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ARRAR Fawzi Hicham

Under the direction of:
Dr. KAOULA Dalel
Under the Co-direction of:
Pr. ATTIA Shady

Thermal analysis and environmental assessment of urban quality in a Mediterranean climate.

"Case of the medina of Algiers"

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Jury members		
Dr. Soufiane BOUKARTA	University of Blida1	President of Jury
Pr. Jacques TELLER	University of Liège	Examiner
Dr. Mohamed BOUKADER	University of Blida1	Examiner
Pr. Rachid BENNACER	University of Paris-Saclay	Examiner
Dr. Dalel KAOULA	University of Blida1	Promoter
Pr. Shady ATTIA	University of Liège	Promoter

University of Liège

Faculty of Applied Sciences

Urban and Environmental Engineering Dept.

Thermal analysis and environmental assessment of urban quality in a Mediterranean climate. “Case of the medina of Algiers”

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Art of Building and Urban Planning

By **ARRAR FAWZI HICHAM**

Supervisor: **Prof. Dr. Shady ATTIA** (University of Liège)

Co-Supervisor: **Dr. Dalel KAOULA**

Jury members: **Dr. Soufiane BOUKARTA** (Université Saad Dahleb Blida 1)

Prof. Dr. Jacques TELLER (Université de Liège)

Dr. Mohamed BOUKADER (Université Saad Dahleb Blida 1)

Prof. Dr. Rachid BENNACER (Université Paris-Saclay)

ALGERIAN DEMOCRATIC AND PEOPLE'S REPUBLIC

I dedicate this work with all my love and gratitude
to my beloved parents,
Saida Saker-Arrar and Zoheir Arrar,
whose endless support, sacrifices, and affection
have been my greatest source of strength and inspiration.

أُهدي هذا العمل بكل الحب والامتنان
إلى والديَّ الحبيبين،
سعيدة ساكر-عرار و زهير عرار،
تقديراً لدعمهما اللامحدود، وتضحياتهما، وحبهما الدائم
الذي كان مصدر قوتي وإلهامي

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Table of abreviations :

M	Metabolic heat production
W	Mechanical work
R	Fluxes of radiation
C	Sensible heat
S	Heat storage
ESK	Latent heat (skin)
ERE	Latent heat (respiratory system)
ESW	Latent heat sweating
PET	Physiological Equivalent Temperature
Tmrt	Mean Radiant Temperature
SVF	Sky View Factor
CFD	Computational Fluid Dynamics
LCA	Life Cycle Assessment
ENVI-met	Environmental Microclimate Modeling Software
BIO-met	Bioclimatic Modeling Tool for ENVI-met
RMSE	Root Mean Square Error
MBE	Mean Bias Error
RayMan	Software for calculating Mean Radiant Temperature
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Pathway
MEMI	Munich Energy Balance Model for Individuals
NBS	Nature-Based Solutions

ABSTRACT :

Historic cities like the Casbah of Algiers are facing increasing environmental challenges due to climate change and rapid urban transformations. This research investigates the thermal dynamics of this historic urban fabric, focusing on the interplay between urban morphology, microclimate, and outdoor thermal comfort. The objective is to assess the effectiveness of traditional passive strategies and explore the integration of nature-based solutions (NBS) to enhance pedestrian comfort while preserving the architectural and cultural integrity of the site. The study employs a multi-method approach, combining in situ measurements, numerical simulations (ENVI-met), and algorithmic modeling. Physiologically Equivalent Temperature (PET) is used as the primary thermal index to evaluate comfort levels under current and future climate scenarios (2050 and 2090). The effectiveness of shading, urban vegetation, and adaptive design strategies is analyzed through comparative simulations. Preliminary findings suggest that compact morphology and traditional materials offer significant thermal advantages, but increasing temperatures due to climate change exacerbate heat stress. The integration of NBS, such as strategic greening and shading structures, has the potential to mitigate urban heat islands while maintaining heritage authenticity. This research contributes to the discourse on sustainable urban heritage conservation by providing a decision-making framework for urban planners, architects, and policymakers. By bridging the gap between climate resilience and heritage preservation, the study offers actionable insights for the adaptation of historic cities in Mediterranean and arid climates.

RESUME :

Les villes historiques comme la Casbah d'Alger sont confrontées à des défis environnementaux croissants en raison du changement climatique et des transformations urbaines rapides. Cette recherche analyse la dynamique thermique de ce tissu urbain historique, en mettant l'accent sur l'interaction entre la morphologie urbaine, le microclimat et le confort thermique extérieur. L'objectif est d'évaluer l'efficacité des stratégies passives traditionnelles et d'explorer l'intégration de solutions basées sur la nature (NBS) pour améliorer le confort des piétons tout en préservant l'intégrité architecturale et culturelle du site. L'étude adopte une approche multi-méthodes, combinant des mesures in situ, des simulations numériques (ENVI-met) et une modélisation algorithmique. L'indice de Température Physiologiquement Équivalente (PET) est utilisé comme principal indicateur thermique pour évaluer les niveaux de confort sous les scénarios climatiques actuels et futurs (2050 et 2090). L'efficacité de l'ombrage, de la végétation urbaine et des stratégies d'adaptation est analysée à travers des simulations comparatives. Les résultats préliminaires suggèrent que la morphologie compacte et les matériaux traditionnels offrent des avantages thermiques significatifs, mais que l'augmentation des températures due au changement climatique accentue le stress thermique. L'intégration de NBS, telles que la végétalisation stratégique et les structures d'ombrage, pourrait atténuer les îlots de chaleur urbains tout en respectant l'authenticité patrimoniale. Cette recherche contribue au débat sur la conservation durable du patrimoine urbain en fournissant un cadre d'aide à la décision pour les urbanistes, architectes et décideurs politiques. En comblant le fossé entre résilience climatique et préservation patrimoniale, elle propose des recommandations concrètes pour l'adaptation des villes historiques en climat méditerranéen et aride.

ملخص

تواجه المدن التاريخية مثل قصبة الجزائر تحديات بيئية متزايدة بسبب تغير المناخ والتحولات الحضرية السريعة. يحلل هذا البحث الديناميكيات الحرارية لهذا النسيج الحضري التاريخي، مع التركيز على التفاعل بين التشكل الحضري والمناخ المحلي والراحة الحرارية لتحسين راحة (NBS) الخارجية. الهدف هو تقييم فعالية الاستراتيجيات السلبية التقليدية واستكشاف تكامل الحلول القائمة على الطبيعة المشاة مع الحفاظ على السلامة المعمارية والثقافية للموقع. تتبنى الدراسة منهجًا متعدد الأساليب، يجمع بين القياسات الموقعية والمحاكاة كمؤشر حراري رئيسي لتقييم (PET) والنمذجة الخوارزمية. يُستخدم مؤشر درجة الحرارة المكافئة فسيولوجيًا (ENVI-met) العددية مستويات الراحة في ظل السيناريوهات المناخية الحالية والمستقبلية (2050 و2090). يتم تحليل فعالية التظليل والغطاء النباتي الحضري واستراتيجيات التكيف من خلال عمليات المحاكاة المقارنة. وتشير النتائج الأولية إلى أن الشكل المدمج والمواد التقليدية توفر ، مثل التخضير NBS فوائد حرارية كبيرة، ولكن زيادة درجات الحرارة بسبب تغير المناخ تزيد من الإجهاد الحراري. إن تكامل الاستراتيجي وهياكل الظل، يمكن أن يخفف من جزر الحرارة الحضرية مع احترام أصالة التراث. يساهم هذا البحث في النقاش حول الحفاظ المستدام على التراث العمراني من خلال توفير إطار عمل لصنع القرار للمخططين الحضريين والمهندسين المعماريين وصانعي السياسات. ومن خلال سد الفجوة بين المرونة المناخية والحفاظ على التراث، فإنه يقدم توصيات ملموسة لتكيف المدن التاريخية مع .مناخ البحر الأبيض المتوسط والمناخ الجاف

I. General Introduction

1 General Background

Historic cities in the Mediterranean region, such as the Casbah of Algiers, embody centuries of architectural and urban evolution shaped by climatic, cultural, and socio-economic factors. Their compact morphology, traditional building materials, and passive cooling strategies have long contributed to a balanced and resilient urban environment. However, the growing impacts of climate change, coupled with rapid urbanization and socio-economic transformations, pose significant challenges to their sustainability.

As temperatures rise and extreme weather events become more frequent, historic urban areas face increasing pressure to adapt while preserving their unique heritage. The Casbah of Algiers, characterized by its dense network of narrow streets, courtyard houses, and strategic coastal positioning, presents a valuable case study for understanding the interplay between urban form, microclimate, and human comfort. The challenge lies in identifying effective adaptation strategies that respect the historical and cultural significance of the site while enhancing environmental performance and thermal comfort for its inhabitants.

Given the increasing frequency of extreme climatic events, the preservation of such historic sites must integrate climate adaptation strategies to ensure long-term sustainability and the well-being of residents. Recent urban transformations, unregulated developments, and demographic pressures have altered the microclimatic balance of the Casbah, exacerbating heat-related discomfort and affecting livability. These changes underscore the need to reassess traditional mitigation strategies while exploring innovative nature-based solutions (NBS) tailored to the specificities of Mediterranean heritage cities.

Research on outdoor comfort has largely focused on three primary approaches: numerical simulations (Ali-Toudert & Mayer, 2006; Berkovic et al., 2012), subjective surveys combined with objective measurements (Jeong et al., 2016; Manavvi et al., 2020), and thermal assessments for existing and future urban projects (Nasrollahi et al., 2017; Lam et al., 2018). However, the diversity of methodologies and models limits the comparability of results and their applicability to specific urban contexts (Coccolo et al., 2016).

Most studies on urban thermal environments have concentrated on modern cities with fragmented morphologies (Givoni, 1998; Ratti et al., 2005; Krüger et al., 2011), while research on heritage cities remains relatively scarce (Ali-Toudert et al., 2006; Achour-Younsi et al., 2016). This thesis aims to bridge this gap by focusing on the Casbah of Algiers, a historic urban fabric whose compact morphology, traditional materials, and architectural features play a key role in temperature regulation. Unlike previous studies primarily focused on contemporary cities, this research integrates an empirical and numerical approach, combining in situ measurements, CFD simulations, and algorithmic modeling to evaluate the combined effect of multiple cooling strategies, including sky view factor (SVF), sea breeze effects, and NBS (He et al., 2015; Venhari et al., 2019).

Several studies have analyzed the role of urban morphology in moderating heat stress, particularly in modern contexts (Charalampopoulos et al., 2013; Johansson et al., 2006; Deng et al., 2020).

Additionally, research on heat adaptation strategies has emphasized reflective materials and high-albedo surfaces (Jacobson et al., 2012; Santamouris, 2014) as well as green infrastructure solutions (Lobaccaro et al., 2015; Liu et al., 2021). However, their effectiveness within historic contexts remains underexplored, as interventions must align with conservation regulations and cultural significance (Bigio, 2014; UN-Habitat, 2008). The challenge of applying these adaptive measures in heritage districts lies in striking a balance between preserving architectural integrity and enhancing environmental resilience.

In this historic urban fabric, Talhi et al. (2018) and Karabag et al. (2017) have examined outdoor microclimatic conditions and vernacular architecture. Talhi et al. (2018) assessed the thermal performance of different urban typologies, combining in situ measurements, subjective surveys, and numerical simulations to highlight variations across configurations. Meanwhile, Karabag et al. (2017) analyzed the architectural principles of traditional dwellings to evaluate their suitability for local climatic conditions, materials, and lifestyle patterns. Their findings underscore the importance of passive cooling techniques in historic districts and the need to refine these strategies in response to climate change.

By integrating these insights, this research expands existing knowledge by developing a predictive model based on the Physiological Equivalent Temperature (PET). This model will quantify thermal conditions in preserved urban spaces under various climate scenarios, offering an evidence-based approach to sustainable rehabilitation.

Furthermore, while most studies have focused on contemporary cities, very few have investigated climate-responsive strategies for heritage districts. The challenge in implementing cooling techniques in traditional settings stems from architectural and regulatory constraints, as well as the necessity to maintain urban authenticity. This research, therefore, provides a scientifically rigorous and reproducible framework for assessing and enhancing outdoor comfort in historic environments.

This thesis aims to develop a methodological framework for assessing and improving outdoor thermal comfort in historic urban environments, with a particular focus on the Casbah of Algiers. By integrating numerical simulations, in situ measurements, and empirical analyses, this research will quantify existing thermal comfort levels, evaluate the impact of climate change scenarios, and propose sustainable rehabilitation strategies. A multi-criteria approach will be adopted, combining microclimatic, architectural, and environmental factors to optimize urban adaptation while maintaining heritage authenticity.

The main objectives of this study are threefold:

1. To analyze the thermal dynamics of the Casbah under current and future climatic conditions.
2. To assess the effectiveness of passive and nature-based mitigation strategies in enhancing outdoor thermal comfort.
3. To develop recommendations that reconcile climate resilience with heritage conservation.

Advances in climate modeling, urban heat mitigation strategies, and NBS offer new perspectives for preserving the climatic resilience of heritage sites. By examining the thermal dynamics of the Casbah and exploring strategies for mitigating heat stress, this study seeks to contribute to the broader discourse on sustainable urban heritage conservation in the face of climate change.

The expected outcomes include a decision-making framework that can guide urban planners, architects, and policymakers in the sustainable rehabilitation of historic districts while ensuring compliance with heritage preservation requirements. By addressing these challenges, this research contributes to bridging the gap between conservation practices and contemporary climate imperatives, ensuring that historic urban spaces remain resilient, livable, and environmentally sustainable for future generations.

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2 The Algerian context: History, Urban morphology, buildings – Challenge and opportunity :

2.1. The Architectural and Urban Evolution of Algiers Through the Centuries: A Historical and Cultural Capital

Algiers, the historical and cultural capital of Algeria, is the product of a long urban evolution shaped by the successive influences of various civilizations. Each period has left its mark on the city's urban fabric and architecture, creating a landscape where Mediterranean heritage, Islamic traditions, colonial reforms, and post-independence modernization intertwine. Far from being static, Algiers continues to evolve, balancing the preservation of its heritage with adaptation to contemporary demands.

2.1.1. Ancient Origins: Icosium and Roman Influence

Human settlements in the Algiers region date back to antiquity when the Phoenicians established a trading post known as Ikosim. This settlement flourished due to its strategic position on the Mediterranean, facilitating commercial exchanges with Carthage and other coastal cities. However, it was under Roman rule, starting in the 1st century BCE, that the city became more structured and was renamed Icosium. Like other Roman colonies, Icosium adopted a grid-based urban layout, with straight roads organized around a forum, which served as the political and commercial center. The city was also equipped with baths, an active port, and a paved road network, facilitating the movement of goods and inhabitants. Despite these developments, Icosium never reached the prominence of other major Roman cities in the region, and following the fall of the Empire, it gradually declined into obscurity. In the centuries that followed, Icosium’s urban organization faded in favor of a more organic settlement pattern influenced by local cultures.

"The Roman world was not just an empire of conquest; it was also an empire of urbanism and spatial organization, where each city was designed as a model of rationality and territorial integration." – Pierre Gros, historian of Roman architecture. - This principle is evident in the structure and expansion limits of Icosium (Figure 1), where urban planning reflected the Roman vision of territorial control and organization.

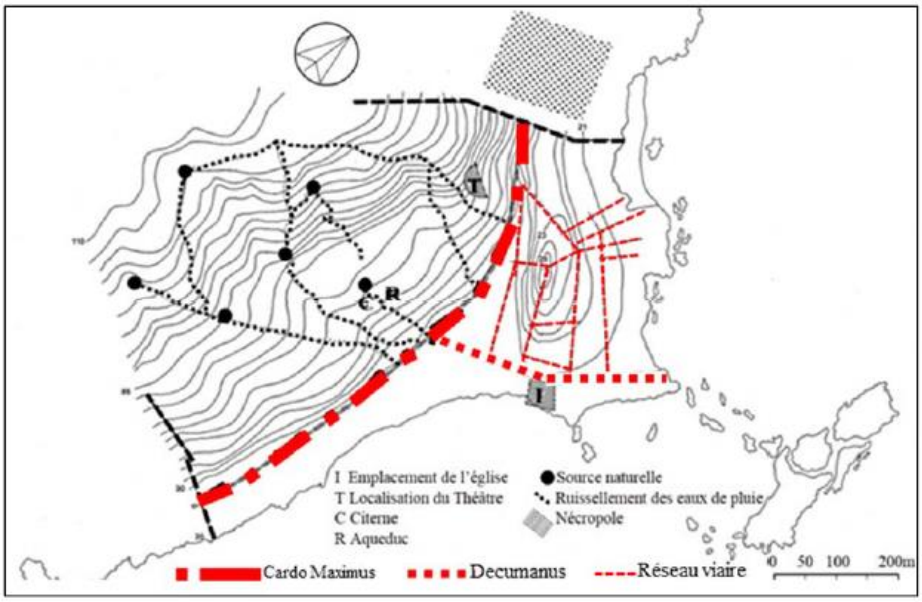


Figure 1: ICOSIUM. Structure and expansion limits. Source: Missoum, 2003.

2.1.2. The Medieval Period: Djazaïr Bani Mezghanna and the Consolidation of a Medina

With the arrival of Arab and Berber dynasties in the 7th century, Icosium gave way to Djazaïr Bani Mezghanna, a city that transformed into a strategic hub for trade and maritime defense. During this period, the city adopted the classic characteristics of Islamic medinas, featuring a dense and labyrinthine urban fabric designed to adapt to climatic conditions and the social needs of the time. The heart of the city was the Casbah, a fortress perched on the heights, housing the main political and religious institutions. Below it, a network of narrow, winding alleys developed, lined with traditional courtyard houses that provided both coolness and privacy for residents. The urban planning of Djazaïr was based on principles of protection and adaptation, limiting sun exposure and facilitating the circulation of sea breezes. This era also saw the expansion of a network of souks, vital economic centers where artisans, merchants, and travelers converged. Algiers thus became an important waypoint on the trade routes connecting North Africa to Andalusia and the Middle East. Thanks to this economic and cultural dynamism, the city's influence continued to grow, reaching its peak under the Ottoman Empire.

"Erase the embellishment, and only the structure remains! What strikes the observer here is the general unity of character." – André Ravéreau, La Casbah d'Alger et le site créa la ville - This unity is particularly evident in the Casbah's urban structure (Figure 2), where the organic development of the city reflects a balance between environmental adaptation and socio-cultural organization.

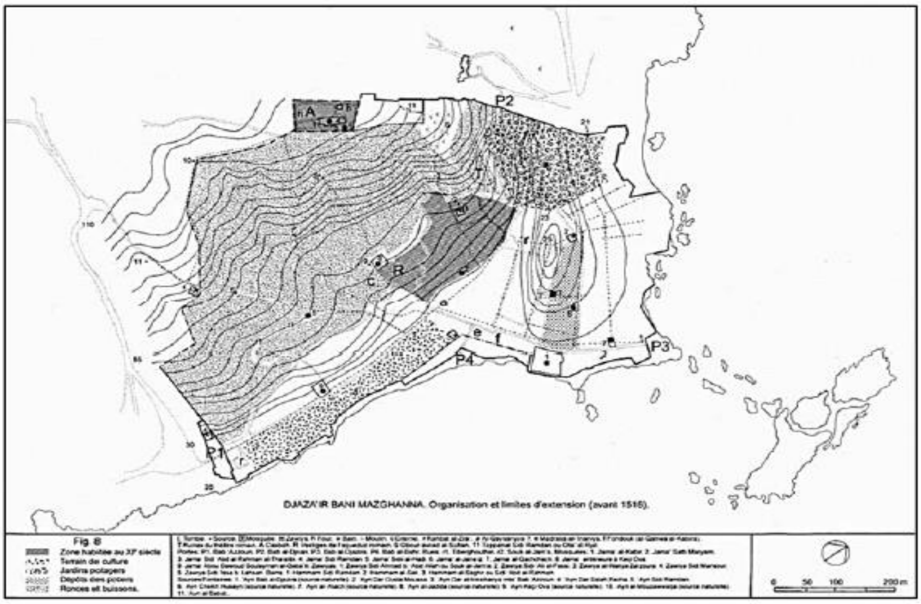


Figure 2: Casbah Plan Period of DJEZAIR BENI MEZGHANA – Source: PPSMVSS Casbah of Algiers

2.1.3. The Ottoman Era: A Fortified City and Architectural Influence

The arrival of the Ottomans in the 16th century marked the golden age of Algiers, which became one of the most feared strongholds in the Mediterranean. Under the protection of the Ottoman fleet and renowned corsairs such as Barbarossa, the city prospered and was equipped with strategic infrastructure. Its defensive system was reinforced with the construction of military forts, including the Fort de l'Empereur, which overlooked the bay, along with several coastal batteries protecting the harbor of Algiers. At the same time, the city experienced an architectural boom with the construction of refined palaces, such as Dar Hassan Pacha, and mosques adorned with ceramics and marble, including the famous Ketchaoua Mosque. Ottoman influences also transformed the Casbah, which was enriched with hammams, public fountains, and a social organization that fostered interactions between communities. Maritime trade and piracy brought wealth to Algiers, attracting merchants and artisans from across the Mediterranean basin. The city became a cultural mosaic where Andalusians, Turks, Berbers, and Arabs coexisted, shaping a unique urban identity. This prosperity lasted until the arrival of the French in 1830, which ended more than three centuries of Ottoman rule.

"The Casbah of Algiers, an extraordinary place, suspended between sky and sea, stands between Andalusia and the Arab Orient. No other has this orientation, this position, this climate, this precise architecture..." – André Ravéreau - This unique positioning and architectural evolution are vividly captured in historical representations of Algiers from the Ottoman period (Figure 3), illustrating the city's transformation into a strategic and cultural hub of the Mediterranean.

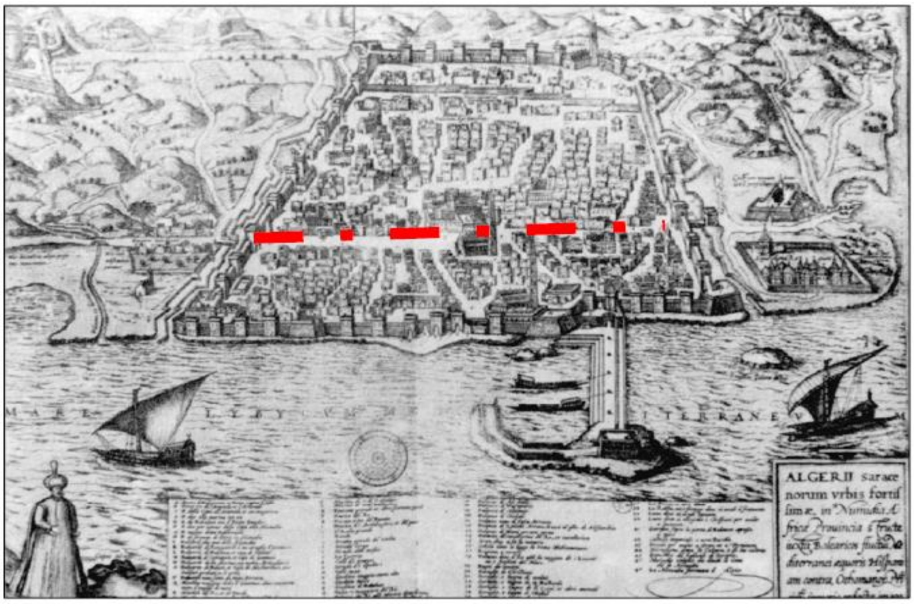


Figure 3: Engraving of Algiers in the Ottoman period (1570 or 1571). Source: Cresti, 1982

2.1.4. The Colonial Era: Restructuring and Imposed Modernization

The French occupation in 1830 triggered a profound transformation of Algiers' urban structure. The city was progressively reshaped following a Haussmannian model, inspired by the transformations of Paris. This modernization led to the partial destruction of the Casbah to make way for wide, straight avenues, arcaded buildings, and grand public squares. The city center was redesigned with administrative and commercial buildings, while new European neighborhoods emerged on the heights, gradually segregating the colonial and indigenous populations. Colonial architecture introduced new building typologies, such as wrought-iron balcony apartments, theaters, and courthouses, giving Algiers the appearance of a European city. However, this transformation came at the cost of increasing marginalization for Algerians, who were relegated to neglected traditional neighborhoods or forced to settle on the outskirts. This urban segregation fueled tensions that would lead to the war of independence and the rejection of the colonial model after 1962.

"We wanted to make Algiers a city of light, where architecture reveals space, where shadow interacts with stone." – Fernand Pouillon - This vision of transformation was embodied in the first colonial interventions that reshaped the city's structure (Figure 4), reflecting a deliberate effort to impose a new urban order.

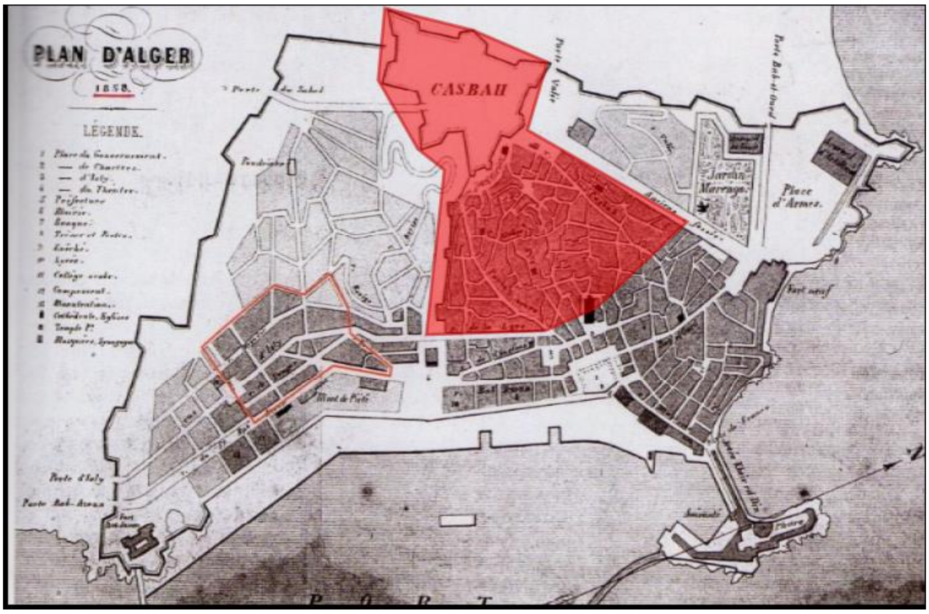


Figure 4: the first colonial intervention. Source: Research “background of the history of EL Djazair”

2.1.5. Independent Algeria: Massive Urbanization and Modernization Challenges

After gaining independence in 1962, Algiers entered a phase of rapid urbanization driven by the urgent need to accommodate a rapidly growing population. In response, the Algerian state implemented large-scale housing policies, leading to the construction of vast collective housing estates on the outskirts, often inspired by the modernist concepts of the 1950s and 1960s. Residential complexes such as Bab El Oued, Kouba, and Les Annassers emerged, breaking away from the city's traditional fabric. At the same time, the unregulated urbanization of certain districts led to the decline of historic infrastructures, particularly in the Casbah, which suffered from neglect and uncontrolled densification. In the following decades, modernization efforts focused on improving transportation, with the development of new roads, the metro, and the tramway. However, the lack of coherent urban planning and the social challenges associated with urban growth continue to pose difficulties for the capital’s development.

