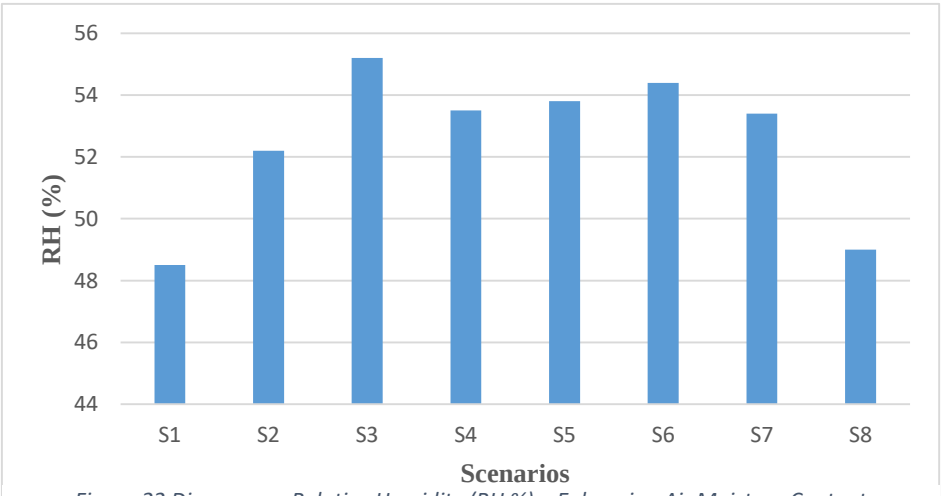


Figure 22 Diagramme Relative Humidity (RH %) – Enhancing Air Moisture Content

Mean Radiant Temperature (Tmrt °C) – Reducing Radiative Heat Stress

All proposed interventions contributed to lowering mean radiant temperatures when compared to the baseline, indicating enhanced shading and surface cooling. Scenario 3 (Vegetation Integration) demonstrated the greatest reduction in Tmrt, attributed to tree canopy shading and cooler surface temperatures beneath vegetation. Scenario 2 (Shading Strategy) also showed strong performance, confirming the efficiency of artificial shading in blocking solar radiation.

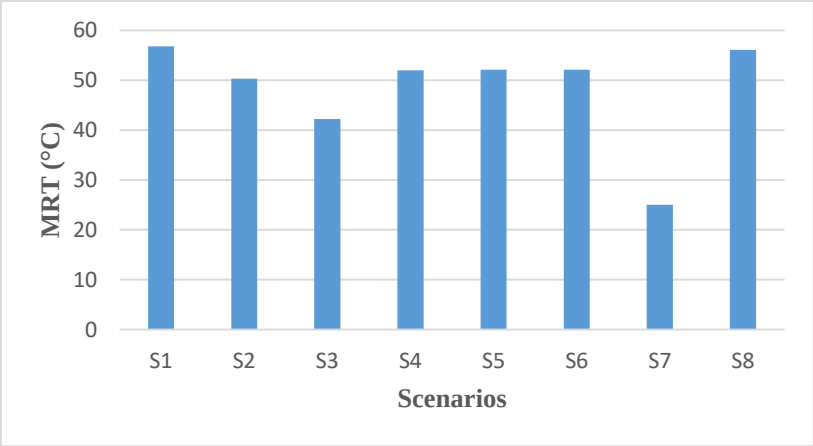


Figure 23 Diagramme Mean Radiant Temperature (Tmrt °C) – Reducing Radiative Heat Stress

Wind Speed (W m/s) – Preserving Air Circulation

Wind flow was moderately impacted by the introduction of physical elements. While dense vegetation and shading slightly reduced wind speed, green infrastructure scenarios such as Scenario 4 (Green Roof), Scenario 5 (Green Walls), and Scenario 6 (Combined Green Roofs and Walls) maintained balanced airflow while still improving thermal conditions.