"The architectural references borrowed from the Casbah, Venice, or Andalusia… are multicultural and seem to prove that different cultures can blend together." – Myriam Maachi Maïza - These various influences are reflected in the successive interventions shaping Algiers' urban landscape (Figure 5), illustrating the city's ongoing struggle between heritage preservation and modern expansion.

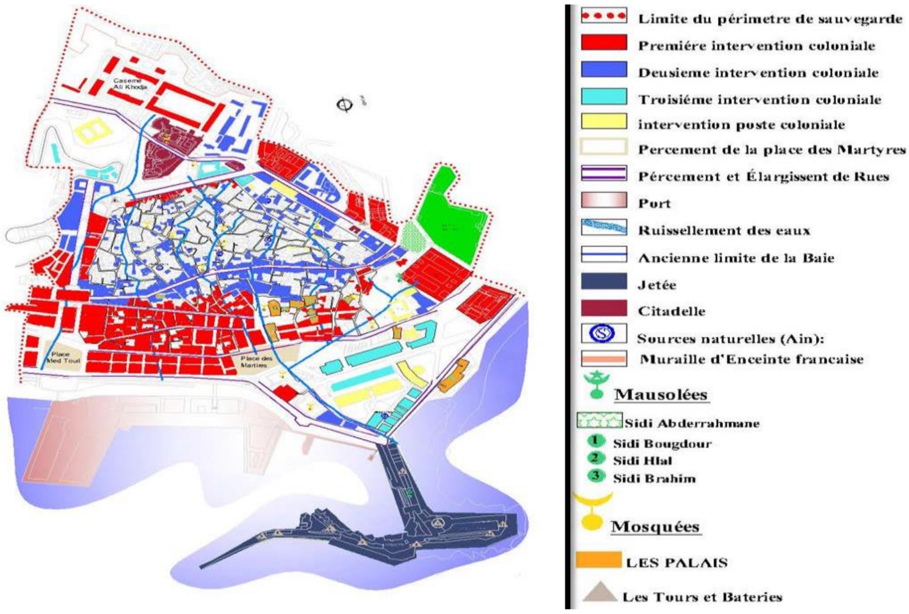


Figure 5: Summary of interventions in Algiers. Source: PPSMVSS

2.1.6. Contemporary Algiers: Between Heritage Preservation and the Pursuit of Modernity

Today, Algiers seeks to reconcile its exceptional architectural heritage with the demands of a modern metropolis. Major rehabilitation projects aim to preserve iconic sites, notably the Casbah, which is listed as a UNESCO World Heritage Site. At the same time, the city continues to develop contemporary infrastructure, including the metro, tramway, and new economic hubs. However, the challenge remains to manage urban sprawl while ensuring a high quality of life for residents. The future of Algiers depends on a balanced approach, combining sustainable development with the enhancement of its unique urban identity.

"Algiers is a city where the past and present collide, where architecture tells a story of contrasts and resilience." – Jean-Claude Vigato, historian of urbanism

2.2. Urban Prospection in Algiers: From the Context of Algiers to the Protected Sector

Algiers, the capital of Algeria, boasts an exceptionally rich urban heritage, shaped by a layering of different historical periods and various architectural influences. From the Ottoman era to colonial and post-colonial transformations, the city has developed around a heterogeneous urban fabric, where the old coexists with the modern.

One of the most emblematic elements of this heritage is the Casbah of Algiers, a remarkable example of Arab-Muslim urban planning, listed as a UNESCO World Heritage Site since 1992. This ancient fabric is characterized by its narrow alleys, courtyard houses, and covered passages, forming an efficient bioclimatic system. However, recent transformations in the city have led to profound changes that threaten the historical balance of this neighborhood.

In response to these challenges, the Protected Sector of Algiers was established under the Permanent Plan for Safeguarding and Enhancement (PPSMVSS) to regulate urban interventions and ensure the preservation of built heritage. This urban prospection aims to analyze the evolution of the urban fabric and identify issues related to conservation and territorial planning.

2.2.1. Presentation of the Casbah of Algiers: A Historical Urban Model

The Casbah of Algiers is a typical example of an Islamic medina, located on a hillside overlooking the Bay of Algiers. Its urban fabric is compact and organic, adapting to the site's rugged terrain. The urban layout is marked by a dense network of winding alleys, designed to promote coolness and provide naturally shaded spaces.

Historically, the Casbah was the administrative, commercial, and residential heart of the city. It housed power structures such as the palaces of Ottoman governors, mosques, and madrasas. The houses were often organized around inner courtyards, where families could gather away from prying eyes and extreme climatic conditions.

The architecture of the Casbah is distinguished by its ingenious bioclimatic design. Traditional houses are built with stone, lime, and wood, materials that provide excellent thermal inertia. Central patios ensure natural ventilation of the interiors, while Sabats (covered passages) create shaded areas in the alleys, reducing the impact of solar radiation.

Despite its historical and architectural significance, the Casbah of Algiers today suffers from advanced degradation. Lack of maintenance, demographic pressure, and inappropriate interventions have led to the collapse of several buildings and the deterioration of its urban fabric. The Protected Sector of Algiers was thus established to address these issues and oversee rehabilitation projects.

2.2.2. The Protected Sector of Algiers: A Framework for Protection and Urban Study

The Protected Sector of Algiers includes several areas with distinct architectural and urban characteristics. It extends beyond the Casbah, integrating colonial and postcolonial urban spaces. This perimeter was defined by the PPSMVSS, which aims to protect and rehabilitate heritage while allowing adaptation to contemporary needs.

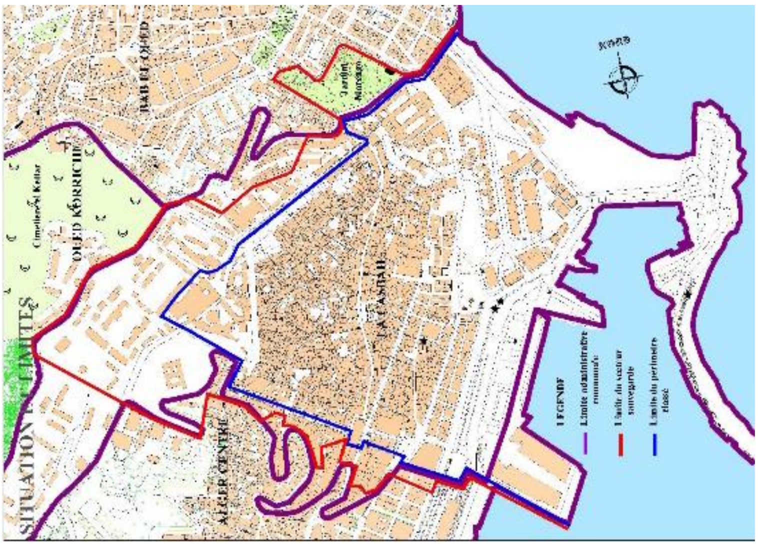


Figure 6: Limits of the protected area Source PPSMVSS

This sector is characterized by the coexistence of different urban fabrics inherited from the various phases of Algiers' development. It includes areas delineated by specific regulations to ensure the preservation of historical and architectural integrity (Figure 6), reflecting a balance between conservation efforts and the evolving needs of the city.**The ancient fabric** (Arab-Ottoman Casbah), dense and organic, marked by traditional architecture adapted to the climate.

The mixed fabric, where historical buildings are interrupted by colonial breakthroughs, modifying urban continuity.

The colonial fabric, characterized by wide, straight boulevards, arcaded buildings, and open public spaces.

The postcolonial fabric, consisting of modern constructions and recent infrastructures, often in contrast with the traditional model.

This morphological diversity provides an ideal field of study to understand the dynamics of urban evolution and the challenges of preserving built heritage.

2.2.3. Global Morphological Analysis of the Protected Sector

An analysis of plots, roads, buildings, and open spaces highlights the existence of five homogeneous zones within the **Protected Sector**.

a. The Five Homogeneous Zones of the Protected Sector

Zone 1: The Upper Casbah
This area includes the neighborhoods of Sidi Ramdane, Amar Ali, and Mer Rouge. It is characterized by a dense traditional urban fabric, organized in a tree-like street system. It houses several classified monuments, reflecting the Ottoman architectural heritage.

Zone 2: The Colonial Belt
Located on the periphery of the sector, this zone features a regular colonial-era urban layout. It contains residential buildings and public facilities (schools, administrative buildings), contrasting with the organic structure of the Casbah.

Zone 3: The Lower Casbah
This includes the neighborhoods of Amar el Kama, Souk el Djemaa, and part of Lalahoum, as well as the buildings bordering Boulevard de la Victoire. This sector presents a mixed fabric, where traditional structures are interrupted by colonial openings.

Zone 4: The Admiralty and Khair-Eddine Jetty
This area includes strategic port infrastructure, which forms a distinct element compared to the surrounding urban fabric.

Zone 5: Spaces in Disruption with the Historical Fabric
This area includes modern structures such as multi-story parking lots and the Music Institute, which struggle to integrate into the traditional built environment.

These distinct zones, each reflecting a different phase of Algiers' urban history, are mapped to highlight their spatial characteristics and heritage significance (Figure 7).

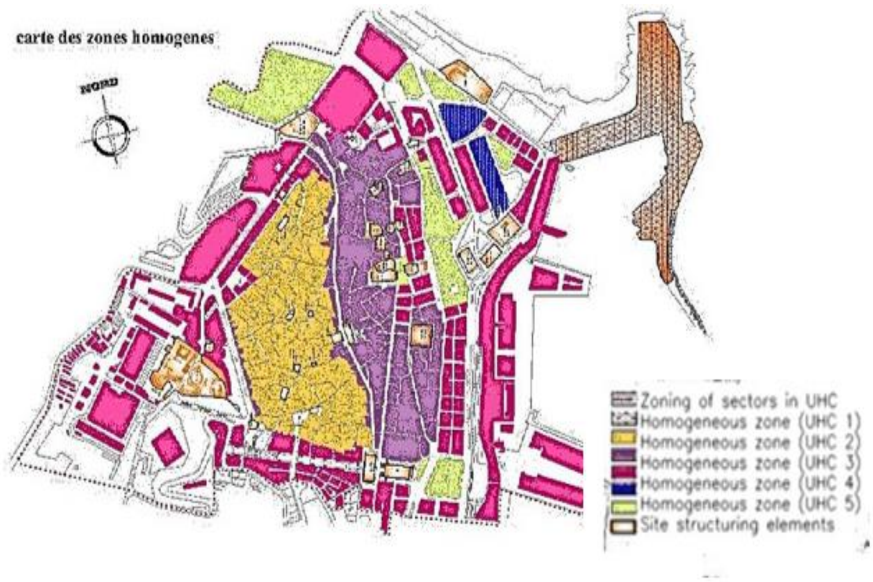


Figure 7: Map of homogeneous areas Source: PPSMVSS

b. Lines of Disruption in the Urban Fabric

The urban evolution of Algiers has generated several fractures in the continuity of the historical fabric. Three major disruptions have been identified:

1. **Break between the Upper and Lower Casbah**
   This rupture was caused by the demolition of two-thirds of the traditional fabric to create a military base, later replaced by the SOCARD project.
2. **Break between the Upper Casbah and the Citadel**
   The construction of Boulevard de la Victoire and Taleb Abderrahmane Street, initially for military logistical reasons, separated the Casbah from its historical environment.
3. **Break between the Lower Casbah and the Port**
   The creation of Boulevard du Front de Mer and Avenue de l'ALN isolated the medina from the sea, altering its historical relationship with the coastline.

These transformations have profoundly modified the spatial organization of the Protected Sector, highlighting the urgency of an integrated rehabilitation approach that respects heritage and contemporary urban dynamics (Figure 8).

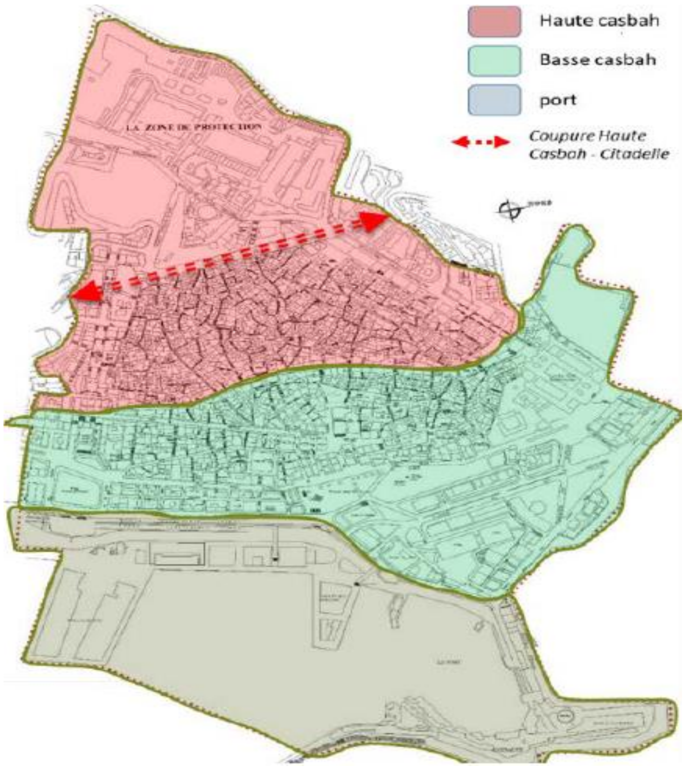


Figure 8: Map of fault lines within the Casbah

The analysis of the Protected Sector of Algiers reveals the evolution of its urban fabric and the challenges of its conservation. The layering of architectural influences has created a complex urban landscape, where modern interventions have sometimes disrupted historical balance.

Today, rehabilitating the Casbah and its surroundings requires an approach that integrates traditional bioclimatic principles while adopting a sustainable vision for urban planning, ensuring the preservation of this unique heritage.

3 Motivation, objectives and expected impacts

Faced with the growing challenges of climate change and the degradation of urban heritage, this research aims to develop an innovative methodological approach for the rehabilitation of historical urban spaces. The major challenge is to ensure a balance between preserving the built environment and improving outdoor thermal comfort, particularly in a Mediterranean context where heat waves are becoming increasingly frequent.

The main objective of this study is to quantify and analyze the existing thermal comfort in the streets of the Casbah of Algiers, assessing the impact of passive strategies on mitigating urban heat islands. To this end, a methodology based on a multi-criteria algorithm will be implemented, integrating various climatic and architectural parameters to optimize the management of microclimatic conditions. In parallel, an environmental analysis will assess the ecological implications of these strategies, ensuring a holistic approach to urban rehabilitation. This approach thus aims to provide a quantifiable and reproducible decision-making framework adapted to the specificities of historic centers, where interventions must comply with strict heritage requirements.

Exploring thermal comfort in traditional urban fabrics represents a significant advancement, allowing for the development of tailored and sustainable solutions for the rehabilitation of historic centers. By relying on a combination of numerical modeling, in-situ measurements, and empirical analyses, this study aims to provide concrete recommendations for urban planners, architects, and building engineers, while also considering the environmental impacts associated with the various adaptation strategies implemented.

This research is also addressed to a wide range of institutional and scientific stakeholders, including international organizations such as UNESCO, ICOMOS, and OWHC, as well as local authorities and heritage managers, particularly urban planners and policymakers. By influencing urban conservation policies, it seeks to integrate climate issues into heritage rehabilitation strategies, thereby ensuring an improved living environment for residents and visitors of historic districts.

The expected impacts of this study are manifold. At the local level, it will enhance the quality of the outdoor environment in the Casbah of Algiers by reducing the effects of extreme temperatures and optimizing the habitability of public spaces, while taking into account the interactions between microclimate and urban ecosystems. On a broader scale, this research will contribute to raising awareness of climate and heritage issues by highlighting the importance of climate change adaptation strategies in historic cities. Finally, through its rigorous methodological approach, it will promote the internationalization of the developed tools, allowing their application in other similar urban contexts worldwide.

Ultimately, this study positions itself as a key lever for reconciling heritage preservation and climate adaptation by proposing innovative and scientifically grounded solutions for the sustainable management of historic urban environments.

4 Problematic, hypothèses and research questions

Historic urban centers, such as the Casbah of Algiers, are spaces where climate, architecture, heritage, and urban evolution intersect in complex ways (Salat, 2011). Preserving their architectural identity and heritage value is a major challenge that must be reconciled with contemporary issues such as thermal comfort and climate change adaptation. These neighborhoods, characterized by dense morphology, narrow alleyways, and traditional building materials, have historically benefited from passive thermal regulation. However, recent urban transformations, increasing demographic pressure, and poorly managed urbanization have disrupted this balance, exacerbating urban heat island effects and necessitating a reassessment of rehabilitation and adaptation strategies (Guedes & Breda Vázquez, 2016).

In the face of climate change effects such as rising temperatures, more frequent heat waves, and shifting wind and humidity patterns (Akbari et al., 1992), heritage conservation can no longer be dissociated from environmental concerns and the thermal comfort of inhabitants. Urban rehabilitation extends beyond preserving historical structures; it must also foster a high-quality built environment that ensures both energy sustainability and user well-being (Pipa, 2017). Consequently, urban and heritage renovation should not only safeguard the past but also integrate solutions adapted to contemporary challenges, incorporating bioclimatic approaches and nature-based strategies (Yau, 2015).

In this context, the morphological and architectural evolution of Mediterranean cities, particularly the Casbah of Algiers, requires in-depth historical analysis. The layering of different architectural periods, from Roman structures to colonial and modern interventions, has shaped a unique yet fragile urban identity (Ravéreau, 1981). This raises critical questions about how successive urban transformations have altered the original thermal balance and what strategies could restore optimal comfort conditions while preserving heritage.

The chosen methodological approach combines empirical observations, numerical simulations, and an assessment of thermal and heritage rehabilitation strategies. It is essential to develop an analytical framework that integrates the Casbah's climatic and architectural dimensions while considering climate warming scenarios projected for 2050 and 2090. The study also includes an experimental dimension through in situ measurements that assess the impact of various environmental parameters on outdoor thermal comfort in public spaces.

Traditional thermal regulation strategies in Mediterranean medinas—such as building layouts that maximize shading, the use of high thermal inertia materials, and the presence of vegetated spaces—have historically ensured optimal thermal comfort despite demanding climatic conditions (Pisello et al., 2016). However, the progressive deterioration of the urban fabric, the lack of appropriate preservation policies, and inadequate interventions have compromised these natural regulation mechanisms. Identifying mitigation solutions suited to the Casbah's historical context is therefore essential for reducing urban heat island effects and improving user comfort while maintaining architectural authenticity (Guedes & Breda Vázquez, 2016).

Moreover, the rehabilitation of the Casbah must be approached from an economic and social development perspective, enhancing the built environment and increasing its attractiveness for both residents and visitors (Yau et al., 2008). A key focus of this study is to assess the relevance of interventions based on natural solutions and passive thermal regulation techniques while integrating urban evolution scenarios and sustainable rehabilitation models (Lucchi, 2018). An environmental assessment of these actions is crucial to measure their ecological impact and ensure a balance between heritage preservation and climate adaptation. Incorporating sustainability criteria and evaluating the thermal performance of interventions will enable the development of precise recommendations for urban rehabilitation.

The following hypotheses guide this research, exploring the relationship between urban morphology, climate adaptation strategies, and thermal comfort in the Casbah of Algiers. These hypotheses will be tested through empirical observations, numerical simulations, and the evaluation of sustainable rehabilitation measures:

1. Thermal comfort levels in the historic urban fabric of the Casbah of Algiers are influenced by microclimatic variations, affecting the perception and use of outdoor spaces.
2. An integrated approach combining in situ measurements and numerical simulations will improve the quantification and prediction of outdoor thermal comfort in the context of climate change, ensuring a rigorous and reproducible methodology.
3. The integration of nature-based solutions (NBS) and urban form optimization can significantly enhance thermal comfort while addressing climate change impacts.

The research questions aim to explore the complex interactions between urban morphology, climate adaptation strategies, and thermal comfort in the Casbah of Algiers. By examining microclimatic variations, heritage conservation challenges, and the effectiveness of mitigation strategies, this study seeks to develop a comprehensive understanding of how historic urban spaces can be adapted to contemporary environmental challenges. The key questions focus on identifying current thermal comfort levels, evaluating predictive models, and assessing the potential of nature-based solutions and rehabilitation strategies in preserving both the cultural and environmental integrity of the Casbah.

The study is structured around the following research questions:

1. What are the current levels of thermal comfort in the historic urban fabric of the Casbah of Algiers, and how do microclimatic variations influence the perception and use of outdoor spaces?
2. How can an integrated approach combining in situ measurements and numerical simulations improve the quantification and prediction of outdoor thermal comfort in the context of climate change while ensuring a rigorous and reproducible methodology?
3. What mitigation strategies, including the integration of nature-based solutions (NBS) and urban form optimization, can significantly enhance thermal comfort while considering climate change impacts?

The ultimate goal of this study is to propose a methodological framework for evaluating and improving thermal comfort in historic urban settings, aligning heritage conservation with contemporary climate imperatives. Through a detailed analysis of microclimatic dynamics and sustainable rehabilitation scenarios, this research aims to provide concrete and applicable recommendations not only for the Casbah of Algiers but also for other historic centers facing similar challenges on a Mediterranean and international scale.

5 Thesis methodology and research strategy

The methodology adopted in this thesis is based on a multidisciplinary approach combining empirical studies, numerical simulations, and the evaluation of thermal and heritage rehabilitation strategies to provide concrete solutions to the challenges posed by climate change in the Casbah of Algiers. The objective is to develop a rigorous methodological framework to analyze the impact of climatic variations on outdoor thermal comfort while integrating sustainable solutions adapted to the historical and urban context of this heritage site. This approach is structured around five research axes, organized into Work Packages (WP) (Table1), each addressing a specific aspect of the study. WP1 (State of the Art) focuses on an in-depth literature review covering key topics such as heritage conservation, outdoor thermal comfort, the evolution of modern and traditional cities, mitigation strategies, and environmental impacts. WP2 (Experimental Investigation and Simulation for the Quantification of Outdoor Thermal Comfort) involves field investigations and numerical simulations to quantify outdoor thermal comfort using both objective measurements (PET, Tmrt indices) and subjective assessments (perception surveys), with cross-referenced analyses providing a better understanding of the interactions between the urban environment and thermal perception. WP3 (Prediction of Climate Change Effects on Outdoor Thermal Comfort) explores the future impacts of climate change on the Casbah through in situ data collection and climate scenario simulations, allowing for an anticipation of thermal comfort trends and the identification of site-specific vulnerabilities. WP4 (Coupling of Different Nature-Based Solutions for Pedestrian Thermal Comfort in a Mediterranean Climate) assesses the effectiveness of nature-based solutions (NBS) in improving pedestrian thermal comfort in the Mediterranean context by simulating different urban reconfiguration scenarios and evaluating the synergies between various mitigation strategies.

Table 1: Composition of the work packages of the thesis

Work Package	Title	Content
WP 01	State of the Art	- Heritage - outdoor thermal comfort - modern and traditional cities - mitigation strategies - climate change - environmental impacts
WP 02	Experimental investigation and simulation for the quantification of outdoor thermal comfort	- Objective approach: Analysis of measurements (PET, Tmrt) - Subjective approach: Questionnaire - Analysis and interpretation of cross-referenced - results
WP 03	Prediction of climate change effects on outdoor thermal comfort	- On-site measurements and data collection - Simulation of climate change scenarios - Evaluation of outdoor thermal comfort trends - Analysis and interpretation of results
WP 04	Coupling of different nature-based solutions for pedestrian thermal comfort in a Mediterranean climate	- Identification and assessment of nature-based solutions - Coupling different mitigation strategies for pedestrian thermal comfort - Simulation of multiple reconfiguration scenarios - Analysis and interpretation of results

PART 01: STATE OF THE ART: FROM URBAN MORPHOLOGY TO MICROCLIMATE

II. PART 01: STATE OF THE ART: FROM URBAN MORPHOLOGY TO MICROCLIMATE

1 Heritage

1.1. Study and analysis of the ecological approach of traditional/heritage towns

Traditional towns across the Mediterranean and North Africa have developed urban and architectural solutions that demonstrate a deep integration with their natural environments. These towns reflect centuries of adaptation to climate conditions, focusing on passive cooling, thermal insulation, compact urban layouts, and efficient resource management. Unlike modern urban developments, which rely heavily on mechanical systems for climate control, these historic cities have preserved self-sufficient, sustainable, and low-energy living models. This study focuses on the Casbah of Algiers, the M'zab Valley, the Medina of Tunis, Fez, Matera, Toledo, and Santorini, analyzing their urban planning, architecture, and material selection to understand how they successfully balance human comfort with environmental sustainability. To support these analyses, relevant scientific studies and academic sources are incorporated to provide a robust evidence base.

1.2. Urban Design as a Climate Response

One of the most striking features of traditional towns is their ability to integrate architecture with topographical constraints. In many cases, the built environment follows the contours of the land, taking advantage of natural slopes, rock formations, and prevailing winds to enhance climate resilience. In Matera, Italy, the historic Sassi cave dwellings are directly carved into limestone cliffs, offering natural insulation against temperature extremes. This approach minimizes the need for additional heating in winter and cooling in summer, as the rock stabilizes indoor temperatures (Brumana et al., 2018). Similarly, Santorini's architecture, built into volcanic terrain, maximizes cross-ventilation and thermal mass cooling, ensuring comfortable indoor conditions with minimal energy use (Santamouris et al., 2001).

1.3. Self-Shading Urban Layouts and Passive Cooling

A fundamental strategy shared by Fez, the M'zab Valley, and the Medina of Tunis is their compact urban fabric, designed to optimize shading and natural ventilation. The narrow streets and closely packed buildings in these towns reduce direct solar exposure, preventing heat buildup during the day (Bourbia & Awbi, 2004). The Medina of Tunis exemplifies adaptive urban planning, where winding alleys and staggered buildings create cool microclimates, making public spaces livable even during peak summer temperatures (Benharkat et al., 2020). In Toledo, Spain, stone-built structures are positioned to block intense summer sun while allowing light and warmth during winter months, demonstrating principles of passive solar design (Aksamija, 2013).