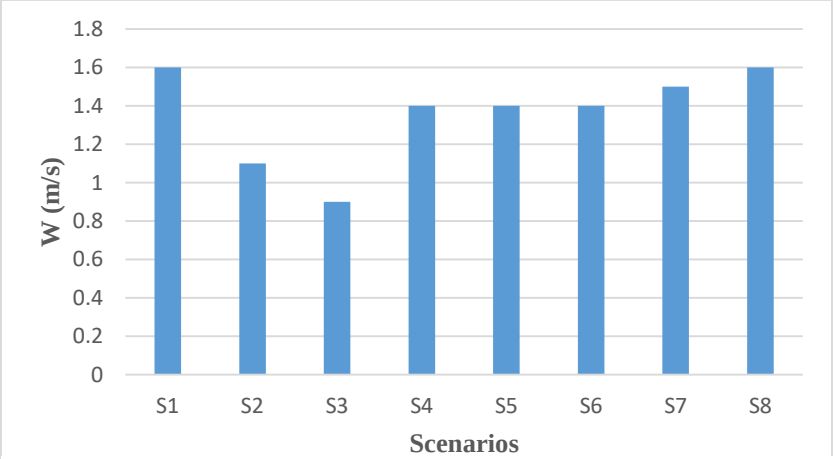


Figure 24 Diagramme Wind Speed (W m/s) – Preserving Air Circulation

1) Microclimate Dynamics

Table 19 Microclimate Dynamics, source : author 2025

Microclimate parameters	Scenarios							
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
Ta (°C)	31,8	30,9	31,1	31, 4	31,5	31,4	31,6	31,5
RH (%)	48,5	52,2	55,2	53,5	53,8	54,4	53,4	49,0
T_{MRT} (°C)	56,8	50,3	42,2	52,0	52,1	52,1	52,0	56,1
W (m/s)	1,6	1,1	0,9	1,4	1,4	1,4	1,5	1,6

2) Thermal Comfort Levels

Thermal Comfort Indices Analysis

This section evaluates the effectiveness of each microclimate intervention scenario through four standardized thermal comfort indices: PET (Physiological Equivalent Temperature), PMV (Predicted Mean Vote), UTCI (Universal Thermal Climate Index), and SET* (Standard Effective Temperature). These indices provide a holistic assessment of human thermal perception, integrating meteorological and physiological parameters.

PET (°C) – Physiological Equivalent Temperature

The PET index measures human thermal comfort by combining air temperature, humidity, wind, and radiation. As shown in Figure 4.5, Scenario 3 (Vegetation Integration) provided the most significant PET reduction, dropping it below 40°C, which is a meaningful thermal relief compared to the baseline (Scenario 1). Scenarios 2 (Shading) and 6 (Green Roofs + Green Walls) also showed improved conditions. These interventions are effective because they reduce both air temperature and mean radiant temperature.

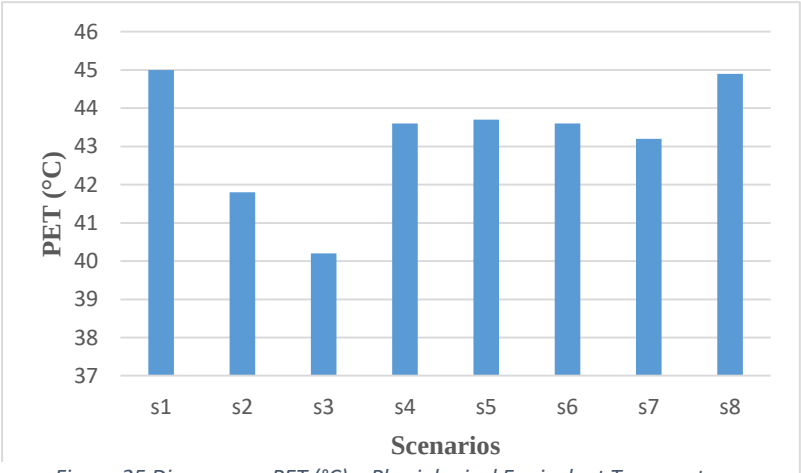


Figure 25 Diagramme PET (°C) – Physiological Equivalent Temperature

PMV – Predicted Mean Vote

The PMV index expresses thermal sensation on a scale from cold (–3) to hot (+3). As illustrated in Figure 4.6, Scenario 3 (Vegetation) demonstrated the most favorable PMV shift, indicating a move toward thermal neutrality. While other scenarios (such as 2, 4, 5, and 6) also reduced PMV slightly, their impact was less pronounced. Vegetation not only moderates temperature but also enhances relative humidity, which contributes to this balance.