1.4. Sustainable Construction and Low-Impact Materials

The ecological approach of these towns is further reflected in their choice of materials, which are selected based on availability, durability, thermal performance, and low environmental impact. In the M'zab Valley, houses are constructed using mudbrick and palm wood, both of which are abundant, biodegradable, and highly insulating. Mudbrick provides excellent thermal regulation, absorbing heat during the day and slowly releasing it at night (Bekkouche & Boucheriba, 2021). In Matera and Toledo, limestone and sandstone are the dominant materials, chosen for their availability, strength, and ability to regulate humidity (Lucchi et al., 2018). In Santorini, volcanic ash, pumice, and lava stone are extensively used, taking advantage of the island's unique geology. These materials are lightweight yet insulating, offering superior fire resistance, durability, and energy efficiency while blending seamlessly with the landscape (Santamouris et al., 2006). In Fez and Tunis, adobe and lime plaster dominate construction. Adobe bricks, composed of sun-dried clay, sand, and organic fibers, require minimal energy to produce and provide breathable, moisture-regulating walls (Benharkat et al., 2020). Traditional materials exhibit high thermal inertia, regulating indoor temperatures naturally and reducing the need for artificial heating or cooling. Additionally, the extraction and use of local stone minimize transport emissions, reinforcing sustainability (Fabbri, 2015).

1.5. Insighs from Contemporary Research on Bioclimatic Architecture

The research conducted by Roberta Zarcone (2018) in her doctoral thesis, *Tradition constructive et innovation pour l'architecture bioclimatique dans la région méditerranéenne en milieu urbain*, provides further insights into how traditional construction techniques can be adapted using modern materials and technologies for improved energy efficiency. Zarcone's study focuses on Palerme, analyzing the evolution of a Mediterranean metropolis and its interaction with climatic constraints. The research highlights how traditional architectural elements, such as courtyards, shading devices, and thermal mass, can be optimized through contemporary innovations in material science and building technology. By integrating modern computational modeling techniques, the study provides tools for evaluating and designing new bioclimatic solutions that merge traditional knowledge with state-of-the-art technology. The findings reinforce the importance of reinterpreting heritage-based solutions to develop urban spaces that are both sustainable and thermally comfortable, reducing reliance on energy-intensive systems.

1.6. Lessons from the Past for Future Sustainable Cities

The ecological strategies embedded in the Casbah of Algiers, the M'zab Valley, Fez, Tunis, Matera, Toledo, and Santorini offer valuable insights for modern urban planning. These towns demonstrate that energy efficiency, resource conservation, and climate adaptation can be achieved without compromising human comfort or architectural aesthetics (Brumana et al., 2018). By revisiting the compact, pedestrian-oriented designs of traditional towns, cities today can reduce their carbon footprint and reliance on mechanized cooling and heating systems. The use of natural, locally sourced materials, inspired by historical construction techniques, can lower the environmental impact of buildings while improving thermal performance (Aksamija, 2013). Rather than viewing these historical towns as relics of the past, they should be recognized as models of ecological intelligence, capable of guiding future sustainable cities towards a harmonious balance between built and natural environments.

2 The Casbah of Algiers: Urban vision, ecological approach, and environmental assessment

The Casbah of Algiers stands as a remarkable example of a traditional urban environment shaped by climatic adaptation. Its compact and labyrinthine layout helps regulate temperature and airflow, creating a naturally cooled microclimate. The narrow, winding streets (derbs) minimize direct solar exposure while enhancing air circulation, a design that fosters passive cooling. Additionally, the dense clustering of buildings provides mutual shading, reducing the urban heat island effect and limiting overheating in public spaces. Situated on a hillside, the Casbah further benefits from the cooling influence of Mediterranean breezes that penetrate its urban fabric, making it one of the most environmentally responsive urban settlements in the region.

The traditional houses (dars) of the Casbah employ passive thermal strategies to maintain comfortable indoor conditions. Thick masonry walls, composed of local stone and lime, offer high thermal inertia, moderating temperature fluctuations by absorbing heat during the day and releasing it at night. Whitewashed facades reflect solar radiation, further reducing heat absorption. Central courtyards (patios) function as thermal regulators, facilitating evaporative cooling through the presence of shaded vegetation and water features. The Sabat, covered passages extending over narrow streets, reinforces shading and contributes to overall thermal comfort for pedestrians, allowing for a more pleasant urban experience even during peak summer months.

Water management played a crucial role in maintaining climatic comfort in the Casbah. Many houses historically featured underground cisterns (majen) for rainwater collection, ensuring a sustainable water supply while also regulating humidity levels. Public fountains, once integral to the urban fabric, not only provided drinking water but also enhanced local humidity, mitigating the dryness of the Mediterranean climate. Though many of these water systems have fallen into disuse, their role in promoting environmental sustainability remains significant. Preserving these historical water conservation techniques can serve as an essential strategy for contemporary urban development facing increasing water scarcity issues.

2.1. Morphology, urban quality in the face of microclimates

2.1.1 The impact of urban morphology and building typologies on environmental performance

Urban morphology plays a fundamental role in regulating microclimates and ensuring thermal comfort in urban environments. The spatial arrangement of buildings, their height, orientation, and the sky view factor (SVF) directly influence the distribution of solar radiation, airflow, and thermal exchanges within the built environment. Compact urban areas, characterized by narrow streets and dense buildings, create a more temperate microclimate by limiting direct solar exposure and promoting natural shading effects. These configurations help reduce daily thermal fluctuations and improve temperature regulation at the street level and in open spaces.

The variation in building heights and the organic layout of structures also enhance natural ventilation, mitigating extreme temperatures. The permeability of urban spaces, dictated by the relationship between built-up areas and open zones, influences air circulation and cooling processes. In coastal cities, sea breezes play a crucial role in microclimate regulation by dissipating heat accumulated during the day and lowering perceived temperatures. However, the absence of ventilation corridors or improperly positioned urban barriers can restrict this beneficial effect, exacerbating heat stagnation.

The orientation of streets and solar control strategies are also essential for optimizing climatic adaptation. Building arrangements often aim to minimize excessive solar gains, with north-facing facades receiving less direct sunlight, while openings are designed to maximize cross-ventilation. Traditional architectural elements, such as wooden lattice screens (moucharabieh), act as natural solar filters, reducing the intensity of radiation while promoting airflow. These bioclimatic solutions help maintain high levels of thermal comfort with minimal reliance on artificial cooling systems.

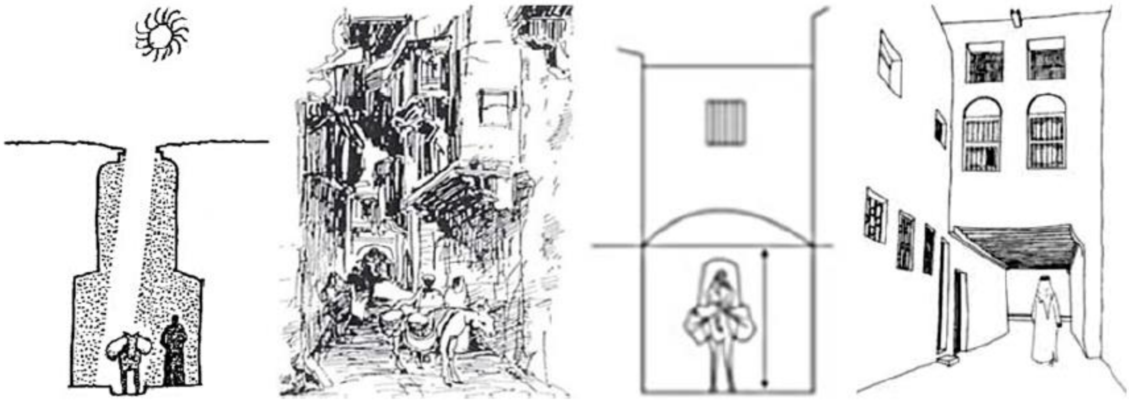


Figure 9:Architectural and urban elements characterizing the streets of Islamic cities: the Qubou on the left (A and B) and the Sabat on the right (C and D). Sources: A and D - Hasan Mansour, 2016. B - Hawra Jaafar Shaikh, 2016. C - Ragette, 2012. - Source - As

Building materials also play a key role in the environmental performance of urban spaces. Reflective surfaces and low-heat-absorption materials, such as white plaster or limestone, reduce heat accumulation, whereas high thermal inertia materials, like brick and massive stone, store and gradually release heat, stabilizing day and night temperatures. However, in poorly ventilated areas, these materials can amplify the urban heat island effect by radiating stored heat during the night.

The example of historic urban fabrics, such as the Casbah of Algiers, illustrates a sustainable urban model based on passive climate adaptation strategies. Its compact layout, natural ventilation systems, and solar control techniques reflect an environmental intelligence developed over centuries. However, modern urban transformations have led to the neglect of many of these bioclimatic principles, reducing their effectiveness. Thus, rehabilitation efforts should focus on reintegrating these strategies while respecting architectural heritage and fostering an approach to renovation that aligns with contemporary climate challenges.

As cities increasingly face the impacts of climate change, preserving and reinterpreting traditional urban planning principles offers valuable insights for contemporary urban development. Integrating strategies such as urban greening, optimizing building orientation, creating natural ventilation corridors, and using high-performance thermal materials could help reconcile thermal comfort with heritage preservation. By leveraging this ancestral knowledge, modern cities can develop more resilient urban models, better adapted to Mediterranean and arid climates, and less dependent on energy-intensive technologies. These principles are evident in the architectural and urban elements characterizing the streets of Islamic cities (Figure 9), where elements like the Qubou and Sabat illustrate the integration of climate-responsive design in historical urban environments.

3 State of art

3.1. Advancements in research on urban environmental performance evaluation: approaches, criteria, metrics, and tools

Outdoor thermal comfort is a determining factor in urban quality of life, influencing public health, the use of outdoor spaces, and the sustainability of urban developments. With the intensification of heat waves linked to climate change, accurately assessing thermal comfort has become essential, particularly in Mediterranean cities where urban heat islands exacerbate unfavorable climatic conditions (Santamouris et al., 2012).

In this context, it is crucial to adopt relevant indicators to quantify the impact of microclimatic conditions on the thermal perception of populations. To date, more than 165 biometeorological indices have been developed to assess human thermal comfort, integrating various environmental and physiological parameters (De Freitas & Grigorieva, 2017). However, not all of them are suitable for outdoor spaces, particularly in Mediterranean climates, characterized by high temperatures, significant relative humidity, and strong solar exposure.

It is therefore essential to analyze the advantages and limitations of these indices to identify the one that is most suited to an approach applied to urban planning and climate change adaptation.

3.1.1. Classification and Comparison of the Main Thermal Comfort Indices

Thermal comfort indices are classified into three main categories based on their calculation methodology and their ability to represent the physiological and behavioral reality of individuals.

a. Linear (or Empirical) Indices

Linear indices are the oldest and simplest to apply. They rely on direct statistical relationships between climatic parameters (temperature, humidity, wind, radiation) and human thermal sensation. These indices are primarily used for quick assessments, but their accuracy is limited as they do not account for human thermoregulation mechanisms.

Wet Bulb Globe Temperature (WBGT) (Yaglou & Minard, 1957)

Widely used to assess heat stress in extreme conditions, particularly in military and industrial sectors, it integrates dry temperature, wet-bulb temperature, and black globe temperature. A study by Budd (2008) showed that WBGT is reliable for predicting heat stroke risk in occupational settings but is unsuitable for urban environments, where the built environment significantly alters thermal fluxes.

Discomfort Index (DI) (Thom & Bosen, 1959)

Commonly used to evaluate thermal discomfort in urban areas, particularly in Mediterranean climates, this index is based on air temperature and relative humidity, without considering wind or solar radiation, which are crucial outdoors. A study conducted in Athens by Pantavou et al. (2014) demonstrated that DI underestimates thermal discomfort during heatwaves due to the omission of solar radiation.

Heat Index (HI) (Steadman, 1979)

Widely used in tropical and subtropical climates, it assesses perceived heat by combining air temperature and humidity. However, studies have shown that it overestimates the effects of humidity and completely ignores the impact of wind and shading, thus limiting its applicability in urban environments (Sherwood & Huber, 2010).

b. Indices Based on the Human Body's Energy Balance

More advanced, these indices incorporate thermal exchanges between the human body and its environment, taking into account phenomena such as convection, evaporation, and radiation. They rely on thermoregulation models, providing a better representation of actual thermal comfort.

Predicted Mean Vote (PMV) (Fanger, 1970)

Designed for air-conditioned indoor spaces, it is based on the human body's energy balance, considering metabolism, clothing insulation, and operative temperature. However, it is unreliable outdoors, where conditions change rapidly. A study in Shanghai (Lai et al., 2014) showed that it accurately predicts thermal comfort in buildings but poorly reflects thermal sensations in open urban environments.

*Standard Effective Temperature (SET) (Gonzalez et al., 1974; Gagge et al., 1986)** Developed to compare different thermal environments (indoor/outdoor), it incorporates radiative exchanges but remains complex to calculate. It is poorly suited to hot and humid climates, being more effective in temperate climates where temperature differences between indoor and outdoor environments are moderate (Pickup & de Dear, 2000).

c. Indices Integrating Physiological and Behavioral Responses

These indices represent the latest generation of tools for evaluating outdoor thermal comfort. They incorporate the physiological mechanisms of the human body (sweating, vasodilation, behavioral adaptation) as well as detailed environmental parameters.

Physiologically Equivalent Temperature (PET) (Mayer & Höppe, 1987; Höppe, 1999)

Based on a thermal balance model of the human body, PET considers air temperature, humidity, wind speed, and solar radiation. It is widely used in urban environments, particularly in Mediterranean climates, as it allows for the assessment of thermal discomfort while accounting for urban morphology. A study conducted in Athens (Matzarakis et al., 2013) showed that PET accurately reflects the thermal discomfort experienced by residents during heatwaves.

Universal Thermal Climate Index (UTCI) (Jendritzky et al., 2009, 2012)

Modeling the physiological response of the human body, it incorporates complex thermodynamic interactions and is recommended for global applications. However, its use in Mediterranean urban environments is less frequent, as it tends to underestimate the effect of solar radiation on perceived heat stress (Błażejczyk et al., 2013).

d. Comparison of Indices: Strengths and Limitations

A comparative evaluation of thermal comfort indices reveals that empirical indices and models based on the human body's energy balance have several limitations in outdoor environments, particularly in Mediterranean regions where urban microclimates strongly influence thermal perception.

e. Limitations of PMV and SET*

Although the Predicted Mean Vote (PMV) is widely used in indoor thermal comfort studies, its application to outdoor spaces is highly criticized. It assumes that conditions are stationary and uniform, which is not the case in open urban environments, where factors such as direct sun exposure, wind effects, and shaded areas significantly influence perceived thermal comfort.

For example, a study conducted in Taipei by Lin and Matzarakis (2008) demonstrated that PMV predicted greater thermal discomfort than actually reported by residents, as it did not account for behavioral adaptation mechanisms such as seeking shade or adjusting clothing.

Similarly, the *Standard Effective Temperature (SET)** is limited by its complex calculation process, making it less practical for large-scale applications in urban studies. An analysis conducted by Johansson and Emmanuel (2006) in Mediterranean cities revealed that SET* overestimated thermal discomfort in the late afternoon, as it did not consider the progressive acclimatization to heat throughout the day.

f. Advantages and Disadvantages of UTCI and PET

The most recent models, the Universal Thermal Climate Index (UTCI) and the Physiologically Equivalent Temperature (PET), are currently the most suitable for assessing outdoor thermal comfort. However, their relevance varies depending on the climatic and urban context.

- **UTCI** is recognized for its high accuracy in quantifying thermal stress, particularly due to its integration of detailed physiological responses of the human body to climatic variations (vasodilation, sweating, thermal regulation). However, recent studies indicate that it is less reliable in dense urban environments, where the influence of urban materials, shading, and reflected radiation plays a key role in thermal perception (Pantavou et al., 2013).

- **PET**, on the other hand, is more sensitive to variations in urban microclimates and better suited to hot and humid climates, where the combined effect of humidity and solar radiation is crucial. A study conducted in Rome and Athens by Matzarakis et al. (2013) showed that PET more accurately reflected urban residents' thermal perception compared to UTCI, mainly due to its better consideration of the effects of solar radiation on the human body.

In a Mediterranean context, where intense solar radiation and low wind speeds amplify the sensation of heat, PET provides a more precise assessment of thermal comfort, particularly during summer heatwaves.

3.1.2. Justification for Choosing PET in Mediterranean and Humid Climates

a. Optimal Consideration of Local Climatic Conditions

The choice of **PET** for evaluating thermal comfort in Mediterranean cities is based on several scientific and methodological criteria. This index integrates the essential variables of the Mediterranean climate, including:

- **High summer temperatures**, amplified by the urban heat island effect.
- **Intense solar radiation**, strongly influencing thermal sensation in the absence of shade.
- **Moderate to high humidity**, reducing the efficiency of sweating and exacerbating thermal stress.
- **Weak winds**, limiting natural cooling by convection.

The Physiological Equivalent Temperature (PET) is a key thermal index for Mediterranean climates, allowing a physiological assessment of human comfort through parameters such as air temperature, vapor pressure, wind speed, and mean radiant temperature (Tmrt). Its unit in °C makes it easily understandable for urban planners and facilitates its application in urban planning (Matzarakis et al., 1999).

In Greece, PET analysis revealed a period of intense thermal stress from June to September, with values exceeding 30°C and sometimes reaching 50°C, along with frequent heatwaves in continental areas (Giles & Balafoutis, 1990). In contrast, cooler temperatures at higher altitudes and the mitigating effect of sea breezes and Etesian winds reduce thermal discomfort on islands (Matzarakis, 1995).

Thanks to its ability to quantify the impact of urban developments and identify risk areas, PET is a crucial tool for climate change adaptation strategies in the Mediterranean (VDI, 1998). A study conducted in Athens by Tseliou & Tsiros (2016) compared several thermal comfort indices and demonstrated that PET is the most reliable for quantifying pedestrian thermal stress in urban environments, due to its sensitivity to microclimatic variations.

b. Better Correspondence with Residents' Thermal Perception

One of the main strengths of PET is its ability to accurately reflect the thermal comfort perceived by local populations. Unlike other indices based on fixed thresholds, PET incorporates the body's natural thermal regulation and behavioral adaptation strategies (seeking shade, adjusting clothing, hydration).

Surveys conducted in Barcelona and Marseille (Salata et al., 2016) showed that PET values closely matched residents' perceptions of comfort or discomfort. These results suggest that PET is a more relevant indicator for studies on urban thermal well-being, especially in areas highly exposed to solar radiation.

c. Optimal Integration into Microclimatic Simulations (ENVI-met)

In the field of urban planning and climate resilience studies, it is essential to use an index compatible with microclimatic simulation models. PET is widely employed in software such as ENVI-met, which allows modeling the impact of urban forms, materials, and vegetation on thermal comfort.

A study conducted in Naples and Lisbon (Lucchese & Andreasi, 2017) demonstrated that PET simulations in ENVI-met effectively assess the efficiency of thermal stress mitigation solutions, such as the addition of vegetation or the use of reflective materials.

The comparative analysis of thermal comfort indices demonstrates that PET is the most suitable indicator for Mediterranean and humid climates. It allows for an accurate assessment of urban thermal comfort by considering:

1. The impact of solar radiation on actual thermal sensation.
2. The effects of urban microclimates, including urban heat islands and the thermal properties of urban materials.
3. The physiological and behavioral adaptation of residents, taking into account the human body's natural thermal regulation.
4. Its integration into microclimatic simulation models, facilitating the analysis of the impact of thermal stress mitigation strategies.

For these reasons, PET has been selected for our study on climate adaptation and outdoor thermal comfort in the Casbah of Algiers. Its integration into our analyses will help identify the most heat-stressed areas, assess the effectiveness of mitigation solutions (vegetation, shading structures, reflective materials), and provide recommendations based on a robust methodology adapted to the Mediterranean context.

3.2. State of art research on outdoor thermal comfort in modern and traditional cities.

3.2.1. Outdoor Thermal Comfort: General Overview

Outdoor thermal comfort is a critical component of urban climatology, influencing human well-being, urban livability, and public space usability. It is determined by a combination of meteorological factors (air temperature, humidity, wind speed, and solar radiation), urban morphology, and personal factors such as clothing and metabolic rate (Nikolopoulou et al., 2001).

Several thermal indices, including the Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), and Predicted Mean Vote (PMV), have been developed to assess outdoor thermal comfort. Studies (Chen & Ng, 2012; Potchter et al., 2018) emphasize that the choice of index depends on climatic context and research objectives.

In urban environments, outdoor thermal comfort is influenced by the built environment, land use patterns, and mitigation strategies. Cities with high-density urban forms experience increased urban heat island (UHI) effects, whereas cities with well-integrated green and blue infrastructure tend to offer improved thermal comfort (Santamouris et al., 2011).

The study of outdoor thermal comfort is crucial in adapting urban areas to climate change, ensuring that urban spaces remain usable and comfortable under rising temperatures. Research has explored the relationship between urban morphology and thermal comfort in both modern and traditional cities, as discussed in the following sections.

3.2.2. Outdoor Thermal Comfort in Modern Cities

Modern cities, characterized by high-density and mixed-use urban patterns, have been extensively studied in terms of their impact on outdoor thermal comfort. These cities often exhibit fragmented and discontinuous urban morphology, including skyscrapers, business districts, and planned urban forms (Ratti, 2005; Steemers, 2006).

Several studies have focused on evaluating the correlation between urban morphology and outdoor thermal comfort. Givoni (1998) explored the effects of urban design on climate and found that green areas significantly impact microclimatic conditions. Similarly, Ratti (2005) examined the relationship between solar radiation and height-to-width (H/W) ratio, demonstrating that large courtyards provide environmental benefits in cold climates.

Other studies investigated the influence of urban geometry on outdoor thermal comfort. Kruger et al. (2011) highlighted the role of the sky view factor (SVF) and aspect ratio in shaping thermal conditions in Curitiba, Brazil. In a study of London, Steemers (2006) categorized six archetypal urban forms and analyzed their influence on solar radiation and daylight penetration. Taleghani et al. (2015) further evaluated outdoor thermal comfort in five urban forms, using the Physiological Equivalent Temperature (PET) index in real models and simulations.

In contemporary urban typologies, pedestrian-level greening has been explored as a mitigation strategy. Jamei (2016) examined the role of urban geometry and street trees in improving thermal comfort. Lai (2019) investigated different urban forms' convective and radiative heat transfer properties, emphasizing the role of urban geometry in shaping outdoor comfort.

Moreover, studies have examined specific climatic parameters such as the urban heat island (UHI) effect and wind cooling potential. Several studies (Hwang et al., 2017; Orosa et al., 2014) analyzed urban heat mitigation techniques, such as vegetation and high-albedo surfaces, demonstrating their effectiveness in reducing heat stress.

Despite substantial research on modern urban environments, the focus remains on cities with contemporary planning frameworks. However, historic urban fabrics require different considerations due to their unique morphological and material characteristics.

3.2.3. Outdoor Thermal Comfort in Traditional Cities

Traditional urban morphologies, characterized by narrow and shallow street corridors, inward-facing courtyards, and homogeneous urban fabric, present distinct challenges and advantages for outdoor thermal comfort. These urban forms often promote closer public interactions and shaded environments, reducing direct solar exposure and improving microclimatic conditions.

Ali-Toudert and Mayer (2006) conducted pioneering research on outdoor thermal comfort in historic cities, focusing on Ghardaia, Algeria. Their findings indicated that deep streets and traditional building materials significantly mitigate heat stress by providing shading and thermal mass storage.

Further research by Johansson and Achour (2008) examined street canyon microclimates in Fez, Morocco, and Tunis, Tunisia, revealing that traditional urban mass contributes to stable outdoor thermal comfort. In Cairo, Egypt, Elnabawy (2016) used empirical measurements and simulations to assess thermal conditions in Fatimid Cairo, emphasizing the role of hierarchical street networks in mitigating heat stress.

Recent studies have expanded the scope of analysis by integrating numerical simulations with in-situ measurements. Matallah et al. (2021) examined microclimatic variations in Biskra, Algeria, and Dhaka, Bangladesh, comparing traditional and modern urban fabrics. Lucchi (2021) analyzed the influence of urban morphology on thermal comfort in Porto, Portugal, and Rome, Italy, using cluster analysis.

Additionally, research has explored heat mitigation strategies in historic cities. Benchekroun (2019) investigated parameters influencing the microclimate of houses in the Casbah of Algiers. Other studies have assessed innovative materials and bioclimatic designs to enhance outdoor comfort in historic urban settings (Rosso et al., 2018; Laureti et al., 2018).

Although studies on traditional urban fabrics are increasing, they remain limited compared to research on modern cities. Figure 1 illustrates the disparity in research focus, highlighting the need for further investigation into traditional urban morphologies.

3.2.4. Conclusion

The state of the art in outdoor thermal comfort research reveals significant progress in understanding the microclimatic effects of urban morphology. Studies on modern cities have primarily focused on urban geometry, material properties, and mitigation strategies such as vegetation and reflective surfaces. In contrast, research on traditional urban fabrics has highlighted the role of narrow streets, courtyards, and local materials in shaping outdoor thermal comfort.

Future research should bridge the gap between modern and traditional urban settings, integrating climate-responsive strategies that respect cultural heritage while enhancing thermal comfort. The findings from traditional cities can offer valuable insights into sustainable urban design, particularly in Mediterranean and arid climates where extreme temperatures pose challenges for urban livability.

3.3. State of art research on climate change

Climate change has emerged as one of the most pressing challenges of the 21st century, significantly impacting urban environments and outdoor thermal comfort. With the rapid increase in global temperatures and urbanization, cities are facing intensified Urban Heat Island (UHI) effects, extreme weather events, and deteriorating microclimatic conditions. This section reviews recent research on climate change, focusing on its effects on outdoor thermal comfort and the mitigation strategies proposed in various studies.

3.3.1. Global Warming and Urban Heat Island Effect

Numerous studies have examined the implications of global warming on urban climates and thermal comfort. The study conducted by Akbari et al. (2015) demonstrates that the UHI phenomenon can increase urban temperatures by up to 10°C, leading to a rise in energy consumption by 5 to 10%. Their research highlights mitigation strategies such as the implementation of cool roofs, which can reduce surface temperatures by 20 to 40°C, and the integration of green spaces, which can lower urban temperatures by up to 3°C.

In the case of Madrid, Aram et al. (2020) explored the cooling effects of large urban parks, such as Retiro Park, showing that temperatures were reduced by 1.6°C within 130 meters of the park and by 0.9°C at 280 meters. Their study underscores the role of urban morphology, vegetation, and topography in enhancing urban thermal comfort.

3.3.2. Impact of Climate Change on Outdoor Thermal Comfort

Research on thermal comfort in urban areas has intensified due to the increasing severity of heatwaves and extreme temperatures. Hwang et al. (2017) investigated the urban heat island effect in Taichung, Taiwan, demonstrating temperature rises of up to 3.2°C between 1979 and 2003, with projections showing further increases by 2039 and potentially severe impacts by 2075-2099. Their study underscores the need for urban adaptation strategies, such as increasing urban vegetation and utilizing high-albedo materials.