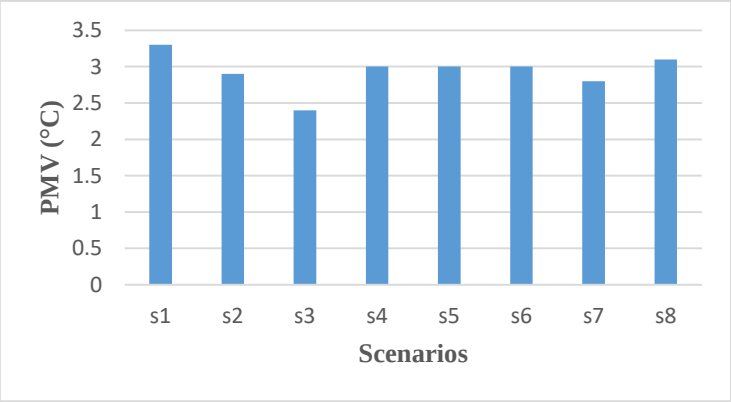


Figure 26 Diagramme PMV – Predicted Mean Vote

UTCI (°C) – Universal Thermal Climate Index

UTCI provides a comprehensive outdoor comfort measure based on a dynamic physiological model. In Figure 4.7, Scenario 3 (Vegetation) again achieved the best reduction in UTCI values, indicating substantial thermal relief. Scenario 2 (Shading) followed closely. These findings align with their impact on other physical parameters like air temperature, humidity, and radiation, confirming their suitability for warm climates.

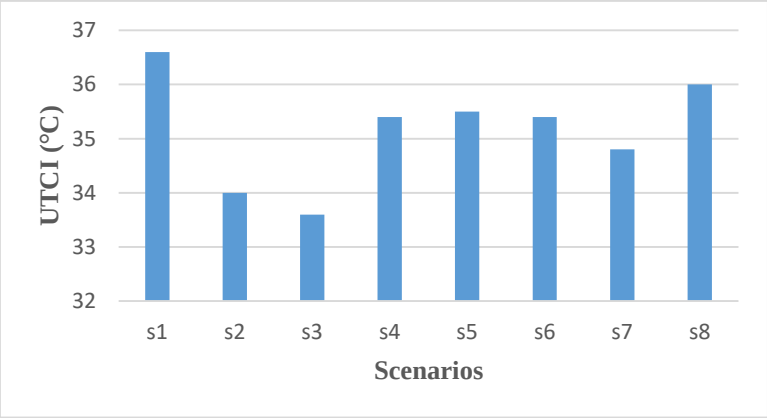


Figure 27 Diagramme UTCI (°C) – Universal Thermal Climate Index

SET* (°C) – Standard Effective Temperature

SET* reflects perceived temperature based on thermoregulation and heat exchange. As shown in Figure 4.8, Scenario 3 (Vegetation) once again yielded the greatest decrease in SET*, followed by Scenario 2 and Scenario 6. The combined effects of shading, evaporative cooling, and improved airflow explain the strong performance of these scenarios in perceived comfort.