Similarly, in Gothenburg, Sweden, Thorsson et al. (2011) analyzed the spatial and temporal variations of mean radiant temperatures (Tmrt) in urban areas. Their findings indicate that by 2080-2099, urban configurations will experience Tmrt increases of up to 3.2°C, with extreme thermal stress periods tripling in duration, emphasizing the importance of integrating shading structures and vegetation in urban design.

A study by Orosa et al. (2014) on the climate of Galicia, Spain, highlights concerning heat conditions, with humidex values exceeding 23 in July and projections indicating an average temperature increase of 1.35°C over the next two decades. The study identifies urban heat islands as significant contributors to thermal discomfort and calls for strategies such as increased vegetation and improved urban design.

3.3.3. Climate Change Impacts on Historic Urban Areas

Understanding the impact of climate change on historic urban environments has become a crucial research area. Laureti et al. (2018) investigated outdoor thermal comfort in historical districts of Rome, highlighting the vulnerability of these areas due to high urban density, reflective building materials, and limited green spaces. Their study suggests increasing surface reflectivity, expanding green spaces, and implementing building retrofits as key mitigation measures.

In Algeria, Matallah et al. (2021) conducted a study in Tolga Oasis and Biskra, revealing alarming increases in perceived temperature (PT) indices. Their results show a projected PT increase of 5.9°C by 2050 and 7.7°C by 2080. The comfortable thermal zone in these regions is expected to decline from 25% in 2020 to nearly 0% by 2080, highlighting the urgency for urban planners to integrate climate adaptation strategies in arid regions.

3.3.4. Conclusion

The growing body of research on climate change and outdoor thermal comfort demonstrates the pressing need for climate adaptation strategies in urban planning. Studies across different climatic zones reveal common mitigation measures, such as increasing vegetation, implementing reflective materials, and optimizing urban morphology to enhance thermal comfort. Given the rising temperatures and extreme climate conditions projected for the coming decades, integrating these strategies into early-stage urban design and renovation processes is essential to ensure resilient and sustainable urban environments.

3.4. State of art research on mitigation strategies

Mitigation strategies play a crucial role in improving outdoor thermal comfort, particularly in urban areas affected by the Urban Heat Island (UHI) effect. Over the past decades, numerous studies have explored different approaches to mitigate thermal stress through urban design and material innovations. The following section provides an overview of the state-of-the-art research on heat mitigation strategies, focusing on key methods such as urban geometry modifications, vegetation integration, high-albedo materials, and water bodies.

3.4.1. Urban Geometry and Morphology

Urban geometry significantly influences microclimatic conditions and human thermal comfort. Compact urban spaces, characterized by a low Sky View Factor (SVF) and a high aspect ratio (H/W), tend to create shaded environments, reducing direct solar exposure and lowering outdoor temperatures. Lai et al. (2019) found that urban morphology has the greatest impact on the thermal environment in summer, followed by vegetation and water bodies. Similarly, Krüger et al. (2011) demonstrated that modifying street orientation and canyon geometry can improve thermal conditions by reducing heat accumulation and enhancing wind flow. These findings highlight the importance of integrating urban morphology considerations in early-stage design processes to optimize outdoor thermal comfort. Additionally, urban ventilation corridors and wind flow optimization strategies have been gaining attention as effective passive cooling methods.

3.4.2. Vegetation and Green Infrastructure

Vegetation is a widely recognized mitigation strategy due to its ability to lower ambient temperatures through evapotranspiration and shading. Several studies emphasize the positive impact of urban greening on microclimates. Taleghani (2018) compared different vegetation forms, including street trees, green roofs, and urban parks, and concluded that greenery is more effective than reflective materials in improving pedestrian thermal comfort. Jamei et al. (2016) highlighted that the effectiveness of vegetation depends on the type, density, and seasonal conditions of the region, with street trees and urban parks playing a vital role in reducing mean radiant temperature (Tmrt). These findings support integrating urban greenery into city planning as a sustainable approach to mitigate heat stress. Moreover, combining different vegetation types, such as vertical gardens and urban forests, has been found to enhance cooling effects in dense urban areas.

3.4.3. High-Albedo and Cool Materials

Cool materials, such as high-albedo pavements and reflective coatings, have been extensively studied for their ability to reduce surface and air temperatures. Santamouris et al. (2011) reviewed advancements in cool materials, including cool roofing, PCM-doped infrared reflective coatings, and thermochromic materials. Their research demonstrated that white cool coatings have superior thermal performance, reducing surface temperatures by up to 20–40°C. However, reflective surfaces can increase pedestrian discomfort by re-radiating heat. To counteract this effect, combining cool materials with shading elements and vegetation is recommended (Santamouris et al., 2011). Recent advancements in nanotechnology-based cool coatings have also shown promising results in further enhancing heat reflectivity while minimizing thermal discomfort.

3.4.4. Water Bodies and Blue Infrastructure

Water bodies, such as fountains, ponds, and urban lakes, provide a cooling effect through evaporative processes. Lai et al. (2019) found that water bodies significantly enhance urban thermal comfort, particularly in dry and arid climates. However, their effectiveness is dependent on factors such as humidity levels and wind patterns. Incorporating water elements in urban spaces, particularly in combination with vegetation, has proven to be an effective heat mitigation strategy in several cities worldwide. Innovative solutions such as misting systems and interactive water features in public spaces are also gaining attention for their immediate cooling effects on pedestrians.

3.4.5. Mitigation Strategies in Historic Urban Areas

Historic urban fabrics often present challenges for implementing mitigation strategies due to preservation constraints. Laureti et al. (2018) investigated thermal comfort in historical districts of Rome and found that high urban density, limited green spaces, and the use of traditional materials increase vulnerability to overheating. Proposed strategies for improving thermal comfort in historic cities include increasing surface reflectivity, enhancing ventilation through urban design modifications, and strategically integrating green infrastructure. These solutions demonstrate the necessity of balancing heritage preservation with modern climate adaptation strategies. Further research is needed to explore hybrid approaches that integrate modern materials with traditional architectural elements to optimize both aesthetic and functional aspects of heritage buildings.

3.4.6. Comparative Effectiveness of Strategies

Comparative studies have assessed the efficiency of different mitigation strategies in various climatic contexts. Taleghani (2018) found that urban geometry plays a dominant role in shaping microclimates, followed by vegetation and reflective materials. Akbari et al. (2015) emphasized the role of cool materials and green spaces in reducing the UHI effect, with energy savings of up to 20% and air quality improvements of 10–20%. These findings highlight the importance of context-specific solutions tailored to each city's climatic and morphological characteristics. Moreover, studies suggest that the integration of multiple strategies within a holistic framework can yield the most significant improvements in outdoor thermal comfort.

3.4.7. Conclusion

Mitigation strategies for improving outdoor thermal comfort are diverse and context-dependent. Urban morphology adjustments, vegetation integration, high-albedo materials, and water elements each contribute uniquely to heat mitigation. While compact urban geometries and green infrastructures remain the most effective solutions, their integration must be carefully planned to avoid negative side effects such as increased thermal radiation from reflective surfaces. Additionally, historic urban areas require specialized adaptation approaches that respect heritage constraints while addressing modern climate challenges. Future research should focus on optimizing hybrid mitigation strategies that combine the strengths of multiple approaches for maximum effectiveness in different urban contexts. Ultimately, developing predictive models and AI-driven optimization frameworks could help urban planners implement the most effective mitigation strategies based on real-time climatic data and long-term sustainability goals.

3.5. State of art - research on environmental impacts

The rehabilitation of existing buildings is recognized as an essential strategy to reduce the environmental footprint of the construction sector. This approach decreases energy consumption, greenhouse gas emissions, and the use of natural resources while preserving the built heritage. Several scientific studies have analyzed the environmental impacts associated with rehabilitation projects, focusing on methods such as life cycle assessment (LCA) and multicriteria evaluation.

Peuportier and Schalbart (2022) demonstrated the importance of LCA in the ecodesign of buildings and neighborhoods. Their research emphasizes that LCA, by integrating dynamic thermal simulation, allows for the evaluation of the environmental performance of buildings throughout their life cycle, from construction to demolition. This systemic approach is crucial for identifying improvement levers and reducing the environmental impacts of rehabilitation projects.

The Scientific and Technical Center for Building (CSTB) has developed a multicriteria analysis method for rehabilitation projects. This method aims to simultaneously evaluate various aspects such as energy performance, carbon impact, occupant comfort, and the preservation of architectural heritage. Such a holistic approach facilitates decision-making by balancing environmental, economic, and social objectives.

A study conducted by Cerema (2023) provided an overview of methods for evaluating the carbon impact in building renovation projects in France. The results indicate that integrating LCA into the design and implementation phases of rehabilitation projects is essential for identifying major sources of greenhouse gas emissions and implementing effective reduction strategies.

The Economic Council for Sustainable Development (2013) published a report highlighting that buildings account for 40% of final energy consumption and 23% of greenhouse gas emissions in France. Improving the energy performance of the existing stock is therefore a priority. The report emphasizes the environmental, economic, and social benefits of energy renovation, including reducing energy poverty and creating local jobs.

Current research converges on the idea that rehabilitating existing buildings, when guided by rigorous methods such as LCA and multicriteria analysis, constitutes an effective approach to reducing the environmental impacts of the construction sector. These methods offer a deep understanding of the effects of design and material choices on the environment, thus enabling the development of sustainable and efficient rehabilitation strategies.

PART 02: EXPERIMENTAL INVESTIGATION AND SIMULATION FOR THE QUANTIFICATION OF OUTDOOR THERMAL COMFORT

III. PART 02: EXPERIMENTAL INVESTIGATION AND SIMULATION FOR THE QUANTIFICATION OF OUTDOOR THERMAL COMFORT

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) (Georgescu et al., 2014; Wang et al., 2019), urbanization and global climate change are two significant factors affecting cities' climate. Indeed, today's world is experiencing a considerable acceleration in terms of 'urbanization, more than 50% of the world's population lives in an urban area, and this proportion is expected to increase. By 2050, 70% of the population will live in towns and cities ("Urbanization and health," 2010). Through different mechanisms, these climatic changes affect human health, tourism, and outdoor activities (Hein et al., 2009; McMichael and Lindgren, 2011). Several studies investigated the impacts of urbanization on the urban climate and human thermal comfort (Emmanuel, 2005; Mahmoud and Gan, 2018; Morris et al., 2017). Therefore, ensuring wellbeing and comfort in the city is an essential indicator in Sustainable Development Goal 11 ("United Nations Development Program. (2015). Sustainable Development Goals. [online]. United Nations. Retrieved from https://www.undp.org/content/undp/en/home/sustainable-development-goals.html," n.d.). Sustainable cities and human settlements, established by the United Nations General Assembly in 2015.

Air temperature, relative humidity, and solar radiation affect thermal comfort in urban climates (Jin et al., 2020). Nikolopoulou studies (Nikolopoulou, 2004) revealed that air temperature, wind speed, and sunshine are the most critical parameters of outdoor comfort and influence thermal sensation. More recent research defines outdoor pedestrian thermal comfort by both meteorological (air temperature, relative humidity, wind speed, and mean radiant temperature) and personal factors (clothing type and activity level) (Jamei et al., 2016a). Urban geometry, defined by the aspect ratio, sky view factor, street orientation, and neighborhood configuration, greatly impacts outdoor thermal comfort (Krüger et al., 2011a; Sharmin et al., 2017a).

Several studies (Rodríguez Algeciras et al., 2016; Santamouris, 2013a) entailing field measurements and simulations highlighted the influence of urban morphology on the thermal comfort of inhabitants. Those studies can be classified into two main groups. Firstly, studies investigated the effect of urban morphology on outdoor microclimate in contemporary and modern urban cities. Secondly, studies investigated the influence of urban morphology on outdoor microclimate in historic urban cities.

First, most of the studies that have evaluated outdoor thermal comfort have been carried out in modern cities. Modern cities mean the modern compact city is identified as a high-density and mixed-use pattern (Russo and Cirella, 2018) with fragmented and discontinuous morphology. Historically the development of means of transport takes the city out of its limits and hinders a fragmented and discontinuous urban fabric (de Roo and Miller, 2020). The modern cities are presented as a patchwork of very diverse urban forms. The postliberal model such as Paris Barcelona, Vienna, Amsterdam. Cities resulting from the urban planning of the CIAM, such as Brasilia, and skyscrapers of the Central business district as like: Singapore, Toronto, Chicago.

Several studies have been carried out on modern urban typologies (Bourbia and Boucheriba, 2010; Givoni, 1998; Johansson, 2006a; Johansson and Emmanuel, 2006a; Ratti et al., 2005; Thorsson et al., 2011a). Table A1 presents the research investigating the correlation between outdoor thermal comfort and urban morphology in modern cities. Givoni investigated the urban design effects on the Urban Climate and the impact of green areas. Similarly, Ratti studied solar radiation and the incident's height-to-width ratio (H/W). Findings show that large courtyards are environmentally adequate in cold climates. Steemers (Salat, 2011) proposed six archetypal generic urban forms for London and compared the incident of solar radiation, built potential, and daylight admission (Johanssen,2006) has meanwhile investigated the influence of urban geometry on outdoor thermal comfort in Fez, Morroco. Taleghani (Taleghani et al., 2015a) evaluated the outdoor thermal comfort within five different urban forms using physiological equivalent temperature (PET) based on real models as well as simulation (Rayman, ENVI-met).

In life quality studies, Kruger (Krüger et al., 2011a) studied the impact of urban geometry on outdoor thermal comfort and air quality through the sky view factor, PET and Tmrt. Jamei (Jamei et al., 2016a) explored the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. Findings showed that the main pedestrian level green infrastructures are urban geometry, street trees, and city parks. Venhari and He (Ahmadi Venhari et al., 2019; He et al., 2015a) studied the significant relationship between the sky view factor and outdoor thermal comfort in Isfahan, Iran, and Beijing, China. Lai (Lai et al., 2019a) investigated the mitigating strategies to improve thermal comfort in urban outdoor spaces. Findings demonstrated that urban geometry changes the radiative and convective heat transfer in outdoor areas. Other studies (Belpoliti et al., 2020; Matallah et al., 2020; Roshan et al., 2020a) explored specific climatic parameters such as the oasis effect or the wind cooling potential on outdoor thermal comfort. In the preceding part, the studies dealt with the link between the urban morphology of modern cities and different climate parameters, indexes, and mitigation strategies. At the same time, they were highlighting their impact on outdoor thermal comfort.

On the other side, few studies addressed the issue of outdoor thermal comfort in traditional urban morphologies. Table A2 summarizes the studies on outdoor thermal comfort in traditional urban morphologies. This latter is characterized by the narrow and shallow street corridors, resulting in closer public interactions and closed private spaces (Dhingra and Chattopadhyay, 2016). The urban morphology of these cities consists of an assemblage of houses' courtyards (patios] linked by a hierarchical street network (Ben Salem et al., 2021). The form was almost completely homogeneous, organized by a system of open spaces and circulations present at all scales (Kiet, 2011). The main characteristics of traditional urban fabric are inward planning, the use of local materials, and the low H/W ratio (Berkani, 2013). Historic centers have mostly undergone reconfigurations at the city limits, thus making this part of the traditional fabric "Hybrid" (Alsayyad, 1995).

Some studies have been carried out on the impact of the urban morphology of these traditional urban fabrics. Ali-Toudert (Ali-Toudert et al., 2005a; Ali-Toudert, F and Mayer H, 2006) was first investigated in an old desert city of Gherdaia, Algeria. The relation of outdoor thermal comfort in a hot and dry concerning urban geometry. At the same time, they studied the development of comfortable street-scale microclimates through design, aspect ratio (H/W), and solar orientation. These studies demonstrated that building materials associated with deep streets play a decisive role in mitigating heat stress in the daytime. Also, traditional constructions' high and heavy walls provide more shading and more heat storage, leading to lower surface temperatures. Johansson and Achour (Achour-Younsi and Kharrat, 2016a; Johansson et al., 2001) studied the street canyon microclimate in Mediterranean Climate traditional neighborhoods in Fez, Morocco, and Tunis, Tunisia, where they found that the large mass of the traditional fabric contributes to a more stable outdoor thermal comfort.

In his studies on the city of Cairo, Egypt, Elnabawy (Elnabawi et al., 2015, 2013) evaluated the microclimate of the traditional urban form of Fatimid city through measurements and simulation to develop a micro-scale numerical model. Matallah and Sharmin. (Matallah et al., 2021a; Sharmin et al., 2017a) studied the variation in microclimatic conditions in Biskra, Algeria, and Dhaka, Bangladesh. Inside several urban fabrics (traditional and new geometries) using ENVI-met software and different weather datasets. Lucchi (Lucchi et al., n.d.) carried out a cluster analysis leading to describe the influence of climatic parameters on the design of city morphology and buildings envelopes. Benchekroun (Benchekroun et al., 2020) investigate parameters that influence the microclimate of houses in Casbah of Algiers. Other studies (Cortesão and Alves, 2010; Makropoulou, 2017; Rosso et al., 2018a) investigate attenuation and mitigation strategies in historical urban canyons. In this sense, the bioclimatic aspect and the impact of innovative materials on outdoor thermal comfort have been studied in Porto, Portugal, and Rome, Italy.

Despite studies that dealt with the morphological and bioclimatic specificities of traditional urban fabrics and the outdoor thermal comfort, their number remains reduced compared to studies in contemporary cities, as demonstrated in Figure 10. Nevertheless, few studies (Achour-Younsi and Kharrat, 2016a; Ali-Toudert, F and Mayer H, 2006; Castaldo et al., 2017) have quantified outdoor thermal comfort in traditional urban morphologies, specifically in the Mediterranean climate, following an empirical approach using PET and Tmrt.

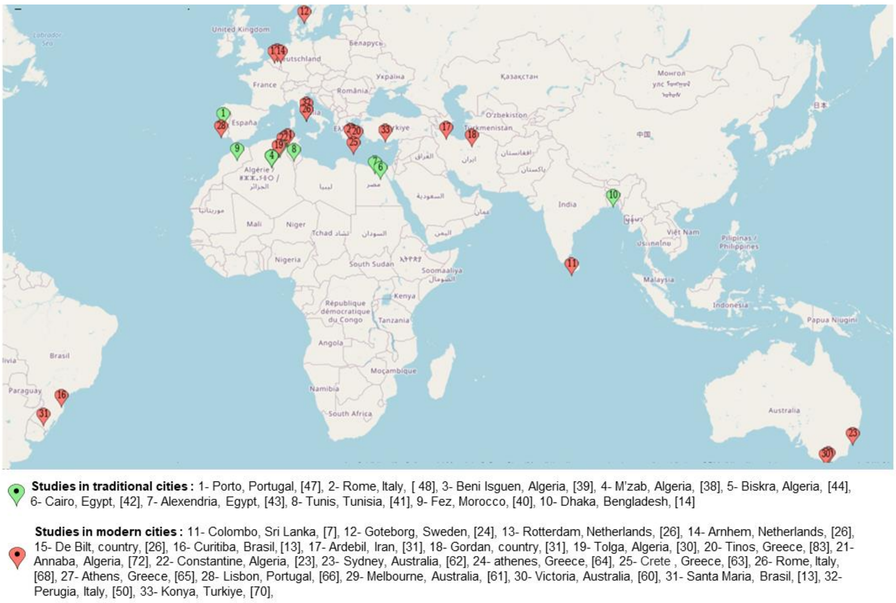


Figure 10 Review of the literature of studies on outdoor thermal comfort in traditional and modern cities in the Studies in traditional cities: 1- Porto, Portugal, (Cortesão and Alves, 2010), 2- Rome, Italy,(Rosso et al., 2018a), 3- Beni Isguen, Algeria, (Ali-Toudert et al., 2005a), 4- M'zab, Algeria,(Ali-Toudert, F and Mayer H, 2006), 5- Biskra, Algeria,(Matallah et al., 2021a), 6- Cairo, Egypt, (Elnabawi et al., 2015), 7- Alexendria,Egypt,(Elnabawi et al., 2013), 8- Tunis, Tunisia,(Achour-Younsi and Kharrat, 2016a), 9- Fez, Morocco,(Johansson et al., 2001), 10- Dhaka, Bengladesh, (Sharmin et al., 2017a)

Studies in modern cities : 11- Colombo, Sri Lanka,(Emmanuel, 2005) *[7], 12- Goteborg, Sweden,*(Thorsson et al., 2011a) *[24], 13- Rotterdam, Netherlands,*(Taleghani et al., 2015a) *[26], 14- Arnhem, Netherlands, [26], 15- De Bilt, country, [26], 16- Curitiba, Brasil,*(Krüger et al., 2011a) *[13], 17- Ardebil, Iran, [31], 18- Gordan, country,*(Roshan et al., 2020a) *[31], 19- Tolga, Algeria,*(Matallah et al., 2020) *[30], 20- Tinos, Greece,* (Andreou and Axarli, 2012a)*[51], 21- Annaba, Algeria,*(Labdaoui et al., 2021) *[52], 22- Constantine, Algeria,*(Bourbia and Boucheriba, 2010) *[23], 23- Sydney, Australia,*(Sharifi et al., 2017) *[53], 24- athenes, Greece,*(Tseliou et al., 2010a) *[54], 25-*

Crete , Greece,(Tsitoura et al., 2014) *[55], 26- Rome, Italy,*(Salata et al., 2016a) *[56], 27- Athens, Greece,*(Nikolopoulou and Lykoudis, 2007a) *[57], 28- Lisbon, Portugal,*(Andrade et al., 2011) *[58], 29- Melbourne, Australia,*(Shooshtarian and Rajagopalan, 2017a) *[59], 30- Victoria, Australia,*(Kenawy and ElKadi, 2011) *[60], 31- Santa Maria, Brasil,*(Krüger et al., 2011a) *[13], 32- Perugia, Italy,*(Castaldo et al., 2017) *[50], 33- Konya, Turkiye,*(Canan et al., 2020) *[61],*

Therefore, this study is motivated by limited knowledge regarding microclimate characterization in historical urban fabrics. This paper investigated outdoor urban comfort through a validated empirical mixed approach to shed light on the microclimatic specificities of these urban fabrics. More specifically, the study examines the outdoor thermal comfort conditions in the subspaces of a complex urban morphology in a Mediterranean climate. The results of this research are significant because they are part of an incremental effort to bridge the knowledge gap regarding the influence of traditional urban morphology on thermal comfort. This work could serve as a basis to aid urban designers and urban managers to obtain answers for future environmental strategies to be adopted to renovate and rehabilitate their cities' fabrics.

Evaluating the existing outdoor thermal comfort is imperative for the characterization of this morphological typology. This study aimed to quantify the microclimate in different subspaces of the Casbah of Algiers. More specifically, the following questions are answered:

- What are the thermal comfort levels in the historical urban fabric?
- How far do the sub-spaces of historical urban fabrics affect the subjective and objective effect of Microclimatic thermal comfort?
- To what extent does the sky view factor affect the outdoor thermal comfort within the Casbah of Algiers?
- What is the effect of the sea breeze on the outdoor thermal comfort inside a historical urban fabric?

In this context, our study is developed to characterize the traditional urban space and characterize the study area as the first step in urban rehabilitation. This approach can be generalized to other cities with similar traditional urban morphology, including Fatimid Cairo (Egypt), Aleppo center (Syria), Sidon historic center (Lebanon), Medina of Tunis (Tunisia), and Medina of Fez (Morocco). Moreover,

The second benefit of this work is to improve the occupants' quality of life. Indeed, the characterization of the outdoor thermal comfort and the thermal stress range will allow identifying the hotspots in traditional cities. Consequently, different urban managerial strategies can improve human interaction and revive public spaces. Achieving thermal comfort in outdoor spaces will encourage leisure activities, such as restaurants, cafeterias, and hotels. Also, local citizens will benefit from outdoor activities and overall improved quality of life in the traditional built environment.

This research makes it possible to highlight the thermal comfort in a specific urban morphology. Indeed, a literature review revealed a scarcity of existing knowledge regarding traditional cities. It is necessary to evaluate the current state of the streets by following an empirical approach to propose targeted solutions. This study can serve as an input for urban planning decision-making and guide urban designers and managers of heritage fabrics.

2 Materials and Methods

A conceptual framework of the study is developed that summarizes and visualizes the research methodology of this paper. As shown in Figure 11, the conceptual study framework is based on three methods, combining the literature review, In-situ measurement of microclimatic data, and the calculation process to assess the thermal comfort levels in the urban fabric. Each step is described in detail in the following sections.

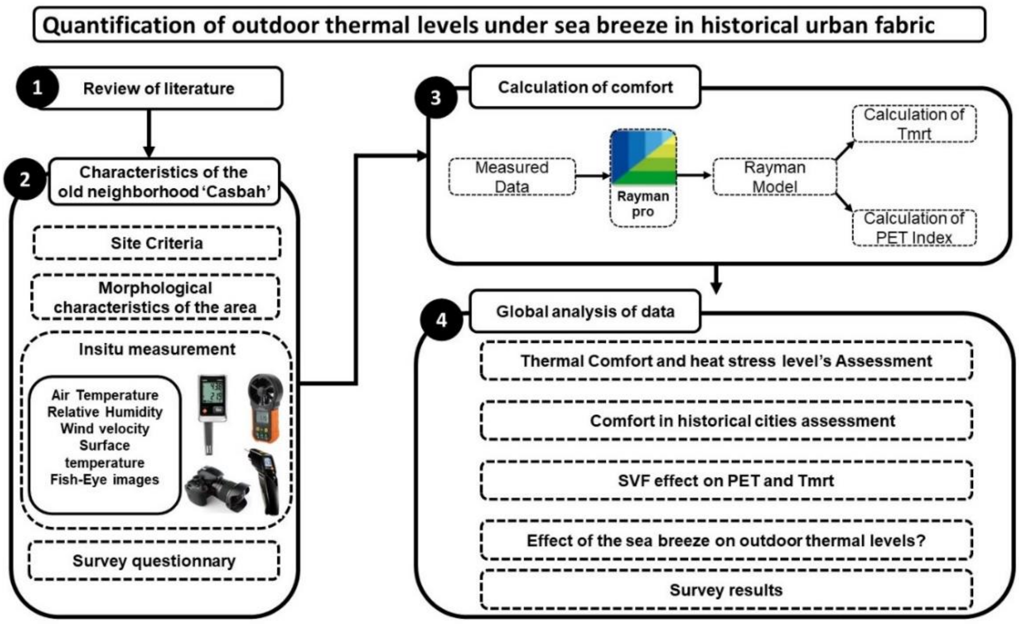


Figure 11: Study conceptual framework

Literature Review

The literature review includes recent publications whose purpose is to evaluate the outdoor thermal comfort zone; however, it focuses on the most relevant publications in the Mediterranean climate. The research was based on Scopus Web of Science, and Google scholar, which resulted in more than 60 publications. The literature review section includes three mains' concepts: Outdoor thermal comfort, assessment methods, and the Mediterranean climate. This article mainly focuses on studies that have been carried out using objective measurements through instrumentation (Meteorological monitoring) from 2010 to 2022 and the subjective analysis through a questionnaire. Other studies carried out with different approaches have been excluded. The results of the literature review are presented in Section

2.1. Characteristics of the old neighborhood "Casbah of Algiers"

2.1.1. Site Criteria

The study has been attended in the Casbah of Algiers situated in the north of Algeria (36° 47′ 00″ N, 3° 03′ 37″ E) at elevation 107m (Figure 12). The Casbah is the historic center of Algiers' city and a historic neighborhood listed as a world heritage site by UNESCO (United Nations Educational, Scientific and Cultural Organization) since 1992. Thus, representing a typo morphology of traditional Islamic architecture construction. Building materials are generally with local materials (Terracotta, lime) (Abdessemed-Foufa, A., 2011; Arrar et al., 2019). The upper part of the Casbah overlooks the sea; the buildings are dense and the streets winding. There are residential areas with local shops and oratories. The lower part is adjacent to the coast (Haedo, D., 2004), the layout of the roads is more regular, following an orderly route. Its proximity to the city gates favors the concentration of its economic, spiritual, political, and administrative functions. The urban space is subdivided into several subspaces, which is one of the characteristics of the traditional urban space (Figure 3). For this study, the PPSMVSS (Permanent plan for the safeguarding and enhancing safeguarded sectors) for the Casbah was consulted at the OGEBC (National Office for the Management and Exploitation of Protected Cultural Assets) and several google maps and satellite images. Our study focuses on the residential area of the Upper Casbah.