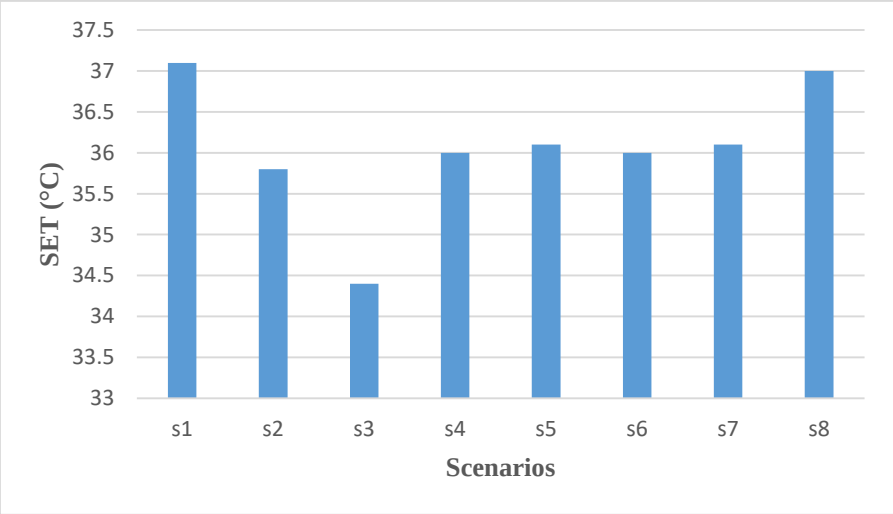


Figure 28 Diagramme SET (°C) – Standard Effective Temperature*

Table 20 Thermal Comfort Levels, source : author 2025

Thermal Indices	Scenarios							
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
PET (°C)	45,0	41,8	40,2	43,6	43,7	43,6	43,2	44,9
UTCI (°C)	36,6	34,0	33,6	35,4	35,5	35,4	34,8	36
PMV (°C)	3,3	2,9	2,4	3	3	3	2,8	3,1
SET (°C)	37,1	35,8	34,4	36	36,1	36	36,1	37

5. Design Proposal

5.1. Proposed Interventions

- Shading solutions: Trees, pergolas, and canopies.
- Landscaping strategies: Vegetation selection and placement.
- Surface material upgrades for thermal efficiency.

- Integration of water features.

5.2. Validation and Discussion

- ENVI-met simulations showing improvements in thermal comfort.
- Comparative analysis of current vs. proposed conditions.

6. General Conclusion (5 pages)

6.1.Summary of Findings

This research investigated the thermal comfort challenges faced by the outdoor courtyard of the Institute of Architecture and Urbanism at Saad Dahlab University, Blida 1, and proposed climate-responsive design strategies to enhance its usability. The study began by identifying key microclimatic problems in the courtyard, including excessive solar radiation, minimal vegetation, poor shading, low airflow, and limited user activity. Using ENVI-met simulations, field surveys, and theoretical research, a set of eight design scenarios were developed to address these conditions through passive and sustainable interventions.

The simulation results demonstrated measurable improvements across all tested thermal parameters. Scenario 3, which focused on vegetation integration, was consistently the most effective in reducing air temperature, PET, UTCI, SET*, and PMV values. Scenario 2 (shading strategy) and Scenario 6 (combined green roofs and green walls) also showed high performance, particularly in reducing mean radiant temperature and maintaining airflow. Water-based strategies and surface material alternatives contributed positively, though their effects were more localized.

Each design scenario was tested using indices widely recognized in microclimate research: Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Universal Thermal Climate Index (UTCI), and Standard Effective Temperature (SET*). Improvements in these indices validated the effectiveness of interventions in reducing heat stress. The use of combined vegetation and shading scenarios achieved PET reductions of up to 5–6°C during peak hours, shifting conditions from severe to tolerable levels.

Subjective user surveys supported the simulation data. Most respondents highlighted high temperatures, lack of shade, and discomfort as primary issues. When asked about improvements, users preferred increased greenery, shaded seating, and water features. These preferences aligned with the scenarios showing the highest performance in microclimate simulations.

From a spatial and architectural standpoint, the proposed interventions not only improved environmental performance but also enhanced the aesthetic and functional qualities of the

courtyard. Strategies like green roofs, vegetated facades, and shaded pathways not only cooled the space but also reactivated underused zones and supported social and academic engagement.

Overall, the study offers a robust and replicable framework for improving outdoor thermal comfort in educational institutions in hot climates. It demonstrates that passive design strategies rooted in microclimatic understanding can significantly transform educational courtyards into livable, inclusive, and sustainable environments.

6.2.Critical Reflections

This thesis demonstrated the potential of passive strategies to mitigate heat stress and improve thermal comfort in educational outdoor spaces, using ENVI-met simulations and user-centered assessments. However, several strengths and limitations must be acknowledged.

Among the strengths is the integration of empirical and simulated data. The methodology combined theoretical thermal comfort principles with user feedback and high-resolution simulation outputs. This triangulated approach ensured that the proposed interventions were both scientifically validated and aligned with user needs.