From the climatic classification found in the literature (Semahi et al., 2020), Algeria has five climate zones according to the Koppen classification (Beck et al., 2018) and seven climatic zones according to the heating and cooling degree-days classification approach (Ghedamsi et al., 2016). According to the meteorological station "Algiers 603900" the heating degree days estimated during the last 30 years were 1440 HDD. However, the cooling degree days are 956 CDD. The average high temperature registered is 35°C on hot days, temperatures can soar to 42°C, and the lowest is 6°C with temperatures on cold nights reaching until 0°. For the climatic classification, according to Köppen-Geiger, Algiers is of the Mediterranean climate type (Csa, hot summer).

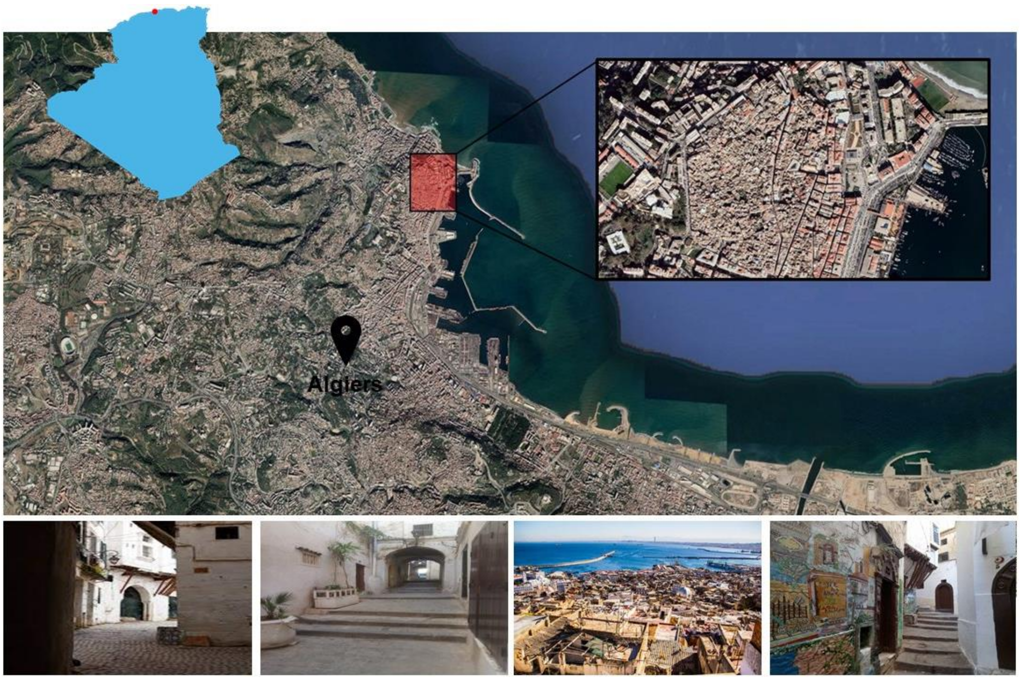


Figure 12: Location of the historic urban fabric studied in the territory of the city of Algiers.

2.1.2. *Morphological characteristics of the conducted stations*

Several measurement points are taken to assess outdoor thermal comfort and determine the impact of the sky view factor on comfort. First, several visits to the site was made to investigate the urban fabric and screen the neighborhood's sub-spaces, where about forty '40' points were taken out. Then, the 14 most representative and significant subspaces (Figure 13) depend on the streets' type, width, length, and orientation. The urban morphological details are explained in Table 2 and are summarized in Figure 4. The methodology followed for the in-situ measurements is explained in the following steps.

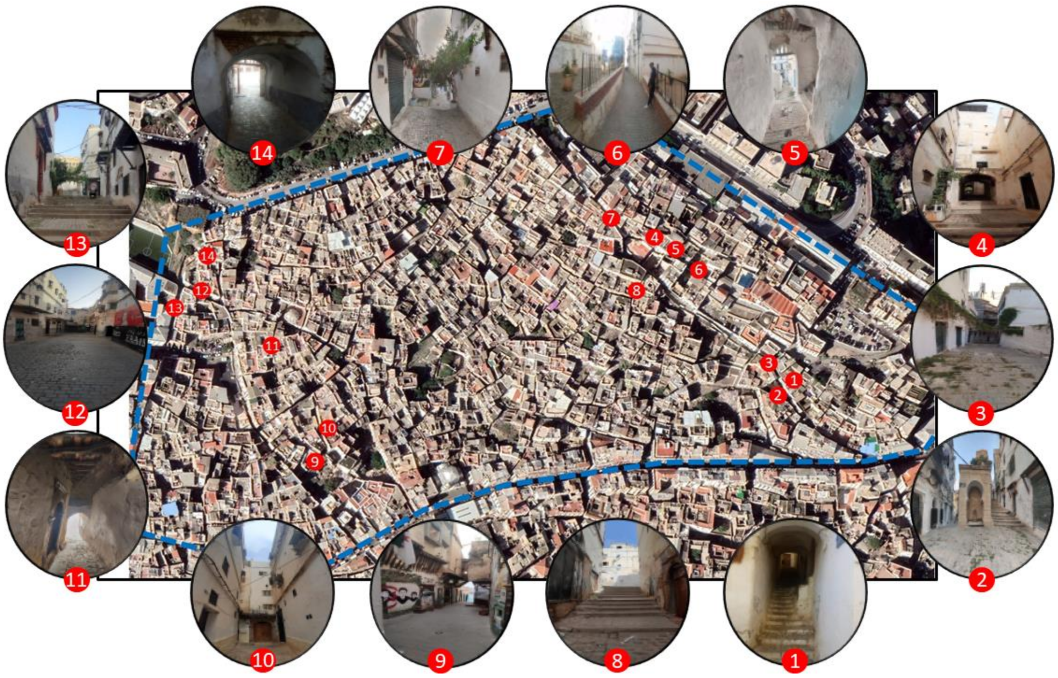


Figure 13: Map of the selected points in the Upper Casbah

Table 2:Morphological characteristics of sites and measurement points

Site	Measurement point	SVF	Street direction	Width	Height	Covered area
	1	0.01	N-S	1.30	3.15	Y
	2	0.24	E-W	5.50	13.20	N
	3	0.18	E-W	2.80	11.30	N
	4	0.00	N-S	2.17	3.30	Y
	5	0.01	N-S	2.10	2.90	Y
	6	0.56	N-S	18.6	8.10	N
	7	0.24	E-W	3.95	8.20	N
Casbah of Algiers	8	0.10	N-S	0.90	12.50	N
	9	0.05	N-S	1.80	8.60	N

10	0.07	N-S	1.97	9.00	N
11	0.00	E-W	1.80	2.20	Y
12	0.29	N-S	4.90	8.95	N
13	0.25	E-W	4.55	8.60	N
14	0.01	N-S	1.95	2.50	Y

2.1.3. Morphological characteristics of the conducted stations

The collected data concerned in-situ measurement and field survey. The in-situ measurements protocol was designed to measure microclimate variables which are: Air temperature (Ta), Relative humidity (RH), Wind speed (Ws), and Surface temperature (TS); this last one is necessary to calculate the Tmrt. The measurements were taken using the Testo 175H1, a reliable and validated instrument for data acquisition (Table 3). All the instruments used were newly acquired, mainly for the study.

Sensors were kept at 1.40 m height from the ground to avoid the effect of surface contact (Ali-Toudert and Mayer, 2007a) Testo 830 Infrared Thermometer for surface temperature measurements (ground and walls). Table 2 lists the name, the range, and the accuracy of the instruments used in the monitoring study. Meteorological measurements were conducted for a period of 7 days twice a year, once in winter (26th January to 1st February) and the other in summer (5th to 11th of August). Measurements have taken place every two hours, from 6 am to 8 pm. The Fish-eye images took the degree of the opening to sky. Processing of the photos and the calculation of the SVF will be done by Rayman software.

Table 3: Instruments used for the study fields: (a) fish-eye camera (b) Testo 175H1 Temperature/Humidity data logger (c) PEAKMETER Anemometer (d) Testo 830 Infrared Thermometer

	Fish-Eye Images Parameters				
	Camera	**Focal length**	**Resolution**	**Dimensions**	**Colors representation**
(a)	Canon EOS 1100 D	32mm	230000 pixels	4272 x 2848	sRGB
	Meteorological Data Parameters				
	Variable	**Device**	**Unit**	**Accuracy**	**Range**
(b)	Air temperature (Ta)	Testo 175H1	°C	± 0.4 °C	-20 to +55 °C

(b)	Relative Humidity (RH)	Testo 175H1	°C	± 2%	0 to 100 %RH*
(c)	Wind Speed (Ws)	PEAKMETER PM6252A	m/s	± 0,1m/s	0.2 to 30.0 m/s
(d)	Surface temperature (Ts)	Testo 830-T2	°C	±1.5 °C	-30 to +400 °C

2.1.4. Survey questionnaire

A survey was carried out for the inhabitants and visitors of the Casbah to determine the subjective feeling of comfort. Our questionnaire was carried out during the January period on a sample of 60 people. 44 men and 16 women, 40 residents, and 20 tourists visiting the Casbah. It has been adapted according to various research conducted on outdoor thermal comfort (Table 4). The field survey has been done in the same periods as the meteorological measurements. First, Participants were asked personal questions about their age, height, and weight. as well as the state of their health and the clothing. Then, questions about meteorological parameters that influence daily comfort with 5-point scale importance. Participants were asked about their satisfaction on different parameters (Air temperature, relative humidity, wind, solar radiation, and shading) in the subspaces with an ASHRAE 7-point scale for pleasantness. Finally, they classified the proposed outdoor spaces from the most to the least comfortable. The survey is accessible in the dataset (Arrar et al., 2022b).

Table 4 : List of studies that engage subjective thermal perception within a questionnaire

Key reference	**City (Country)**	**Sensation scale**	**Survey field**	**Climate zone**
(Lam et al.2019) (Lam et al., 2019)	Melbourne (Australia)	ASHRAE 7-point scale (Thermal sensations)	2198	Cfb
(Kenawi et al. 2011) (Kenawy and ElKadi, 2011)	Geelong (Australia)	9 – Points Scale, McIntyre 3 points) (Thermal sensation, thermal preference, perception of individual weather parameters)	100	Cfb
(Shooshtarian et al. 2017) (Shooshtarian and	Melbourne (Australia)	ASHRAE 7 point (Thermal acceptance, thermal	1059	Cfb

Rajagopalan, 2017a)		sensation, overall comfort) (McIntyre 3 points) Thermal preference		
(Sharifi et al. 2017) (Sharifi et al., 2017)	Sydney (Australia)	ASHRAE 7 points (Thermal sensation)	-	Cfa
(Tsitoura et al. 2014) (Tsitoura et al., 2014)	Crete (Greece)	ASHRAE 5/3 -point scale (Microclimatic parameter, Thermal comfort, and wind tolerance)	200	Csa
(Tseliou et al. 2010) (Tseliou et al., 2010a)	Athens (Greece)	5-point scale (Thermal sensation)	9189	Csa
(Nikolopoulou et al. 2007) (Nikolopoulou and Lykoudis, 2007a)	Athens (Greece)	microclimatic conditions and use of open	1503	Csa
(Andrade et al. 2011) (Andrade et al., 2011)	Lisbon (Portugal)	5/3 -point scale (Atmospheric conditions, thermal and wind preferences)	943	Csa
(Pantavou et al. 2014) (Pantavou et al., 2014)	Athens (Greece)	7-point scale (Thermal sensation)	1706	Csa
(Salata et al. 2016) (Salata et al., 2016a)	Rome (Italy)	ASHRAE 7-point scale and the McIntyre scale (Thermal perception, thermal preference)	941	Csa
(De Freitas et al. 2015) (de Freitas and Grigorieva, 2015)	Caloundra (Australia)	ASHRAE 9-point scale (Pleasantness scale)	179	Csb
(Canan et al. 2020) (Canan et al., 2020)	Konya (Turkey)	ASHRAE 7-point scale	2000	Csa

		McIntyre scales (Thermal perception thermal preference)		
(G.Ramos et al, 2021) (Ramos et al., 2021)	Sao paulo (Brazil)	thermal adaptive behaviour	3,259	Cfa
(Labdaoui et al. 2021) (Labdaoui et al., 2021)	Annaba (Algeria)	ASHRAE 7-point scale	1230	Csa

2.2. Calculation of comfort

In this section, we follow the steps in the processing data to calculate the PET index and the Tmrt for the quantification of thermal comfort.

2.2.1. Measured data

The shared dataset (Arrar et al., 2022a) gathers meteorological data measured during the reference weeks. Figure A1 shows the distribution of the average daily air temperature in the measurement points. Table 5 is an example of the measured data summarized in the latter. Fish-eye images used in the data inputs to calculate the sky view factor, taken by the Canon EOS 1100D cameras, are summarized in Figure 14 according to the order of the measurement points.

Table 5: Example of Measured meteorological data input

				Summer	Day: 7	12 P.M
Unit	**°C**	**%**	**m/s**	**°C**	**°C**	**°C**
Points	**Ta**	**HR**	**Ws**	**TGround**	**TWall 1**	**TWall 2**
1	18.5	71.6	1.4	18.1	18.0	17.9
2	20.0	66.7	0.3	18.0	18.2	18.1
3	19.1	69.2	1.1	18.6	18.5	18.2
4	19.0	69.1	0.1	18.3	18.3	18.2
5	18.1	72.0	1.1	18.1	18.0	17.7
6	19.1	69.5	0.2	21.5	20.4	19.9
7	19.1	70.0	0.1	18.1	17.9	17.6
8	19.8	67.2	1.4	19.0	18.6	18.5
9	18.6	70.9	1.5	18.1	18.0	18.0
10	19.4	68.8	0.0	18.1	18.2	18.0
11	18.7	70.0	0.7	18.0	18.0	17.9
12	19.0	68.8	0.7	17.9	18.7	18.5
13	18.9	68.8	1.2	19.2	18.9	18.7
14	19	69.1	2.0	18.6	18.5	18.6

Figure 14: Fisheye in different measurement points

2.2.2. Calculation process (Rayman model)

Rayman pro 3.1 Beta software is a micro-scale radiation model developed at the Chair for Meteorology and Climatology (Matzarakis et al., 2010, 2007). The program is used to calculate the Tmrt (Mean radiant temperature) and the PET (Physiologically Equivalent Temperature) in the fourteen selected points. The Tmrt was calculated by using the surface temperature and the air temperature on Rayman. For the SVF calculation, it was necessary to process the fish-eye image with the GIMP 2.10 (GNU Image Manipulation Program) on a square shape with high resolution (300 dpi) and transfer it into the RayMan software (Matallah et al., 2020).

To proceed with the calculation in Rayman, it is necessary to select the day and time for the start of the in-situ measurements. The main input parameters are Air temperature (TA), relative humidity (RH), wind speed (Ws) and the surface temperature (Ts). Rayman will then automatically determine the mean radiant temperature (Tmrt) and proceed to the calculation of the PET values. Personal metabolism data are based on the standard case described by Taleghani (Taleghani et al., 2015a) for a normal 35-year old male person of 1.75 m high and 75 kg, with a metabolic rate of 80 Watt. An activity level of 80 W arises when a normal person is walking with 1.2 m/s.

All meteorological parameters and SVF were inserted as Input data in the Rayman model to calculate Physiologically Equivalent Temperature (PET). Geographical data: (36° 47′ 00″ N, 3° 03′ 37″ E) and elevation 107m were also used in the study.

2.2.3. Calculation of Tmrt

The mean radiant temperature (Tmrt) is an essential meteorological input parameter for the human energy balance. Therefore, the most substantial influence is on thermo-physiologically significant indexes like PET (Physiological Equivalent Temperature) (A,Matzarakis and Mayer H, 2000). In this study, globe temperature sensor was not used. According to the Rayman model, the mean radiant temperature was calculated through metrological and site-specific parameters. As well described by Matzarakis(Andreas Matzarakis, 2018).

Mean radiant temperature is calculated by the Rayman software using the following parameters "air temperature, relative humidity and surface temperature" as well as fish-eye images. Indeed, according to Matzarakis (Andreas Matzarakis, 2018) mean radiant temperature (Tmrt) can be calculated by

RayMan. This is done based on meteorological parameters and the location of interest. The validation of the results of the RayMan calculation agrees with similar results obtained from experimental studies (Matzarakis et al., 2007). This is why Rayman software, as well described in all papers by Matzarakis, does not use the globe temperature for calculating the mean radiant temperature

2.2.4. Calculation of PET Index

The most critical factors of PET are the mean radiant temperature Tmrt (◦C) (Yung-Chang Chen and Matzarakis, 2014a), wind speed (m/s), and air temperature (◦C) (Andreas Matzarakis, 2018). Relative humidity RH (%) only shows a very weak impact on PET (Fröhlich and Matzarakis, 2016a). The thermal impact of the actual environment in PET is assessed through a human energy balance equation (1). Based on MEMI model "Munich Energy Balance Model for Individuals" (P. R. Höppe, 1999).

$$M + W + R + C + E_{SK} + E_{RE} + E_{SW} + S = 0 \tag{1}$$

M: metabolic heat production ESK: latent heat (skin)

W: mechanical work ERE: latent heat (respiratory system)

R: fluxes of radiation ESW: latent heat sweatingC: sensible heat

S: heat storage

PET results were classified into nine classes of thermal perception (Very cold, Cold, Cool, slightly cool, Comfortable, slightly warm, Warm, Hot, and Very hot).

3 Results

3.1. Thermal comfort and heat stress level's assessment:

The assessment of PET shows that during the studied period there are seven different thermal comfort zones (Table 6 - 7): Cool, slightly cool, neutral, slightly warm, warm, hot, and extremely hot. Based on the PET ranges for the Mediterranean climate (Potchter et al., 2018a) (Table 8). Table 6 shows almost a similarity in evolution for all measuring points. For January, PET temperatures are stable from 6.00 am to 8.00 am, and from 6.00 pm to 8.00 pm. PET values increase during the daytime from 8.00 a.m. to 12.00 p.m. After midday, from 1.00 pm to 6.00 pm, the PET temperatures decrease with values in the neutral zone of thermal comfort, with nevertheless, some values of slightly warm (26 °C – 28 °C) and warm values (> 28 °C), Creating slight and moderate heat stress (points 2,3,6,7 and 10) at 12:00 pm.

Assessment of PET shows an extremely low temperature in point 8 (14.9 °C) and 12 (14.5 °C) at 8.00 pm and point 6 (14.8 °C) from (6.00 am to 8.00 am) and (6.00 pm to 8.00 pm) creating a period of discomfort called moderate cold stress. Measurement point 6 is most of the time in areas of thermal stress and the most affected by temperature variations.

Table 6 : Assessment of the outdoor thermal comfort level stress via PET index in the 14 study cases in January 2021.

District	Measurement point	PET 6:00 am	PET 8:00 am	PET 10:00 am	PET 12:00 pm	PET 2:00 pm	PET 4:00 pm	PET 6:00 pm	PET 8:00 pm
Casbah of Algiers	1	18	17.4	21.3	25.5	24.5	22	17.6	15.9
	2	17.1	17.7	22	29.5	26.7	22.1	17	16.2
	3	17.3	16.5	22.7	28.7	25.1	21.8	16.9	17
	4	17.4	18.6	22.8	27.7	26	23.1	19	17.4
	5	17.6	16.1	19.4	25	23.8	21.5	17	16.4
	6	14.8	14.8	22.8	29	23.6	18.7	14.8	14.7
	7	16.5	16.6	21.9	26.9	28.2	22.3	16.5	16.6
	8	16.8	16.9	21.5	25.5	23.3	20.9	17.7	14.9
	9	18.5	18.5	22.7	26.5	24.9	22.7	18	18.4
	10	18.8	18.7	24.4	28.8	28.4	24.1	18.5	18.9
	11	18.9	18.4	23.4	27.3	27.1	23.5	18.4	18.3
	12	16.4	15.3	19.8	24.9	23.4	21.2	15.5	14.5
	13	17.7	15.9	21.7	26.1	22.8	20	16.8	15.1
	14	17	15.6	20.6	25.2	22.3	20.3	17.1	15.4

	12 – 15	15 – 19	19 – 26	26 – 28	28 – 34
Thermal comfort	**Cool**	**Slightly Cool**	**Neutral**	**Slightly warm**	**Warm**
Stress level	**Moderate cold stress**	**Slight cold stress**	**No thermal stress**	**Slight heat stress**	**Moderate heat stress**

Table 7 shows two phases in the variations of PET in August's values and an overall similarity, from 6:00 am to 12:00 am an increase in values at all points, and from 02:00 pm to 08:00 pm a decrease in PET. An apparent period of discomfort (> 28 °C) throughout the day (From 8:00 am to 8:00 pm), with only the measurement point 6 at 6:00 am (24.8 °C) being in the neutral thermal comfort zone.

Results demonstrate an extreme heat stress level (> 36 °C) from 10:00 am to 4:00 pm in all points studied. Peak zone over 40 °C at the midday hours (12:00 pm to 02:00 pm) except for the measurement points (5,9 and 13). It should be noted that the extreme temperatures are in measurement point 6 with the lowest temperature (24.8 °C at 6:00 am) and the peak temperature (42.7 °C at 12:00 pm).

Table 7:Assessment of the outdoor thermal comfort level stress via PET index in the 14 study cases in August 2021.

District	Measurement point	PET 6:00 am	PET 8:00 am	PET 10:00 am	PET 12:00 pm	PET 2:00 pm	PET 4:00 pm	PET 6:00 pm	PET 8:00 pm
Casbah of Algiers	1	27.2	32.8	38	41.1	41.2	37.9	32.7	29.1
	2	26.5	33.2	39.2	42.1	41.7	39.1	33.3	28.3
	3	27.1	33.1	38.8	42.3	40.4	38.3	33.1	28.4
	4	26.8	31.9	37.1	40.7	39.9	37.1	32.5	28.5
	5	26	32	37.7	39	39.5	37.3	32.5	28.6
	6	24.8	35.8	42.1	42.7	38.2	41.2	33.7	26.3
	7	26.2	32.9	37.8	41.4	40.8	37.4	33.1	27.8
	8	26.9	33	37.5	42.3	40.9	37.3	32.4	28.3
	9	27.1	31.6	36.6	39.8	38.4	36.7	32.7	28.7
	10	27.8	32.8	38.7	42.2	41	38.3	32.9	28.8
	11	27.9	32.8	39.2	41.8	41.2	38	32.8	28.9
	12	26.6	34.9	40.6	41.5	40.6	41.3	34.9	28.2
	13	26.1	32.1	37.2	39.5	39.9	36.2	32	28.1
	14	27.4	32.1	37	40.2	40.4	38.1	32.7	28.4
	19 - 26	26 - 28		28 - 34		34 - 40		> 40	
Thermal comfort	Neutral	Slightly warm		Warm		Hot		Extremely hot	
Stress level	No thermal stress	Slight heat stress		Moderate heat stress		Strong heat stress		Extreme heat stress	

Table 8:PET range for Middle/Western Europe and the adjusted PET for the Mediterranean climate

Thermal sensitivity	Grade of physiological Stress	Mid/West Europe (Matzarakis,1999) (Matzarakis A, et al., 1999) Cfb	Csa Mediterranean (Potchter et al., 2018) (Potchter et al., 2018a) Csa
Very Cold	**Extreme cold stress**	< 4	< 8
Cold	**Strong cold stress**	4 – 8	8 – 12
Cool	**Moderate cold stress**	8 – 13	12 – 15
Slightly Cool	**Slight cold stress**	13 – 18	15 – 19
Neutral	**No thermal stress**	18 – 23	19 – 26
Slightly warm	**Slight heat stress**	23 – 29	26 – 28
Warm	**Moderate heat stress**	29 – 35	28 – 34
Hot	**Strong heat stress**	35 – 41	34 – 40
Extremely hot	**Extreme heat stress**	> 41	> 40

3.2. Comfort in historical cities assessment:

3.2.1. Tmrt values assessment:

The Tmrt values are very sensitive to solar radiation hours. Figure 15 shows the mean radiant temperature in January and August in the 14 measurement points. In January, three phases are observed in the graph. In January, the graphs we observe three phases: First, stable temperatures during sunrise and sunset (6:00 a.m. to 8:00 a.m.; 6:00 p.m. to 8:00 p.m.). Then, an increase in Tmrt values all morning long (8:00 a.m. to 12:00 p.m.). At last, a drop in temperature during the afternoon (2:00 p.m. to 6:00 p.m.). However, in August, the graph shows two phases. An increase in temperature from 06:00 am to 12:00 pm and a decrease from 02:00 pm to 08:00 pm. The highest values in January (35 °C) are recorded in points (2;6) at 12:00 pm and point 7 at 02:00 pm. In August, extreme values (> 50 °C) are recorded in points 6 and 12.

In January, the curves of the measured points are parallel with a maximum interval of 3°C. Curve 6 presents specific variations with a strong affection in the daylight hours. Going from the coldest point (12 °C) at 6:00 am, to the hottest point (35.5 °C) at 12:00 pm. For August, all the curves show the same development. Except 6 and 12 which record the highest temperatures during the day (8h00 to 18h).

Figure 6 shows that point 6 is the least comfortable in January with extremely low temperatures and in August with temperatures above average by (≈ 4°C).

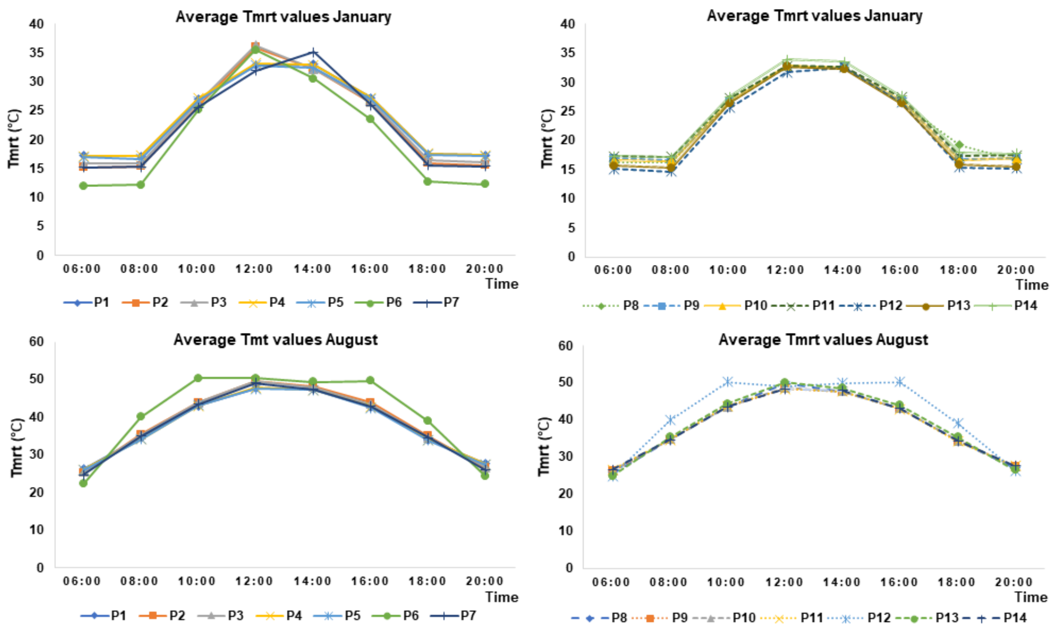


Figure 15: The average daily mean radiant temperature distribution in the 14 points studied in January and August 2021.

3.2.2. Subjective comfort:

According to our observation and based on 60 respondents. Air temperature and humidity have the most significant impact on daily comfort (Figure A2). Figure A3 shows point’s pleasantness scale in subspaces for different parameters (Air temperature, humidity, wind speed, shading, and sun effect). Point 5 stands out with the most positive votes on the pleasantness scale Figure 16 shows user's preference for subspaces. As stated by the results of the votes, the sub-spaces are distributed in 3 categories: The most comfortable (ranking 1 to 2), moderately comfortable (ranking 3 to 6), and the least comfortable (7 to 9).

Spaces that emerge to be the most comfortable are the points with a low sky view factor (5, 7, and 9) with more than 15 votes for each on ranking 1/9 or 2/9. On the other hand, measurement points (6 and 10) with large openings to the sky are the most uncomfortable for users with the lowest rank (over 25 voices for each at the last position).

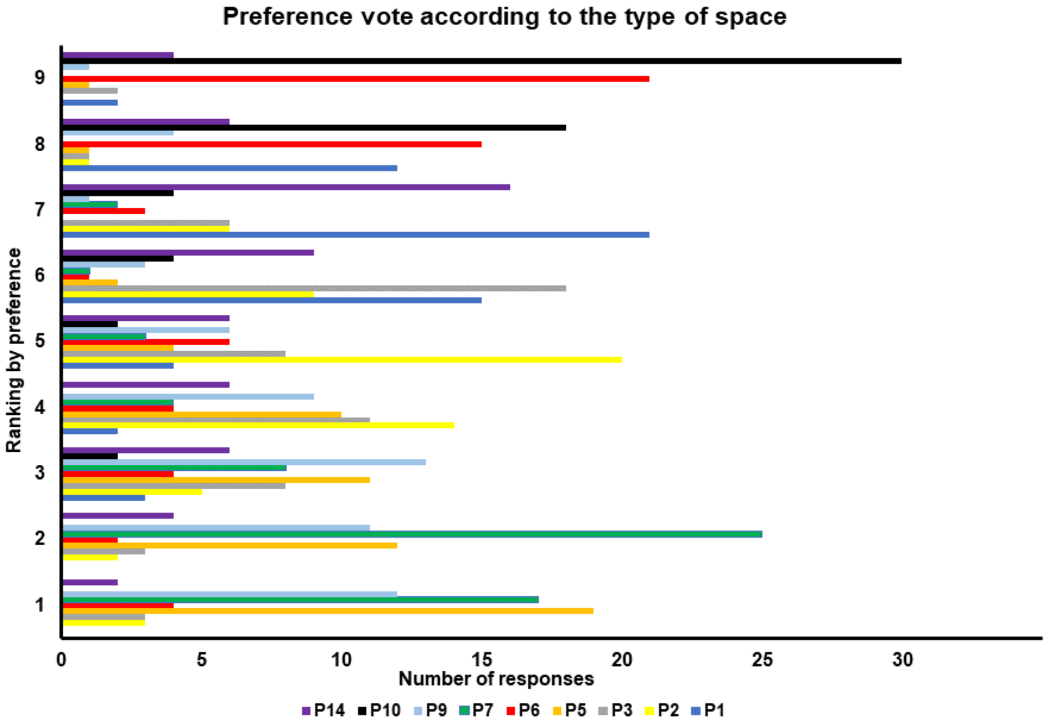
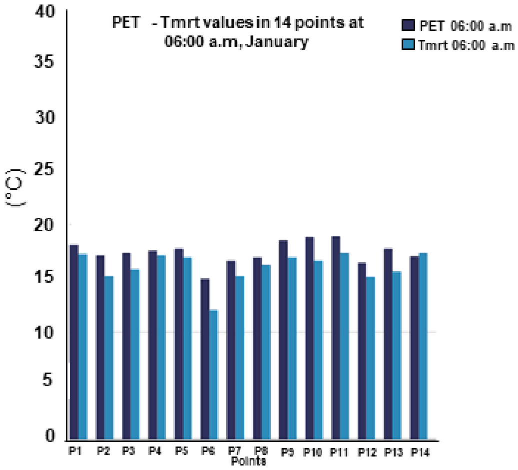


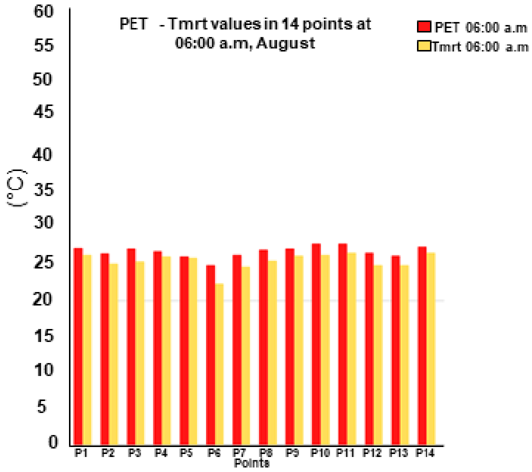
Figure 16: Users' feeling of comfort vote according to the type of space in Casbah of Algiers

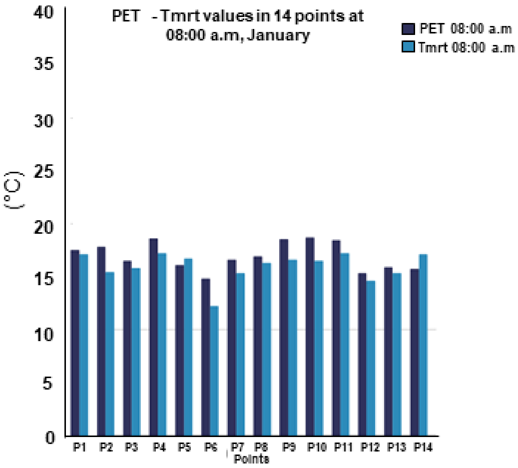
3.3. Sky view factor effect on PET and Tmrt

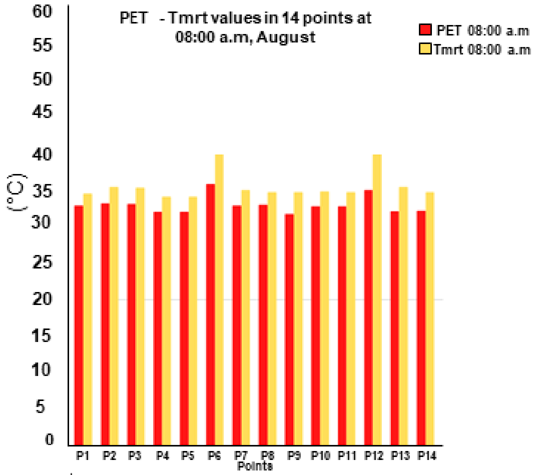
The assessment of PET and Tmrt depending on the SVF during different day hours is illustrated in Figure 8. In January, the PET values are higher than the Tmrt values during sunrise (6:00 am; 8:00 am). During the daylight (10:00 am to 04:00 pm) Tmrt values are greater than those of PET (°C). The curves remain parallel despite a significant difference (8°C) which is recorded at the midday (12:00 pm - 2 pm) (Figure 17). So, the mean radiant temperature is very impacted by the sun since its values increase significantly during daylight.

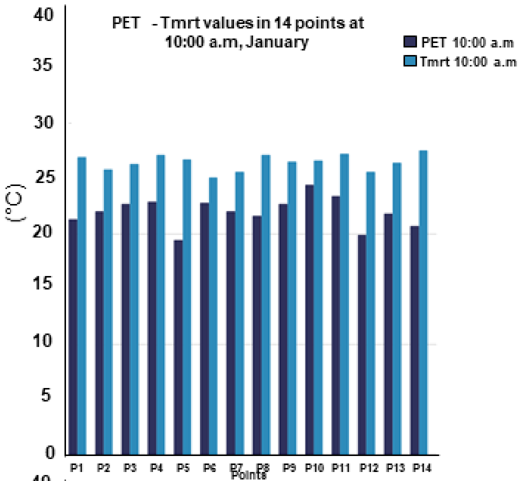
In August, the assessment represents two distinct thermal periods of the day. The first period was observed during sunrise and sunset (6:00 a.m. and 8:00 p.m.), the second was during daylight (8:00 a.m. to 6:00 p.m.). The PET and Tmrt values were too close in the first period (6:00 a.m. and 8:00 p.m.), as seen in the Figure A6. In the middle of the day (from 8:00 a.m. to 6:00 p.m.). Values of Tmrt were much higher than those of PET (±7 °C), but the curves were parallel, which demonstrates a stable difference throughout the day but with an increasingly significant variation in the middle of the day (12:00 p.m. and 02:00 p.m.).

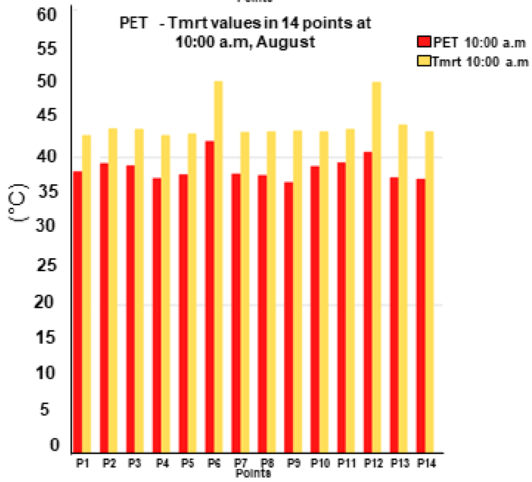

PET - Tmrt values in 14 points at
06:00 a.m, January
PET 06:00 a.m
Tmrt 06:00 a.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points

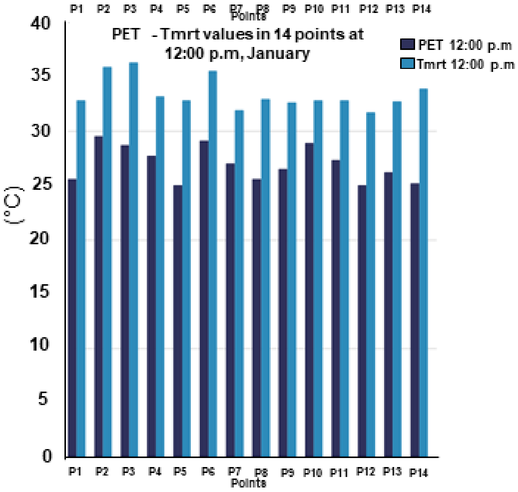

PET - Tmrt values in 14 points at
06:00 a.m, August
PET 06:00 a.m
Tmrt 06:00 a.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points

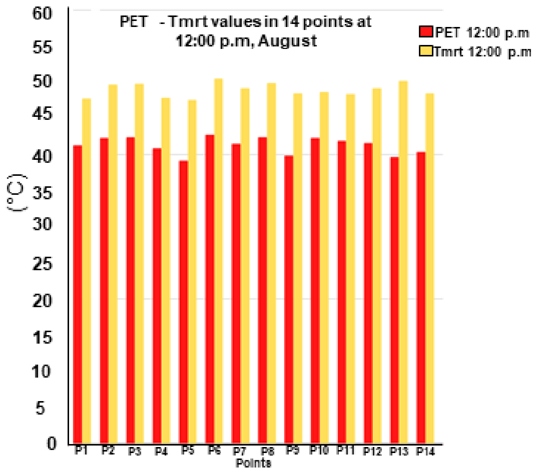

PET - Tmrt values in 14 points at
08:00 a.m, January
PET 08:00 a.m
Tmrt 08:00 a.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points


PET - Tmrt values in 14 points at
08:00 a.m, August
PET 08:00 a.m
Tmrt 08:00 a.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points


PET - Tmrt values in 14 points at
10:00 a.m, January
PET 10:00 a.m
Tmrt 10:00 a.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points


PET - Tmrt values in 14 points at
10:00 a.m, August
PET 10:00 a.m
Tmrt 10:00 a.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points


PET - Tmrt values in 14 points at
12:00 p.m, January
PET 12:00 p.m
Tmrt 12:00 p.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points


PET - Tmrt values in 14 points at
12:00 p.m, August
PET 12:00 p.m
Tmrt 12:00 p.m
(°C)
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14
Points

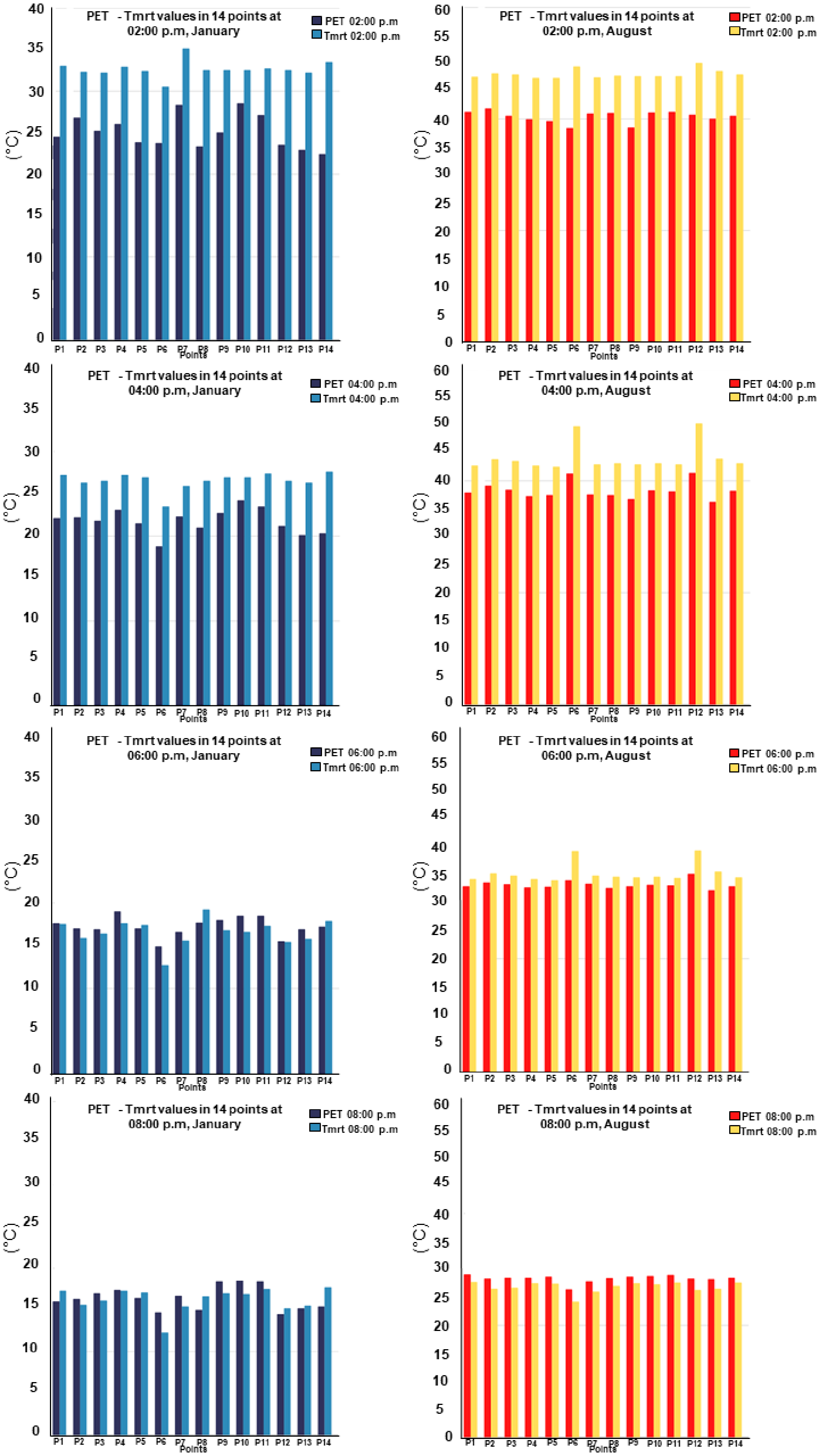

PET - Tmrt values in 14 points at 02:00 p.m, January
PET 02:00 p.m
Tmrt 02:00 p.m
PET - Tmrt values in 14 points at 02:00 p.m, August
PET 02:00 p.m
Tmrt 02:00 p.m
PET - Tmrt values in 14 points at 04:00 p.m, January
PET 04:00 p.m
Tmrt 04:00 p.m
PET - Tmrt values in 14 points at 04:00 p.m, August
PET 04:00 p.m
Tmrt 04:00 p.m
PET - Tmrt values in 14 points at 06:00 p.m, January
PET 06:00 p.m
Tmrt 06:00 p.m
PET - Tmrt values in 14 points at 06:00 p.m, August
PET 06:00 p.m
Tmrt 06:00 p.m
PET - Tmrt values in 14 points at 08:00 p.m, January
PET 08:00 p.m
Tmrt 08:00 p.m
PET - Tmrt values in 14 points at 08:00 p.m, August
PET 08:00 p.m
Tmrt 08:00 p.m
(°C)
Points
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14

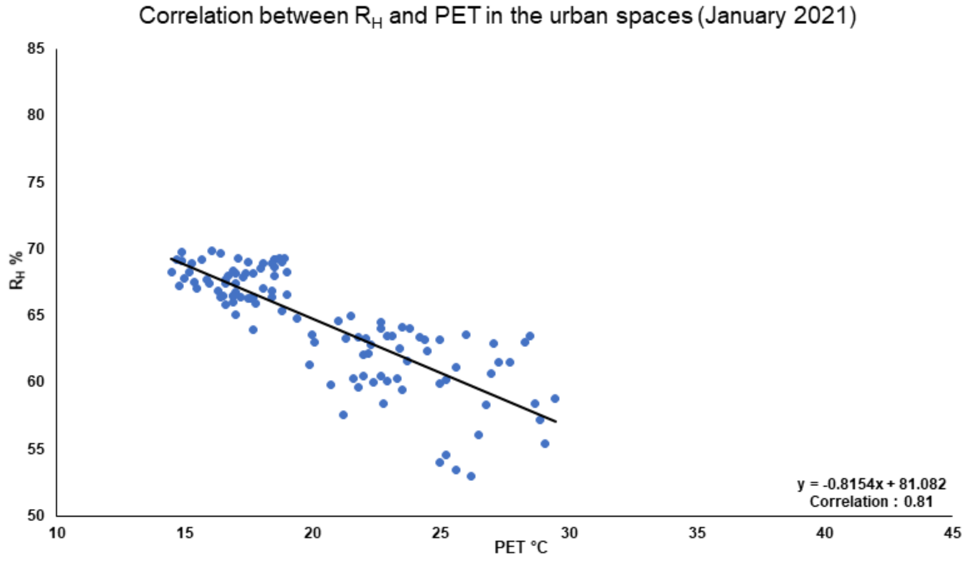
Figure 17: Assessment of PET and Tmrt levels in 14 studied points during January and August 2021 from 6:00

3.4. Effect of the sea breeze on outdoor thermal levels

This section studies the impact of wind and relative humidity on overall comfort in the Casbah of Algiers. According to the shared dataset [74] very low wind speed measurements were noticed inside the study site, with averages (< 0.5 m/s) in almost all the sub-spaces. Given the proximity of the sea, a strong impact on relative humidity is to be highlighted, with values reaching more than 70% in January and almost 80% in August.

Correlation analysis was conducted to examine the significance of the impact of relative humidity on outdoor thermal comfort (PET) under different combinations of external meteorological conditions and urban morphological configurations (14 measurement points). According to Figure 18, a very important correlation rate between the values of the relative humidity and the PET, with $R^2 = 0.81$ in January, where we notice a gradual decrease in relative humidity with the increase in temperature at midday.

In August, the correlation is $R^2 = 0.79$, with relative humidity values of more than 75%, recorded mainly at the beginning of the day (6:00 am) and in the evening (8:00 pm) with a drop in humidity values at midday in the points measured.



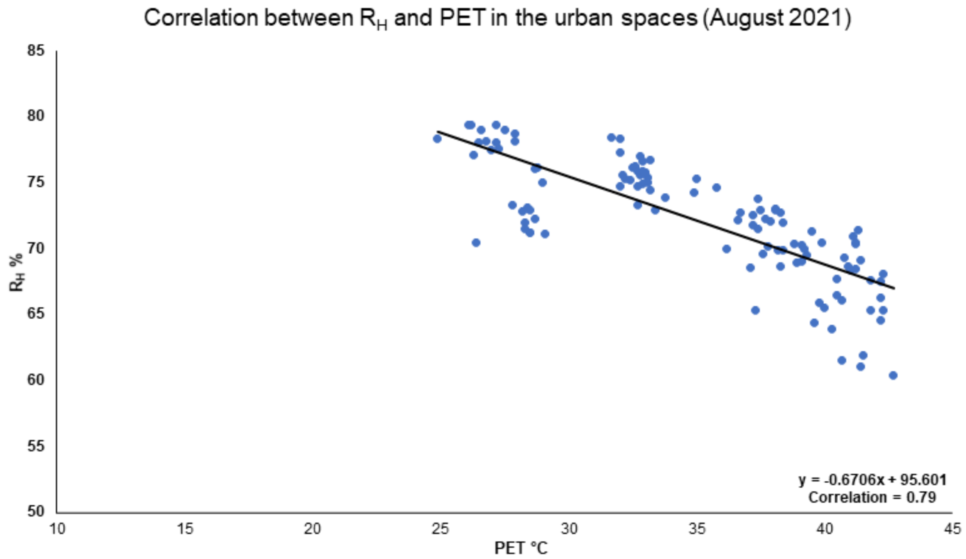


Figure 18: Overall correlation between relative humidity and PET in the 14 points studied in January and August

4 Discussion

The present study was conducted to assess the outdoor thermal comfort in the historic fabric Casbah of Algiers and the impact of the urban subspaces on microclimate in Mediterranean climatic conditions. The study focuses on investigating the thermal comfort parameters and values in 14 measurement points during January and August.

4.1. Major findings and recommendations

Our study dealt with the existing microclimatic variations in the sub-spaces of the Casbah of Algiers. Firstly, covered passages and streets with low SVF present the best performances of thermal comfort over all the measurement periods. Indeed, in the two subspaces, solar radiation control plays a decisive role in mitigating and protecting from heat perception in hot seasons. Indeed, the high level of shade and the punctual winds make it possible to reduce the temperature up to 2°C than the other subspaces. During cold periods, covered passages store heat by the destratification of the air, allowing these subspaces to have warmer temperatures. In fact, a difference which reached ΔPETMax.Jan = 3.7 °C was recorded between covered passages and other subspaces. These findings align with the work of Ali-Toudert (Ali-Toudert, F and Mayer H, 2006), Andreou(Andreou and Axarli, 2012a), and Elnabawy (Elnabawi et al., 2013) on the influence of urban morphology of traditional cities in creating urban microclimates.

Secondly, measurement points 6 and 12 (see Figure 4) present the most uncomfortable points during January and August (PETJan.P6 = 19.1°C, PETJan.P12 = 18.8°C) (PETAug.P6 = 35.6°C, PETAug.P12 = 36.1°C). Indeed, for point 6 these significant variations are justified by the size of the square. The wide opening to the sky in this space results from the collapse of houses, which induces strong solar radiation during the day and increases the place's temperature considerably. The rehabilitation of collapsed houses in this space is strongly recommended to avoid these high-temperature variations and thus find a comfortable microclimate in this area. For point 12, the north-south orientation benefits from the sun all day long. In addition, the high sky view factor of the street and its multiple intersections increase the sunshine of the street canyon throughout the day. A suspended vegetation cover is recommended in this type of street to increase its shade and thus reduce perceived temperature.

Thirdly, the values of mean radiant temperature are related to the sky view factor; in January, indicate a negative correlation exists (r= -0.96). Values with a low opening to the sky such as P4, P11, P14 have the highest temperatures and are therefore comfortable in winter (TmrtP4= 23.7°C, TmrtP11= 23.7°C, TmrtP14= 24.0°C). At the same time, the values with a high opening to the sky, such as P6, P12, P13, have the lowest temperatures (TmrtP6= 20.5°C, TmrtP12= 22.1°C, TmrtP13= 22.5°C). Indeed, this is explained because the points with low sky view factor store heat and emit it in cold weather. According to (Hien and Jusuf, 2010), when the correlation is negative, it means that during this time, surfaces start to release the heat back to the atmosphere. In August, the existing correlation is positive (r= 0.82). The higher the SVF, the higher is the mean radiant temperature. In summer, the solar radiations are longer and, therefore, as has also been demonstrated in the study of (Wang et al., 2016a). The more open an area will result in receiving more solar radiation. This results in a higher Tmrt i.e. (TmrtP6= 40.7°C, TmrtP12= 41.2°C, TmrtP7= 39.6°C). On the contrary, areas with a low sky view factor can maintain in August temperatures at a cool level (TmrtP1= 37.9°C, TmrtP4= 37.8°C, TmrtP5= 37.7°C). According to (Oke and East, 1971), shading is the most important factor in providing a cooler temperature. These findings align with the work of Wang and Venhari (Ahmadi Venhari et al., 2019; Hwang et al., 2011) on the role of the sky view factor in human thermal comfort and heat stress. We recommend increasing shading in areas with a high sky view factor by rehabilitating deteriorated areas or by introducing specific shading strategies to improve the inhabitants' urban thermal comfort.