Another strength lies in the detailed microclimatic assessment and the diversity of proposed design strategies. The use of eight scenarios allowed a nuanced understanding of the effectiveness of each intervention type. The simulations also considered multiple comfort indices and environmental parameters, offering a well-rounded picture of thermal behavior.

However, the study also faced limitations. First, the simulations were conducted for a single representative day (October 13), limiting seasonal generalizability. Thermal comfort conditions in colder or peak summer periods may vary, and additional simulations would be needed to fully evaluate year-round performance.

Second, while the ENVI-met software is a powerful tool for microclimate modeling, it has limitations regarding airflow simulation accuracy and dynamic user behavior. Real-world factors such as human movement, daily schedules, and behavioral adaptations were not fully captured.

Third, the implementation feasibility of some design interventions, particularly those involving water features or structural modifications (e.g., green roofs), may face constraints due to budget, maintenance, and technical challenges. These aspects require further study through stakeholder interviews or cost-benefit analyses.

Despite these limitations, the study makes a valuable contribution to the field of climate-adaptive design in higher education settings. It provides evidence-based design guidance for architects, planners, and university administrators aiming to create thermally comfortable and sustainable outdoor environments.

6.3.Future Perspectives

Future research on outdoor thermal comfort in educational settings can build upon the findings of this study in several ways.

First, expanding the temporal and seasonal scope of simulations is essential. Running ENVI-met analyses for both summer and winter periods would yield a more comprehensive understanding of comfort variability and inform adaptive design solutions tailored to different seasonal needs.

Second, integrating behavioral data into simulation models could enhance accuracy. User tracking tools, observational studies, or time-lapse photography could complement surveys and provide real-time data on user distribution, movement, and adaptation in response to climate conditions.

Third, interdisciplinary collaboration with environmental engineers, horticulturists, and social scientists would enrich the design process. Such collaboration can improve plant species selection, irrigation system design, and social inclusion strategies.

Fourth, future research should investigate the long-term maintenance, cost-effectiveness, and user satisfaction of implemented solutions. Post-occupancy evaluations (POEs) can assess how well interventions perform over time and how users engage with them, providing feedback loops for continuous design refinement.

Finally, applying this research framework to other campuses across different climatic zones in Algeria and beyond would help generalize findings and promote a wider shift toward thermally

inclusive educational design. Institutions can adapt the methods presented here to local conditions, thereby enhancing thermal resilience, ecological quality, and educational equity.

By pursuing these directions, the study of outdoor thermal comfort can evolve into a vital component of sustainable campus planning, ensuring that educational spaces remain usable, healthy, and inspiring despite changing climatic realities.

References

1. IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/ [Accessed 13 Jun. 2025].

2. Oke, 1987. Boundary Layer Climates. 2nd ed. London: Routledge.

3. World Health Organization (WHO), 2021. WHO Guidance for Climate-Resilient and Environmentally Sustainable Health Care Facilities. Geneva: World Health Organization. Available at: https://www.who.int/publications/i/item/9789240036727 [Accessed 13 Jun. 2025].

4. Kabisch et al., 2015. Human–Environment Interactions in Urban Green Spaces: A systematic review of contemporary issues and prospects for future research. Environmental Impact Assessment Review, 50, pp.25–34. https://doi.org/10.1016/j.eiar.2014.08.007

5. International Energy Agency (IEA), 2022. The Future of Cooling: Opportunities for energy-efficient air conditioning. Paris: IEA. Available at: https://www.iea.org/reports/the-future-of-cooling [Accessed 13 Jun. 2025].

6. IUCN, 2020. Nature-based Solutions and Climate Change. Gland, Switzerland: International Union for Conservation of Nature. Available at: https://portals.iucn.org/library/sites/library/files/documents/2020-020-En.pdf [Accessed 13 Jun. 2025].

7. UN-Habitat, 2014. Planning for Climate Change: A strategic, values-based approach for urban planners. Nairobi: United Nations Human Settlements Programme (UN-Habitat). Available at: https://unhabitat.org/planning-for-climate-change-a-strategic-values-based-approach-for-urban-planners [Accessed 13 Jun. 2025].