Fourthly, we refer to the insignificant effect of the sea breeze despite the proximity between the Casbah of Algiers and the sea. Indeed, the wind values recorded during the two measurement campaigns remain relatively low, which induces the concentration of a high rate of humidity in the measured streets. Nevertheless, for the PET values of measurement points 12 and 13. Although the streets are adjacent, with similar height and width ratio (H/WP12 = 1.82, H/WP13 = 1.89), ΔPET between them is: 2.2°C. The latter is linked to the orientation (P12: North-South, P13: East-West), to the average wind velocity (WsAvg.P12 = 0.20 m/s; WsAvg.P13 = 0.48 m/s). But also to the presence of suspended vegetation in the entrances of the street P13. We recommend conducting a more in-depth study of the impact of traditional urban morphology on wind flows.

Finally, the results of our survey campaign are consistent with the outdoor thermal comfort calculations. Figure A2 shows that relative humidity is the parameter that influences the most comfort of the inhabitants. Also, according to the survey, measurement points 6 and 10 are the most uncomfortable subspaces, as indicated in the PET comfort results ($PET_{AUG.P6}$ = 42.7°C; $PET_{AUG.P10}$ = 42.2°C). The survey questionnaire was able to bring out the subjective feelings of residents and visitors.

4.2. Strength and limitations of the study

One of the specificities of this study is its empirical and comparative approach to assessing the outdoor thermal comfort in historical urban fabrics (Ali-Toudert, F and Mayer H, 2006; Castaldo et al., 2017). A mixed approach was adopted involving in-situ measurements, the calculation of the two Indexes, mean radiant temperature (Tmrt) and Physiological Equivalent Temperature (PET), and subjective questionnaires for inhabitants.

The durations of in-situ measurements in similar studies can be from two to three days (Ketterer and Matzarakis, 2015; Labdaoui et al., 2021). However, in this study, the period of in-situ measurements was extended to 7 days, in January and August. The reason for the extension was to have a greater precision of the results during these periods. Therefore, the study can shed light on a different urban morphology that is not commonly investigated in mainstream literature. The Casbah of Algiers displays a H/W ratio different from the classical modern cities (Chatzidimitriou and Yannas, 2017) with pedestrian traffic inside the historical site. The absence of trees and vegetation within the historic fabric means that specific mitigation strategies must be developed (Laureti et al., 2018a).

Finally, this study allows scientists to understand the outdoor conditions in historic cities better. Knowledge collected through this study can indeed be exported to similar urban fabrics worldwide. Since our survey sample included only 60 people, a larger number of respondents could be explored in future studies to have more precise answers regarding the perception and sensation of subjective comfort (Andrade et al., 2011; Tsitoura et al., 2014). And thus be able to make a complete study on TSV in Mediterranean climates (Labdaoui et al., 2021; Salata et al., 2016a).

4.3. Implication on practice and future work

Planners should consider mitigation strategies for cases of extreme heat stress to improve the comfort of the inhabitants in traditional urban cities. But also, to visitors to the Casbah of Algiers, a UNESCO World Heritage Site, and therefore a very attractive region for tourists (Nasrollahi et al., 2017a) and economic activities.

One of the strategies that can be developed is the introduction of vegetation (Fahmy et al., 2020a) in the streets to reduce exposure to the sun (Lin et al., 2010a) and thus the stress level. Future studies may have longer measurement periods to study the outdoor thermal behavior of the urban fabric over a whole season and then over a full year. Then, the creation of a local urban climate model-based measured climatic parameters can improve the overall evaluation accuracy. This can be done by placing a climatic station in the historic fabrics, thus taking measurements over long periods and charcterize the outdoor thermal comfort(Roshan et al., 2019). Next, interventions at the urban scale can be carried out to improve user's comfort by testing and implementing adaptation and mitigation strategies. The introduction of vegetation into the subspaces of the urban fabric and optimization of the solar reflectance index (SRI) of the façade can play a major role.

Finally, one of the interesting research projects to investigate is the likelihood of discomfort in the future under climate change (Früh et al., 2011). This latter refers to long-term shifts in temperatures and weather patterns, which could greatly influence outdoor thermal comfort. This study can be carried out by coupling current measurements with future climate scenarios, using software such as ENVI-met or Rayman. This research may have significant implications for advising decision-makers in similar Mediterranean environmental contexts to improve the existing urban fabric, contributing to more liveability and vitality in outdoor areas.

5 Conclusions

The present study evaluates the microclimatic comfort conditions in the historical urban fabrics in the Mediterranean environment "Casbah of Algiers." To this end, an empirical investigation was performed in 14 subspaces. In the present study, the research scale was limited to the most significant subspaces in the historical city to evaluate the thermal comfort conditions within their microclimates. The measured data (Air temperature, relative humidity, wind velocity, surface temperature, and fish-eye images.) were taken between 26th January – 1st February and 5th – 11th August, several times in the day (From 6 am to 8 pm, every 2 hours).

The outdoor comfort indexes "Physiologically Equivalent Temperature (PET) and mean radiant temperature (Tmrt)" and the sky view factor (SVF), were evaluated through the RayMan tool in the 14 reference points where the modeling and calculation were made to identify the heat stress level. In January, it emerged that PETJan is in the "no thermal stress" zone 38.4% of the daytime. The cold stress percentage is 49.1% and was recorded mainly at sunrise and sunset, while a 12.5% rate of heat stress is present at midday. In August, heat stress is almost permanent. In fact, 52.67% of the time PETAug is in strong or extreme heat stress, while the rest of the daytime is slight. The impact of the SVF on the Tmrt has been demonstrated in the various sub-spaces of the Casbah. With also the most significant temperature variations occurred in vacant spaces following collapses. Additionally, the 'Sea breeze effect' on the outdoor thermal comfort was insignificant (during the study period). Future studies should investigate to expand our knowledge on heat stress and sea breeze with both in situ and station measurements for various climatic parameters during all months and seasons in historic cities.

IV. Towards Anticipating the Effects of Climate Change on Outdoor Thermal Comfort

The detailed analysis conducted in Part 02 allowed for the evaluation of outdoor thermal comfort conditions in the high Casbah of Algiers through a network of 14 representative measurement points. Thanks to in situ measurement campaigns carried out in winter and summer, as well as numerical simulations, we were able to quantify the influence of morphological and microclimatic factors on thermal comfort indices, particularly PET (Physiological Equivalent Temperature) and Tmrt (Mean Radiant Temperature).

The results obtained helped identify areas with the most significant microclimatic variations, influenced by urban morphology, shading rates, and exposure to ventilation flows. Among these, four subspaces stand out particularly due to their high traffic from both residents and visitors to the Casbah:

1. **Zone 3: Busy commercial street**
2. **Zone 6: Open square attracting visitors**
3. **Zone 7: Lively intersection between several passages**
4. **Zone 12: Historic street with high solar exposure**

These spaces were selected for a detailed analysis in Part 03 because they concentrate high pedestrian traffic, making the issue of thermal comfort particularly crucial.
The analysis of microclimatic data and thermal indices led to several key observations:

- The Sky View Factor (SVF) plays a determining role: Spaces with a high SVF (large openings to the sky, such as at Point 6) experience extreme temperatures in summer, while more enclosed streets (e.g., Point 9) retain coolness better.

- Solar exposure directly influences thermal perception: North-South oriented streets (such as at Point 12) accumulate more heat than East-West oriented streets.

- The effect of the sea breeze is limited in the high Casbah due to building density, which amplifies thermal accumulation in more enclosed alleys.

- Semi-covered spaces (e.g., Point 5) provide better thermal conditions thanks to attenuation of solar radiation and temperature regulation.

To improve thermal comfort in the Casbah of Algiers while respecting heritage constraints, several mitigation strategies can be implemented. Installing lightweight shading devices, such as shade sails or pergolas, would reduce solar exposure in open spaces. The use of materials with high solar reflectance on façades and floors would also help limit thermal accumulation and mitigate the urban heat island effect. Introducing vegetation, in the form of hanging plants or pots in streets and open squares, would provide cool spots and improve relative humidity. Optimizing urban ventilation by maintaining natural air passages and limiting obstacles to the circulation of sea breezes could help regulate temperature in more enclosed spaces. Finally, raising awareness among heritage managers and urban planners about the importance of integrating thermal comfort criteria into Casbah rehabilitation projects would ensure a sustainable approach tailored to future climate challenges.

Synthesis of Results and Analytical Perspectives for Part 03

The evaluation of current outdoor thermal comfort conditions in the Casbah of Algiers revealed significant climatic constraints influenced by urban morphology, solar exposure, and the capacity of materials to store heat.

However, beyond this empirical analysis, one crucial question remains:

How will these conditions evolve in the face of climate change effects?

Climate projections for the Mediterranean region predict a rise in average temperatures, intensified heatwaves, and changes in wind and humidity patterns. These changes will have direct consequences on outdoor thermal comfort, particularly in historic districts where adaptation interventions are constrained by heritage requirements.

It is in this context that Part 03 is positioned, aiming to predict the effects of climate change on outdoor thermal comfort by 2050 and 2090, relying on:

- The integration of IPCC climate scenarios (RCP 4.5 and RCP 8.5) to anticipate future variations in temperature, solar radiation, and relative humidity.

- Advanced numerical simulations using ENVI-met software, combining in situ data and predictive models to quantify changes in thermal comfort in the four identified subspaces.

- The evaluation of thermal responses in areas most exposed to climate change, focusing on high-traffic places and the implications for users.

- The exploration of mitigation and adaptation strategies suited to historic fabrics, such as optimizing façade materials, improving shading devices, and introducing passive cooling solutions compatible with heritage requirements.

Thus, this transition marks the shift from an empirical analysis of the current situation to a prospective approach, essential for anticipating future climate changes and proposing sustainable solutions adapted to historic public spaces in the face of the challenges of the 21st century.

PART 03: Prediction of climate change effect on outdoor thermal comfort

V. PART 03: Prediction of climate change effect on outdoor thermal comfort

1 Introduction:

Urbanization is rapidly increasing, with projections suggesting that 68% of the global population will live in urban areas by 2050(United Nations Department of Economic and Social Affairs, 2019). This growth brings challenges in managing climate change, as cities, major centers of pollution and energy consumption, are particularly vulnerable to heatwaves, rising sea levels, and extreme weather events.

Southern Europe and North Africa will face severe climate impacts, including heat stress, drought, and more frequent storms (Pachauri et al., 2015). Urbanization exacerbates the Urban Heat Island effect, leading to thermal discomfort and degrading microclimatic conditions, especially in tropical cities. These conditions can adversely affect public health.

In this climate change context, microclimate studies have gained increasing attention. Urbanization presents various challenges to the livelihoods and well-being of city residents, notably through the Urban Heat Island effect, which adversely affects human health by causing thermal discomfort. Consequently, outdoor thermal comfort has emerged as a vital issue amid rapid global urbanization. Factors such as global warming, the heat island effect, air pollution, and the loss of green spaces are rapidly degrading microclimatic conditions in densely populated tropical cities. These deteriorating microclimatic conditions can have serious health implications for individuals utilizing outdoor urban spaces, yet research in this area remains relatively limited.

Outdoor spaces are essential for urban livability, offering movement and recreation opportunities. Improving thermal comfort through sustainable urban planning is key to addressing climate impacts and ensuring vibrant, resilient cities.(Chen and Ng, 2012a). Therefore, integrating sustainable urban planning strategies from the early design phases is crucial.

The Early Design Stage, as defined by the Royal Institute of British Architects (RIBA) (Denison, 2024), encompasses stages 0 to 2 of the Plan of Work. It begins with identifying objectives and opportunities during the project strategy (Hosseini et al., 2019) (Stage 0) and progresses to creating a Project Brief that outlines expectations and constraints (Stage 1). The initial design phase (Stage 2) allows urban planners and architects to develop proposals that integrate community needs and environmental considerations (Zheng et al., 2023). In summary, this early stage establishes a solid foundation for urban development, addressing user needs from the beginning. This work provides a framework for urban planners and managers to develop effective environmental strategies for urban renovation, outlining a workflow that can be used to conduct this study in a rigorous and reproducible manner

In recent years, researchers have concentrated on understanding outdoor thermal comfort across various climate zones globally. Studies in this field are generally categorized into three main approaches: numerical simulations, subjective surveys with objective measurements, and assessments of outdoor thermal comfort for existing or future projects (Coccolo et al., 2016). Our research will combine these methodologies to create a comprehensive framework for conducting long-term climate scenario studies.

According to the study by Kumar (Kumar and Sharma, 2020a), understanding outdoor thermal comfort is crucial for adapting cities to user needs and mitigating urban heat islands. Research highlights various approaches to outdoor thermal comfort, notably the role of vegetation in mitigating perceived heat (Jeong et al., 2016; Manavvi and Rajasekar, 2020). Mitigation strategies include integrating vegetation and shading structures, such as photovoltaic canopies (Ali and Patnaik, 2018). Specific indices for hot climates, such as mPET, have also been developed to enhance comfort assessment (Golasi et al., 2018; Lin et al., 2019). Additionally, studies demonstrate that trees and water bodies can improve comfort for pedestrians (Jeong et al., 2016; Wang et al., 2017). Lastly, the promotion of tourism aims to enhance the comfort of tourist sites to attract more visitors (Lam et al., 2018; Nasrollahi et al., 2017b). These findings provide varied insights into enhancing thermal well-being in urban settings.

Numerous studies have explored outdoor thermal comfort through numerical simulations (Ali-Toudert and Mayer, 2006a; Berkovic et al., 2012). with review studies offering deeper insights identified vegetation (parks, street trees, green roofs) and high albedo materials (reflective roofs, pavements) as key mitigation strategies. In this study, we chose to use PET as it is the most commonly recommended index for assessing outdoor thermal comfort in Mediterranean climates. PET effectively simulates the body's temperature perception by accounting for crucial meteorological factors such as air temperature, humidity, wind speed, and solar radiation. While PET has some limitations in hot and humid climates, it remains highly suitable for Mediterranean regions characterized by hot summers and low humidity, making it a reliable tool for thermal comfort assessment, as noted by Lin and Matzarakis (2008), Potchter et al. (2018), and Roshan et al. (2020).

This study addresses the critical need to understand outdoor thermal comfort, particularly in the context of climate change and its impacts. While the variety of models and methods available reflects a growing interest in this field, it also poses challenges in synthesizing results due to the limitations inherent in each approach. The research implements a comprehensive workflow that integrates on-site measurements, model calibration, computational fluid dynamics (CFD) simulations, and climate change impact analyses.

This work provides a framework for urban planners and managers to develop effective environmental strategies for urban renovation. By quantifying thermal comfort through empirical data and numerical modeling, the study aims to create a predictive algorithm that can forecast thermal comfort conditions over the next century. This approach seeks to identify effective mitigation strategies for extreme climate scenarios and enhance the rigor and reproducibility of research methodologies. The proposed workflow will be a valuable resource for future urban projects, whether in initial design phases or ongoing renovation efforts, contributing to the development of resilient and adaptive urban environments.

Overall, the goal is to establish a robust methodological framework for evaluating outdoor thermal comfort by combining empirical data with predictive models, thereby facilitating informed decision-making in urban planning. The study specifically explores the following questions.

How can outdoor thermal comfort be quantified to anticipate conditions in the coming decades in the context of climate change?

To what extent does an integrated approach of on-site measurements and CFD simulations enhance the accuracy of thermal comfort predictions?

Which workflow can be used to conduct this study in a rigorous and reproducible manner?

This study pioneers a microclimatic mesh analysis of the Casbah of Algiers through the installation of 12 climate stations, each covering approximately 11,478 m^2. Remote sensing techniques were employed to preselect hotspot locations for these stations, coupling satellite imagery with in-situ measurements of microclimatic data and surface temperatures. This integrated approach allowed for a thorough analysis of microclimatic variations within this historic site.

This study introduces a workflow methodology for assessing outdoor thermal comfort across entire sites by combining in situ measurements, CFD simulations, and algorithmic post-processing to generate decade-averaged PET values under current and future climate scenarios (RCP 4.5 and 8.5). Integrating insights from global thermal comfort studies and Mediterranean climate research, it consolidates previous approaches into a streamlined workflow supporting mid- to long-term climate resilience planning. This predictive tool aids urban planners and designers in creating adaptive urban designs specifically tailored to Mediterranean cities to mitigate thermal discomfort due to climate change. This workflow illustrates a systematic approach to understanding outdoor thermal comfort in the context of climate change, using a combination of field measurements, remote sensing, and advanced modeling techniques. Following data collection, the model was simulated and calibrated in ENVIMET, using in situ measurements across the four most representative zones and conducting simulations of future climatic scenarios.

The Physiological Equivalent Temperature (PET) was calculated, enabling the development of a predictive model known as Equation P. This model provides hourly and annual PET forecasts based on specific measurement days and simulated outcomes. Equation P focuses on average PET values across scenarios, allowing for the assessment of outdoor thermal comfort under global warming scenarios in a Mediterranean climate.

The research offers a comprehensive examination of climate scenarios from the past (1989), the present (2021), and the future (2050 and 2090 under IPCC 4.5 and 8.5 scenarios) to characterize thermal comfort in Mediterranean cities. It also explores how climate change affects this comfort, along with the physical activities of residents and tourists in historical city centers.

The study addresses constraints in a historical district where interventions are regulated, emphasizing the importance of balancing urban heat mitigation with cultural heritage preservation. By analyzing future climate scenarios at both micro and macro scales, the research highlights the impacts of climate change and examines complex interactions relevant to urban design and renewal.

This parameterization adds value by assessing the effects of various scenarios and how parameters influence comfort thresholds over the coming decades. It evaluates IPCC climate scenarios 4.5 and 8.5 for 2050 and 2090, analyzing microclimatic effects and integrating them into a predictive model. This model combines climate scenarios to provide hourly and annual PET forecasts, offering a comprehensive understanding of outdoor thermal comfort under varying future conditions.

The algorithm developed within this study enables the scheduling of urban design interventions and restoration projects for the historic fabric, offering projections and actionable insights at 10-year intervals.

This research significantly contributes to urban climatology by providing a structured workflow to assess thermal discomfort over multiple years and develop targeted solutions within historic urban areas. The focus on characterizing urban heat in historic Mediterranean regions includes a case study demonstrating results across four preselected sites. A predictive comfort algorithm based on PET for the study area aims to align with Sustainable Development Goal 11, which seeks to make cities inclusive, safe, resilient, and sustainable.

The research supports this goal by enabling comfort prediction and responsible intervention in ancient cities, balancing cultural heritage preservation with adaptive measures. This approach offers a framework for improving thermal comfort through nature-based solutions and urban renewal design, serving as a valuable resource for urban planners and architects.

Reinforce the importance of this research in the Introduction, particularly by clarifying the benefits of optimization based on algorithm configuration.Finally, this study bridges the knowledge gap regarding climate change impacts on traditional urban areas, with findings applicable to other historic cities with similar urban structures, such as Fatimid Cairo (Egypt) (Attia, 2006), Toledo (Spain), the Medina of Tunis (Tunisia), and the Centro Storico of Naples (Italy).

2 Literature review:

Recent studies on outdoor thermal comfort in relation to climate change and rising temperatures have been increasing, especially in urban areas. With summers becoming longer and more unbearable, understanding and addressing thermal comfort is crucial. This literature review examines over 100 publications from Scopus and Web of Science, focusing on outdoor thermal comfort, climate change, and global warming, as well as historic cities. The review prioritizes studies that utilize objective measurements and CFD simulations published between 2010 and 2024, excluding those that employ different methodologies. We have selected in the Table 9 the key studies related to the three themes: "Global Outdoor Thermal Comfort," "Global Warming and Climate Change," and "Traditional Cities and the Mediterranean Region," which are presented in the table below.

Table 9:Literature review

Global Outdoor thermal comfort studies			
City (Country)	**Köppen classification**	**Key findings**	**Reference**
Several cities	Global	This study presents two main themes: the growing interest in outdoor thermal comfort (OTC) studies due to urbanization and climate change and the geographical and methodological gaps in the current research landscape. The key findings are: 71% of studies aim to understand thermal comfort in outdoor urban spaces. 12% focus on heat mitigation strategies like integrating vegetation and shaded shelters. 5% explore the impact of urban greenery on pedestrian comfort. In terms of geographical distribution, 56.20% of the studies were conducted in Asia, 21.49% in Europe, but only 3.31% in Africa and 3.30% in North America. Use of thermal comfort indices: Out of 165 developed indices, PET and UTCI are the most widely used due to user-friendly software. Under-explored regions: Africa, North America, and Australia offer significant potential for future OTC studies.	(Kumar and Sharma, 2020b)
Several cities	Global	The study highlights an overreliance on single climatic variables and the need to integrate thermophysiological indices. It points to a gap between qualitative and quantitative assessments and confirms the superior impact of green spaces on thermal comfort. The effects of canopies and surface materials, as do water/misting systems, require further research. Finally, strengthening the links between urban planning and climatology is essential, particularly in Mediterranean regions.	(Santos Nouri et al., 2018)
Several cities	Cfa, Cfb, Csa, Dfb	Outdoor spaces are crucial for urban quality of life and sustainability, as they promote pedestrian and social activities. However, outdoor thermal comfort is complex and influenced by climatic, physical, physiological, psychological, and behavioural dimensions. A multidimensional approach, combining local climatic conditions with human perceptions	(Chen and Ng, 2012a)

		and behaviours, is necessary to assess this comfort. The quality and location of infrastructures significantly impact the use of public spaces. This highlights the need for predictive tools to guide urban design. These tools should allow for the simulation of different scenarios and anticipate the impact of microclimatic conditions. Tools like ENVI-met and agent-based simulation systems are essential for integrating these dimensions into the analysis of outdoor thermal comfort. .	
Guangzhou (China)	Cfa	This study evaluates outdoor thermal comfort using two indices: PET (Physiological Equivalent Temperature) and UTCI (Universal Thermal Climate Index). - PET has a linear relationship with operative temperature. Below 32°C, air velocity improves PET, while factors like humidity, clothing insulation, and metabolic rate have minimal impact. - UTCI shows an exponential relationship with operative temperature. As temperature increases, the effect of air velocity decreases, but relative humidity has a more pronounced effect. - A field survey revealed that metabolic rate and clothing insulation adjust with weather conditions, impacting thermal comfort sensations. In summary, both PET and UTCI are essential for assessing outdoor thermal comfort, but they respond differently to environmental and personal factors.	(Fang et al., 2018)
Guangzhou (China)	Cfa	This study on outdoor thermal comfort in a humid subtropical region of China reveals several key findings. The neutral PET values were 15.6°C in winter and 25.6°C in spring, with no neutral value in summer. The comfortable temperatures were 18.8°C in winter and 30°C in spring, while residents preferred lower values in summer. Behavioural adjustments indicated that residents favoured sunny areas in winter and shaded areas in summer, with attendance peaks occurring at specific times based on the seasons. The acceptable PET range was found to be 18.1°C to 31.1°C,	(Li et al., 2016)

		which is broader than that observed in other regions. The study emphasizes the importance of incorporating sunny and shaded spaces into outdoor design to enhance thermal comfort and utilization rates.	
		Studies on global warming and climate change	
Madrid (Spain)	Csa	The study by Aram et al. emphasizes the significance of large urban parks, such as Retiro Park in Madrid, in enhancing thermal comfort in densely populated cities. It reveals that air temperatures are reduced by 1.6 °C at 130 meters and 0.9 °C at 280 meters from the park compared to a heat island area, while over 81% of respondents view the park as the place providing the highest level of thermal comfort. The study also highlights the crucial role of urban structure, topography, and building aspect ratio in the park's cooling effectiveness, confirming that these green spaces are essential for mitigating heat island effects and supporting sustainable development goals.	(Aram et al., 2020)
Taichung (Taiwan)	Cfa	The study examines the effects of urbanization and urban heat islands (UHI) on thermal comfort, noting significant increases in ambient temperatures that heighten the risk of overheating and diminish residents' quality of life. UHI has led to temperature rises of up to 3.2 °C between 1979 and 2003, with projections indicating further increases through 2039 and even more severe impacts expected by 2075–2099. These rising temperatures create uncomfortable living conditions, especially in summer, affecting outdoor activities and overall well-being. The dynamic modeling reveals the spatial impacts of UHI on thermal comfort, underscoring the need for effective adaptation strategies, such as increasing urban vegetation and using reflective materials to improve outdoor comfort and urban climate.	(Hwang et al., 2017)
Gothenburg (Sweden)	Cfb	The study of Thorsson examines the spatial and temporal variations of mean radiant temperatures (Tmrt) and thermal comfort in the compact city of Gothenburg, Sweden, under the influence of climate change projected for 2080-2099. The results indicate that urban geometry creates significant differences in Tmrt, particularly during the summer months. Open spaces are warmer than narrow streets in summer, with Tmrt discrepancies reaching up to 21.4 °C. By the end of the century, Tmrt is expected to rise by 3.2 °C, which is 0.4 °C higher than the projected increase in air temperature (2.8 °C), largely due to a decrease in summer cloud cover. The duration of extreme thermal stress will triple, reaching 20 to 100 hours per year depending on the urban configuration, while intense thermal stress periods in winter will decrease by 400 to 450 hours.	(Thorsson et al., 2011b)

Galicia (Spain)	Cfb	This study on the climate of Galicia, Spain, reveals concerning heat conditions due to climate change, with average temperatures of 20°C in summer and 6°C in winter, alongside a relative humidity reaching 70% throughout the year, resulting in humidex values exceeding 23 in July. An analysis of 50 weather stations over 10 years identified high-risk areas, particularly near the city of Ourense, where maximum summer temperatures can exceed 35°C. Projections indicate an average temperature increase of 1.35°C over the next 20 years, with a peak of 1.89°C in spring and a maximum projected humidex of 43 by 2030, which is considered dangerous. The urban heat island effect exacerbates health risks, necessitating prevention strategies based on the humidex index for better urban design and reduced energy consumption.	(Orosa et al., 2014)
Several cities	Global	In the study by Akbari et al., it is demonstrated that the urban heat island (UHI) phenomenon can lead to temperature increases of up to 10°C in cities, significantly impacting energy consumption, which can rise by 5 to 10%. To address this issue, mitigation technologies such as cool roofs—capable of reducing surface temperatures by 20 to 40°C—and green spaces—which can lower temperatures by 2 to 4°C—can decrease urban temperatures by as much as 3°C. These measures can result in energy savings of up to 20% and improve air quality by 10 to 20%. Global initiatives like the "100 Cool Cities" program promote the adoption of context-specific solutions supported by international standards. Additionally, it is crucial to develop tailored materials and programs for each city in collaboration with local policymakers to maximize climatic and energy benefits.	(Akbari et al., 2015)
Tolga (Algeria)	Bwh	The study reveals a significant increase in thermal stress in the multifamily housing neighborhoods of the Tolga Oasis region in Algeria, with projected rises in the Perceived Temperature (PT) index of 5.9 °C by 2050 and 7.7 °C by 2080 compared to 2020. The comfortable thermal zone is expected to decline dramatically from 25% in 2020 to 1% by 2050 and ultimately 0% by 2080, indicating a concerning deterioration of thermal conditions. A new algorithm has been developed to predict outdoor thermal comfort over short, medium, and long-term periods, highlighting the vulnerability of urban forms to climate change. The study emphasizes the need for urban planners and architects to incorporate these projections into their designs. It calls for the Algerian government to revise urban housing strategies to address anticipated extreme weather conditions.	(Matallah et al., 2021c)
Studies on outdoor thermal comfort in traditional cities and Mediterranean region			