8. Kelz, Evans & Röderer, 2015. The Restorative Effects of Redesigning the Schoolyard: A study of greenery and outdoor space in educational settings. Environment and Behavior, 47(3), pp.259–284. https://doi.org/10.1177/0013916513499580

9. OECD, 2006. Environment and School Initiatives: Education and the environment. Paris: Organisation for Economic Co-operation and Development. Available at: https://www.oecd.org/education/environment-and-school-initiatives.htm [Accessed 13 Jun. 2025].

10. Ali-Toudert & Mayer, 2007. Effects of Asymmetry, Galleries, Vegetation, and Materials on Outdoor Thermal Comfort. Solar Energy, 81(6), pp.742–754. https://doi.org/10.1016/j.solener.2006.10.007

11. Gaitani, Mihalakakou & Santamouris, 2007. On the Use of Bioclimatic Architecture Principles in Order to Improve Thermal Comfort Conditions in Outdoor Spaces. Building and Environment, 42(1), pp.317–324. https://doi.org/10.1016/j.buildenv.2005.08.018

12. ASHRAE, 2020. ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

13. Fanger, 1970. Thermal Comfort: Analysis and Applications in Environmental Engineering. Copenhagen: Danish Technical Press.

14. Nicol et al., 2012. Adaptive Thermal Comfort: Principles and Practice. Abingdon: Routledge.

15. de Dear and Brager, 1998. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions, 104(1a), pp.145–167.

16. Johansson et al., 2016. Outdoor thermal comfort in Nordic cities: Microclimate simulation and field measurements. Urban Climate, 17, pp.170–186. https://doi.org/10.1016/j.uclim.2016.05.002

17. ASHRAE, 2017. ASHRAE Handbook—Fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

18. Ali-Toudert & Mayer, 2006. Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. Building and Environment, 41(2), pp.94–108. https://doi.org/10.1016/j.buildenv.2005.01.013

19. Kastner-Klein & Plate, 2004. Wind tunnel study of thermal comfort in city canyons. Meteorologische Zeitschrift, 13(5), pp.379–386. https://doi.org/10.1127/0941-2948/2004/0013-0379

20. Thorsson et al., 2007. Thermal bioclimatic conditions and patterns of behaviour in an urban park in Göteborg, Sweden. International Journal of Biometeorology, 51(2), pp.169–183. https://doi.org/10.1007/s00484-006-0064-1

21. de Freitas & Grigorieva, 2015. A comprehensive catalogue and classification of human thermal climate indices. International Journal of Biometeorology, 59(1), pp.109–120. https://doi.org/10.1007/s00484-014-0823-3

22. ISO 7730, 2005. Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva: International Organization for Standardization.

23. Höppe, 1999. The physiological equivalent temperature – A universal index for the biometeorological assessment of the thermal environment. International Journal of Biometeorology, 43(2), pp.71–75. https://doi.org/10.1007/s004840050118

24. Matzarakis et al., 1999. Applications of a universal thermal index: Physiological equivalent temperature. International Journal of Biometeorology, 43(2), pp.76–84. https://doi.org/10.1007/s004840050119

25. Matzarakis, Mayer & Iziomon, 1999. Applications of a universal thermal index: Physiological equivalent temperature. International Journal of Biometeorology, 43(2), pp.76–84. https://doi.org/10.1007/s004840050119

26. Nikolopoulou & Steemers, 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. Energy and Buildings, 35(1), pp.95–101. https://doi.org/10.1016/S0378-7788(02)00084-1

27. Bröde et al., 2012. Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). International Journal of Biometeorology, 56(3), pp.481–494. https://doi.org/10.1007/s00484-011-0454-1

28. Jendritzky et al., 2012. UTCI—Why another thermal index? International Journal of Biometeorology, 56(3), pp.421–428. https://doi.org/10.1007/s00484-011-0513-7

29. Norton et al., 2015. Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. Landscape and Urban Planning, 134, pp.127–138. https://doi.org/10.1016/j.landurbplan.2014.10.018

30. Oke, 1988. Street design and urban canopy layer climate. Energy and Buildings, 11(1–3), pp.103–113. https://doi.org/10.1016/0378-7788(88)90026-6

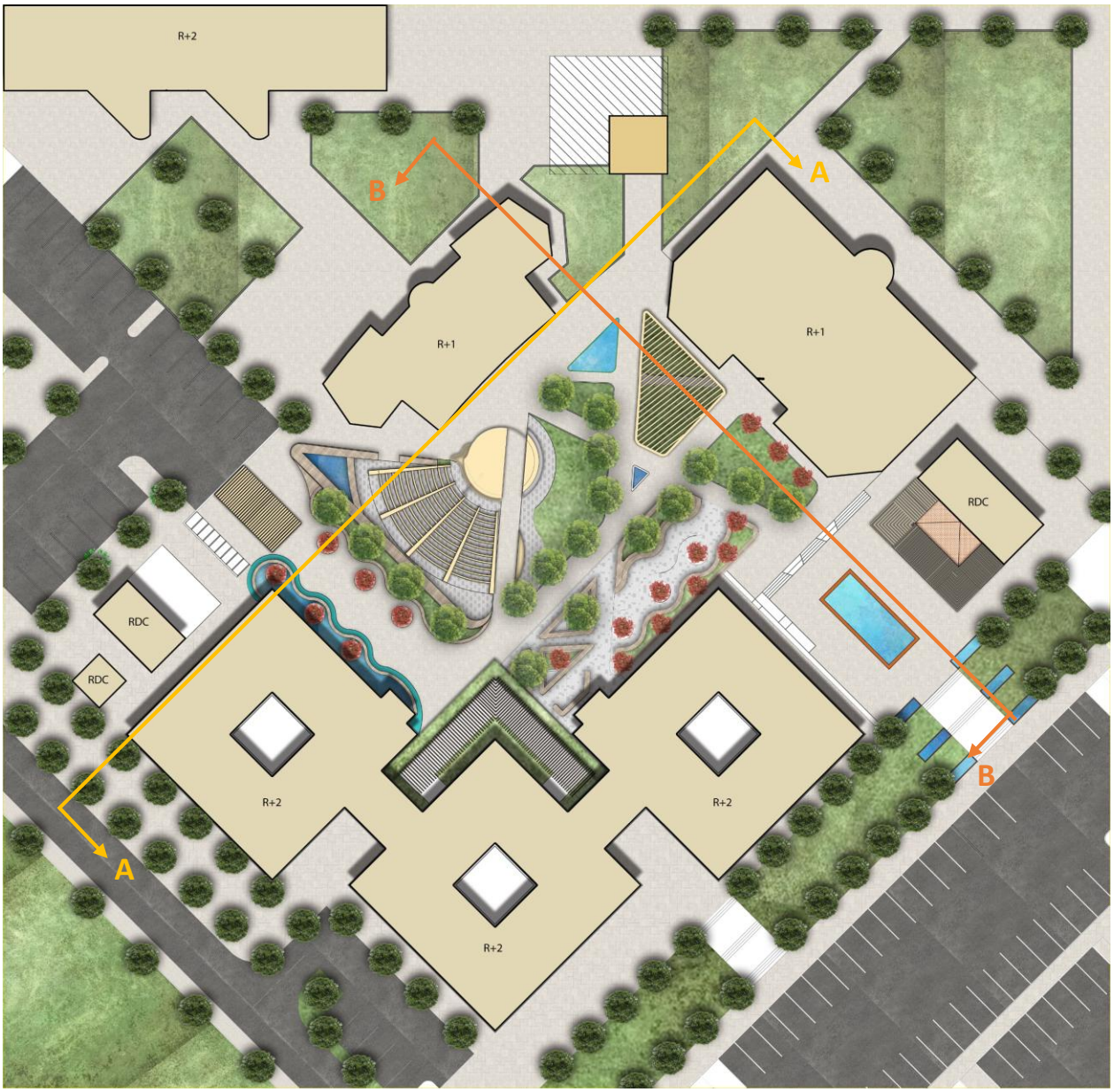
31. Shashua-Bar et al., 2011. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. International Journal of Climatology, 31(10), pp.1498–1506. https://doi.org/10.1002/joc.2177

List of tables

List of figures

APPENDICES

APPENDICES



Site plan

Façade section AA

APPENDICES

Façade section BB