Rome (Italy)	Csa	The study of Satala on outdoor thermal comfort in Rome was conducted using 1,009 questionnaires, of which 941 were valid. The neutral Physiological Equivalent Temperature (PET) values were established at 26.9 °C for the hot season and 24.9 °C for the cool season, while the preferred values were 24.8 °C and 22.5 °C, respectively. The comfort range for PET was defined between 21.1 and 29.2 °C, corresponding to the ASHRAE 7-point scale. The newly created index, the Mediterranean Outdoor Comfort Index (MOCI), allows for the evaluation of thermal comfort, and the Predicted Percentage of Dissatisfied (PPD) relationship has been adapted for this population. These results can serve as tools to optimize thermal comfort in Mediterranean urban spaces.	(Salata et al., 2016b)
Several cities	Csa, Cfa, Cfb	The study found that biometeorological indices (PET, THI, K) correlate strongly with mean climatic temperature, leading to misclassifications of outdoor thermal comfort sensations. For the "very cold" ASV class in winter, R2R^2R2 was 0.80 for PET and 0.67 for THI, often misclassifying extreme sensations into adjacent classes. Adjustments yielded minor improvements, with Somers' D rising from 0.43 to 0.50 for PET and from 0.29 to 0.46 for K, but no polynomial models outperformed first-order linear ones. Overall, the findings emphasize the indices' limitations in accurately capturing outdoor thermal comfort, highlighting the need for reformulation to improve adaptability.	(Tseliou et al., 2010b)
Konya, (Turkey)	BSh	The study on outdoor thermal comfort in Konya, Central Anatolia, revealed key findings regarding summer thermal perceptions: The Neutral PET (Physiological Equivalent Temperature) was 26.8 °C, and the Preferred PET was 19.2 °C, with a Comfort Range of 21.6 °C to 32.0 °C. 54% of participants experienced PET values above 32 °C, leading to 60.8% reporting discomfort, while only 33% found the outdoor conditions comfortable. Meanwhile, 64.3% preferred cooler temperatures. These results emphasize the importance of green spaces in reducing summer heat and the need for thermal comfort indices to improve residents' quality of life.	(Canan et al., 2019)
Rome, (Italy)	Csa	This study investigates the impact of innovative materials, such as colored mortars incorporating infrared (IR) reflective pigments, on outdoor thermal comfort in historical urban canyons. The materials examined aim to mitigate the effects of urban heat islands by enhancing the albedo of exposed surfaces. The key findings are:	(Rosso et al., 2018b)

		An increase in albedo from 0.10 to 0.25, leading to a surface temperature reduction of up to 2°C. The use of marble paving stones decreases the MOCI index by 5 to 6°C and the PMV index by 0.3 units, improving pedestrian thermal comfort. Applying these materials also reduced the energy consumption of surrounding buildings by 15%, contributing to urban sustainability.	
Barcelona, (Spain)	Csa	The study on Barcelona's thermal bioclimate shows that shading is the most effective strategy for improving urban thermal comfort, particularly during periods of heat stress (PET > 29°C). Between 2001 and 2015, 45.5% of hours were classified as comfortable (13°C < PET < 29°C), while 44.8% were considered cold (PET < 13°C), and only 9.5% of the time experienced heat stress (PET > 29°C). Increasing wind speed helps reduce heat discomfort in summer, especially when PET exceeds 35°C while reducing wind speed improves comfort during cold conditions (PET < 18°C) in winter. These findings highlight the importance of shading and wind management in enhancing outdoor thermal comfort, with considerations for street orientation and urban vegetation.	(Rodríguez Algeciras and Matzarakis, 2016)

3 Methodology:

The paper's conceptual framework outlines a systematic research methodology, as illustrated in Figure 19. The framework integrates three key methods: literature review, in-situ measurement of microclimatic data, and numerical simulations. The study begins with a presentation of the literature review and selection criteria, followed by a measurement campaign. Subsequently, the model for the four study areas is developed, involving the characterization of urban geometry and building properties to calibrate the simulated model with the real-world model.

The next step involves simulating climate scenarios using data from 1989, 2020, and future projections for 2050 and 2090, considering RCP 4.5 and 8.5. The PET Index is calculated for each scenario. Finally, a comprehensive analysis of the results is performed during the data post-processing phase. The design/investigation criteria, goal, principles, and objectives are intended to guide architects in integrating climate-responsive strategies into their designs, ensuring that urban spaces remain comfortable and sustainable in the face of climate change.

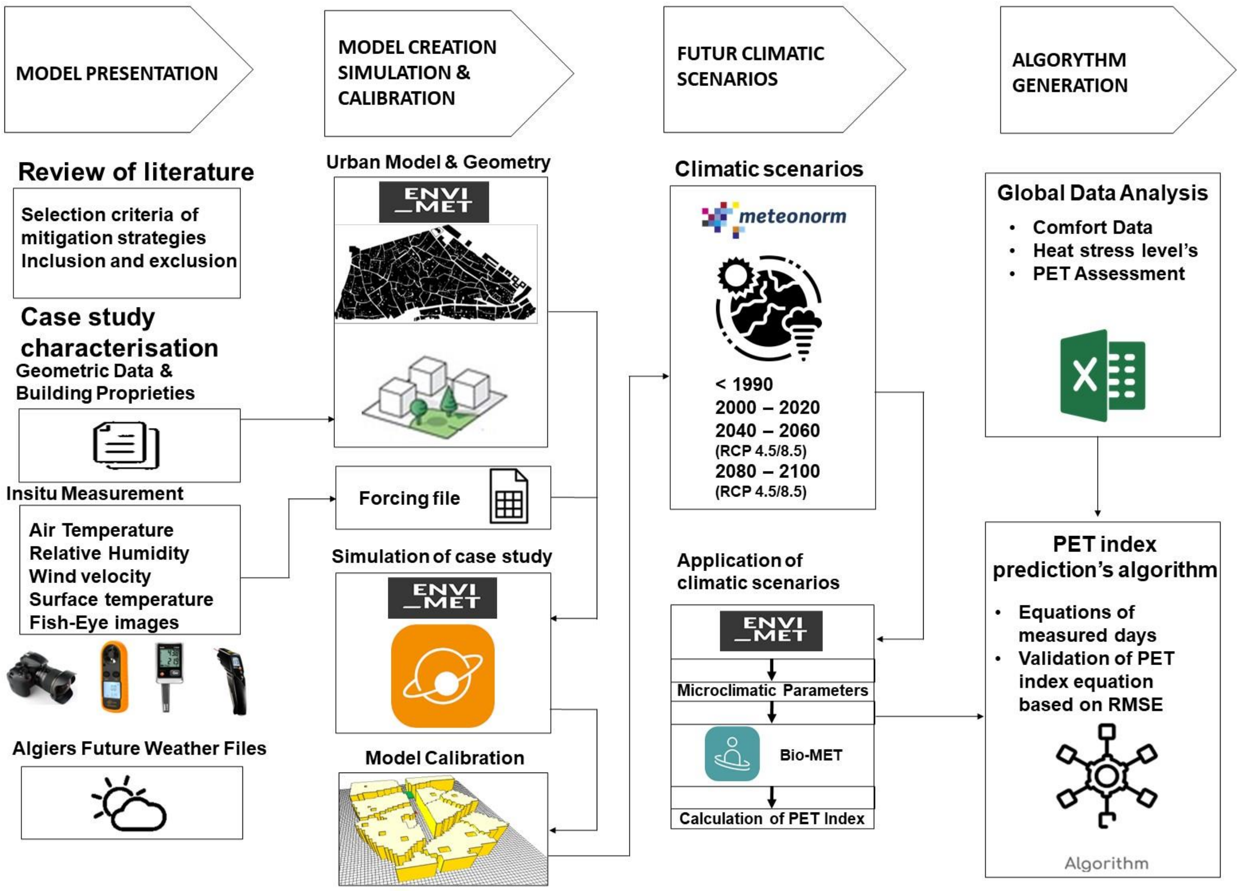


Figure 19: Study conceptual framework

3.1. Case study characterization

The study was conducted to examine the outdoor thermal comfort within a specific area. It took into account several factors, including solar radiation, the thermal properties of materials, urban airflow patterns, and human activities. In order to assess the influence of microclimatic conditions, measurements were collected at multiple locations that varied in terms of sky view factors, street types, and orientations. To ensure the accuracy of the results, a carefully defined time-based protocol was established for conducting field measurements, effectively minimizing potential sources of interference.

Figure 21 provides a comprehensive breakdown of urban morphological characteristics. To examine the diverse urban morphology, four specific measurement points were carefully chosen. Our in-situ measurements involved the use of recently acquired instruments to record various microclimate parameters, namely Air temperature (Ta), Relative humidity (RH), Wind speed (WS), and Surface temperature (TS). In addition to these measurements, Fish-eye images were captured to evaluate the degree of exposure to the sky (Table 10).

We selected four key sites that are the most representative of the Casbah of Algiers. These include urban canyons of varying widths and heights, as well as a public square. These urban morphologies were chosen based on their orientation and height-to-width ratios. A prior study, which analyzed a wide range of measurement cases, included a comprehensive PET assessment. From this research, we identified these four distinctive sites, characterized by their height-to-width ratio, orientation, presence or absence of vegetation, and sun exposure. This analysis, detailed in the paper (Arrar et al., 2022f), involved in-situ measurements using the equipment described in Section 3.1.2.

Figure 20 : Morphological parameters of the selected sites in the Casbah of Algiers

3.1.1. Insitu measurement:

The research employed a rigorous scientific methodology to investigate the concept of outdoor thermal comfort, offering a concise overview. This approach involved using precise measurement techniques and specialized instruments to record a range of microclimatic variables at multiple locations within the study area, as presented in Table 11. The resulting dataset is now available for future research endeavours and in-depth analysis (Arrar et al., 2022c).

Table 10: Fish-Eye and Meteorological Tools Used for the Study

	Fish-Eye Images Parameters				
	Camera	**Focal length**	**Resolution**	**Dimensions**	**Colors representation**
(a)	Canon EOS 1100 D	32mm	230000 pixels	4272 x 2848	sRGB
	Meteorological Data Parameters				
	Variable	**Device**	**Unit**	**Accuracy**	**Range**
(b)	Air temperature (T_a)	Testo 175H1	°C	± 0.4 °C	-20 to +55 °C
(b)	Relative Humidity (R_H)	Testo 175H1	°C	± 2%	0 to 100 %RH*
(c)	Wind Veloc(Bruse, 2004)ity (V_a)	PEAKMETER PM6252A	m/s	± 0,1m/s	0.2 to 30.0 m/s
(d)	Surface temperature (T_s)	Testo 830-T2	°C	±1.5 °C	-30 to +400 °C

This research aimed to investigate the outdoor thermal comfort experienced in the streets of the Casbah of Algiers, particularly in diverse climatic scenarios, using the Physiological Equivalent Temperature (P.E.T). In order to accomplish this goal, on-site measurements played a pivotal role in fine-tuning our simulation models. We collected data on several key variables, including air temperature (Ta), relative humidity (RH), wind speed (WS), and surface temperature (TS). Additionally, we employed fish-eye imagery to assess the degree of openness to the sky.

Our study involved comparing the influence of microclimatic conditions by conducting measurements at various locations with different sky view factors, street types, and orientations. To ensure the accuracy and reliability of our findings, we established a well-defined time protocol for conducting field measurements, minimizing the potential for external interference. The details of the study site modeling using the ENVI-met software are presented in Table 11.

3.1.2. Algiers current and future weather files:

a. Algiers current weather :

The Mediterranean area has been identified as a region significantly impacted by climate change, with distinct increases in temperature during the summer and changes in rainfall patterns (Giorgi and Lionello, 2008; Lionello et al., 2012). Algiers is situated in the Warm Mediterranean Climate zone, known for its scorching summers, with typical high temperatures reaching 35°C on hot days and occasionally surging to 42°C. Conversely, the average temperature during the coldest month ranges from 0°C to 6°C. Over the past three decades, the meteorological station "Algiers 603900" has recorded the following data for heating and cooling degree days: 1440 heating degree days (HDD) and 956 cooling degree days (CDD). These statistics offer valuable insights into the energy requirements for heating and cooling in the area.

The importance of studying climate scenarios such as IPCC 4.5 and 8.5 cannot be overstated in the context of outdoor thermal comfort. These scenarios provide crucial insights into future climate trends and the potential impacts of climate change on thermal conditions in urban areas. By analyzing both scenarios, we can prepare for the worst-case scenario while also understanding the benefits of taking action to reduce emissions. This helps in designing more resilient urban environments and developing effective adaptation strategies for outdoor thermal comfort. It also provides a comprehensive view of how different levels of greenhouse gas emissions might impact public health, energy demand, and urban infrastructure. Given the already existing challenges in the Mediterranean region, including extreme summer temperatures and changes in rainfall, the implications of these climate projections on outdoor thermal comfort are significant. Understanding these future climate scenarios allows for better planning and management of outdoor spaces to ensure the health and comfort of urban populations in the face of a changing climate.

b. Algiers RCP 4.5 Scénario :

The RCP 4.5 scenario (Representative Concentration Pathway 4.5) is one of the greenhouse gas emission scenarios used by the Intergovernmental Panel on Climate Change (IPCC) to project future climate changes. Under the RCP 4.5 scenario, greenhouse gas emissions increase until 2050 and then begin to decrease due to policies aimed at reducing these emissions.

For the Mediterranean region, according to IPCC reports, projections under the RCP 4.5 scenario suggest an increase in the region's average temperature by around 1 to 2 degrees Celsius by mid-century (2050) and by 2.5 degrees Celsius by the end of the century (2090). Heatwaves in the Mediterranean region are already common, but climate change is expected to intensify them, making them more frequent, longer, and more intense.

It is important to note that these projections are subject to uncertainties and may vary depending on many factors, including actions taken to reduce greenhouse gas emissions.

c. Algiers RCP 8.5 Scénario :

The RCP 8.5 scenario, used by the IPCC to study future climate projections, envisions a continuous increase in greenhouse gas emissions without significant mitigation measures. This would result in a significant concentration of these gases in the atmosphere, and according to IPCC projections based on this scenario, significant temperature increases are expected by the end of the century.

In the Mediterranean region, these climate changes, such as rising temperatures and changes in precipitation patterns, are expected to have notable impacts. For instance, by the mid-century (around 2050), the average temperature in the region is estimated to increase by 1.5°C to 2.5°C compared to pre-industrial levels. These trends are projected to intensify by the end of the century (around 2090), with more pronounced increases generally ranging from 3°C to 5°C above pre-industrial levels.

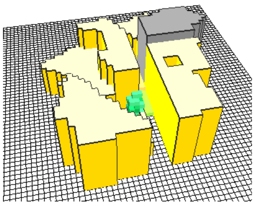
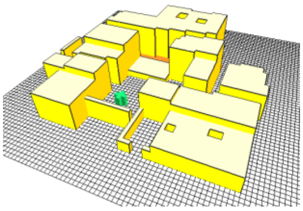
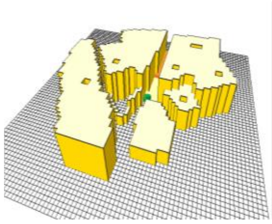
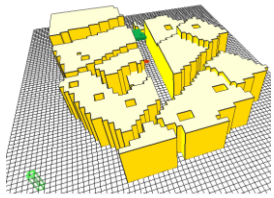
As for precipitation, while specific projections vary, many studies indicate a trend towards decreased rainfall in certain parts of the Mediterranean region, especially during summers. This could exacerbate issues of water stress and increase the risk of drought.

3.2. Simulation Model and Outdoor Thermal Comfort Assessment:

3.2.1. Urban model & geometry:

Table 11: Input of data for the models of the four sites in ENVI-met software.

Position	Zone 1	Zone 2	Zone 3	Zone 4
Street orientation	E-W	N-S	E-W	N-S
Longitude (°)	36.78	36.78	36.78	36.78
Latitude (°)	3.05	3.05	3.05	3.05
Grid size	71 m × 63 m	76 m × 76 m	71 m × 71 m	84 m × 69 m
Dx – Dy - Dz = size of grid	1m x 1m x 1m	1m x 1m x 1m	1m x 1m x 1m	1m x 1m x 1m
DEM Levels in model	0.00 m to 3.00 m	0.00 m to 2.00 m	0.00 m to 2.00 m	0.00 m
Building material	Walls: - Created wall: W1: Terracotta;Lime mortar;Lime plaster W2:Concrete wall (hollow block)	Walls: - Created wall: Terracotta;Lime mortar;Lime plaster	Walls: - Created wall: Terracotta;Lime mortar;Lime plaster	Walls: - Created wall: Terracotta;Lime mortar;Lime plaster
	Roofs: Created roof: Terracotta;Lime mortar;Lime plaster	Roofs: Created roof: Terracotta;Lime mortar;Lime plaster	Roofs: Created roof: Terracotta;Lime mortar;Lime plaster	Roofs: Created roof: Terracotta;Lime mortar;Lime plaster
Soil	Granit pavement (single stones) Granit shining Loamy soil	Granit pavement (single stones) Concrete pavement gray Granit shining Loamy soil	Granit pavement (single stones) Granit shining Loamy soil	Granit pavement (single stones) Granit shining Loamy soil
Vegetation	Robinia / False Acacia (Young) (7.31m)	Palm,small trunk,dense, small (5m)	Created tree: spherical (small trunk. sparse.small (5 m)	Hanging vegetation (50cm)

3D model				
		Simulation		
Start Date	08.08.2021	08.08.2021	08.08.2021	08.08.2021
Start time	00h00	00h00	00h00	00h00
simulation time	72h	72h	72h	72h
Time Step	2s	2s	2s	2s
Surface data iteration	15	15	15	15
Wind iteration	450	450	450	450
Radiation iteration	300	300	300	300
Plant data iteration	300	300	300	300
Type of meteorological boundary conditions	Full forcing - CSV	Full forcing - CSV	Full forcing - CSV	Full forcing - CSV

3.2.2. Meteorological parameters forcing :

We opted for the comprehensive approach by selecting the "full forcing" option when configuring microclimatic parameters in our study. To ensure the accuracy and completeness of our meteorological inputs, we relied on CSV files containing a wide range of meteorological parameters that were recorded at specific monitoring sites. These CSV files were integrated into the ENVI-met software through its full forcing manager settings.

It's important to note that these CSV data files encompassed every relevant meteorological parameter monitored during our in-situ data collection period, which took place from August 5th to 11th, 2021. This meticulous inclusion of meteorological data not only enhances the precision of our study but also allows us to comprehensively model and analyze the microclimatic conditions during that specific timeframe.

3.2.3. Simulation of case study :

ENVI-met is a specialized software used to analyze microclimates by simulating interactions between buildings, soil, vegetation, and air. It replicates key atmospheric processes and is widely used in urban planning and landscape architecture to address air quality and the heat island effect. Microclimatic data points were selected based on typologies from (Arrar et al., 2022f). , focusing on path usage, height-to-width ratio, and sun exposure via the sky view factor. ENVI-met was chosen for its accuracy in simulating urban microclimates, generating outputs like BIOMET data, heatmaps, and microclimatic indices, such as air temperature, humidity, surface temperature, and radiant temperature (Table 3 settings).

ENVI-met's three-dimensional, non-hydrostatic microclimate modeling provides high spatial resolution and time precision, with grid resolutions of 0.5 to 10 meters and time steps of 1 to 5 seconds (Taleghani et al., 2015b). Its ability to simulate urban climates makes it computationally demanding but highly detailed. The software is validated for urban microclimate assessment and is known for its capacity to calculate mean radiant temperature (Tmrt) (Matallah et al., 2021d). considering short-wave and long-wave radiation fluxes from surfaces and the atmosphere (Ali-Toudert and Mayer, 2007b). ENVI-met is also essential for outdoor thermal comfort simulations (Tsoka et al., 2018).

The study focused on four parameters required for calculating the Physiologically Equivalent Temperature (PET): air temperature, relative humidity, wind speed, and mean radiant temperature (Huttner and Bruse, 2008).

In the modeling process, the study areas were set up in the "SPACES" workspace, where geographic coordinates, grid dimensions, and rotation were defined. 2D drawings based on existing plans were incorporated, and building materials, heights, and vegetation types were specified using ENVI-met’s "DB Manager" tool Table 03. Output data was generated in 60-minute intervals, covering building, radiation, soil, and vegetation data.

- Time step T0 (2s) - Time step T1 (2s) - Time step T2 (1s).

Concerning update timing, we relied on the default values provided by the software:

Plant processes: 600s ; Surface Data: 30s ; Radiation and Shadows: 600s ; Flow field: 900s

Hence, we can determine the number of iterations as follows:

$$\boldsymbol{Number\ of\ iterations} = \frac{\text{Simulaion Time Step}}{\text{Update interval}} \quad (1)$$

In summary, ENVI-met is a sophisticated and widely recognized software tool used for detailed microclimate modeling in urban environments. It offers high spatial resolution, accurate simulations, and the ability to analyze various meteorological parameters critical for assessing outdoor thermal comfort and urban planning. Your modeling process involved setting up the study areas, specifying geometric details, and defining material properties to create a comprehensive simulation in ENVI-met.

3.2.4. Model Calibration:

In this research, we conducted a comparative analysis between the data obtained through measurements and those generated by the ENVI-met model simulation. The primary objective of this step was to assess the accuracy and reliability of the ENVI-met model in reproducing real-world conditions. To be considered adequately calibrated, it was imperative to ensure that the model's outputs fell within the limits defined by ASHRAE Guideline 14 for neighborhood-level models. According to ASHRAE Guideline 14, acceptable calibration thresholds require the Normalized Mean Bias Error (NMBE) to be within ±5% and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) not to exceed 15% for monthly data, ensuring that the model’s performance closely aligns with observed conditions.

Root Mean Square Error (RMSE): This metric quantifies how closely the simulation model matches the variability observed in the measured data. Essentially, it measures the degree to which the model accurately captures the fluctuations present in real-world data.

Mean Bias Error (MBE): MBE is a dimensionless measure that provides insight into the overall bias or systematic error between the measured and simulated data, with a specific focus on time resolution. (Attia et al., 2021).

Furthermore, this validation process centered on the parameter of "air temperature," which was analyzed over a continuous 72-hour simulation period, aligning with the approach suggested by Taleghani (Taleghani et al., 2014b) Table 12 summarizes the validation results for the simulated models across the four zones under consideration. For our study, the validation and correlation between the simulated and measured data are presented in Figures 22 and 23.

$$\boldsymbol{RMSE} = \sqrt{\frac{\boldsymbol{1}}{\boldsymbol{n}} \cdot \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} (\boldsymbol{Sim_i} - \boldsymbol{Obs_i})^2} (\%) \quad (1)$$

$$\boldsymbol{MBE} = \frac{\boldsymbol{1}}{\boldsymbol{n}} \cdot \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} (\boldsymbol{Sim_i} - \boldsymbol{Obs_i}) \ (\%) \quad (2)$$

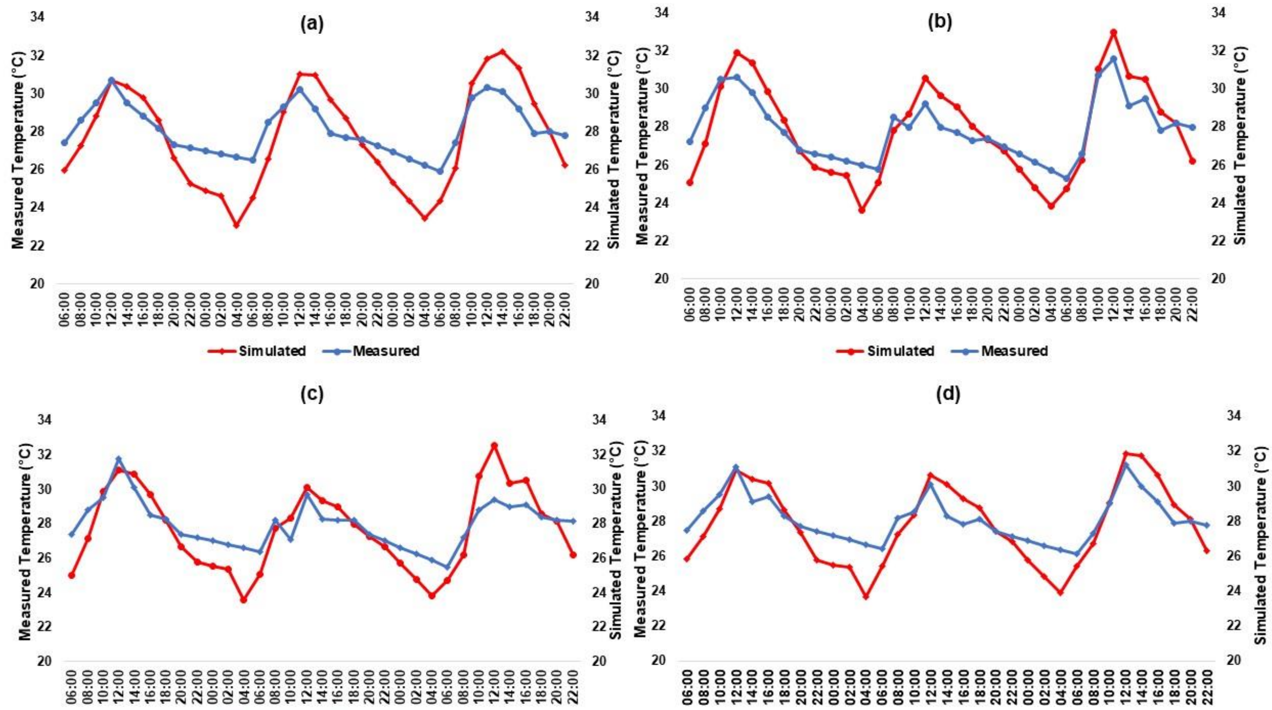


Figure 21: Validation measured/ simulated for 08-10.08.2021

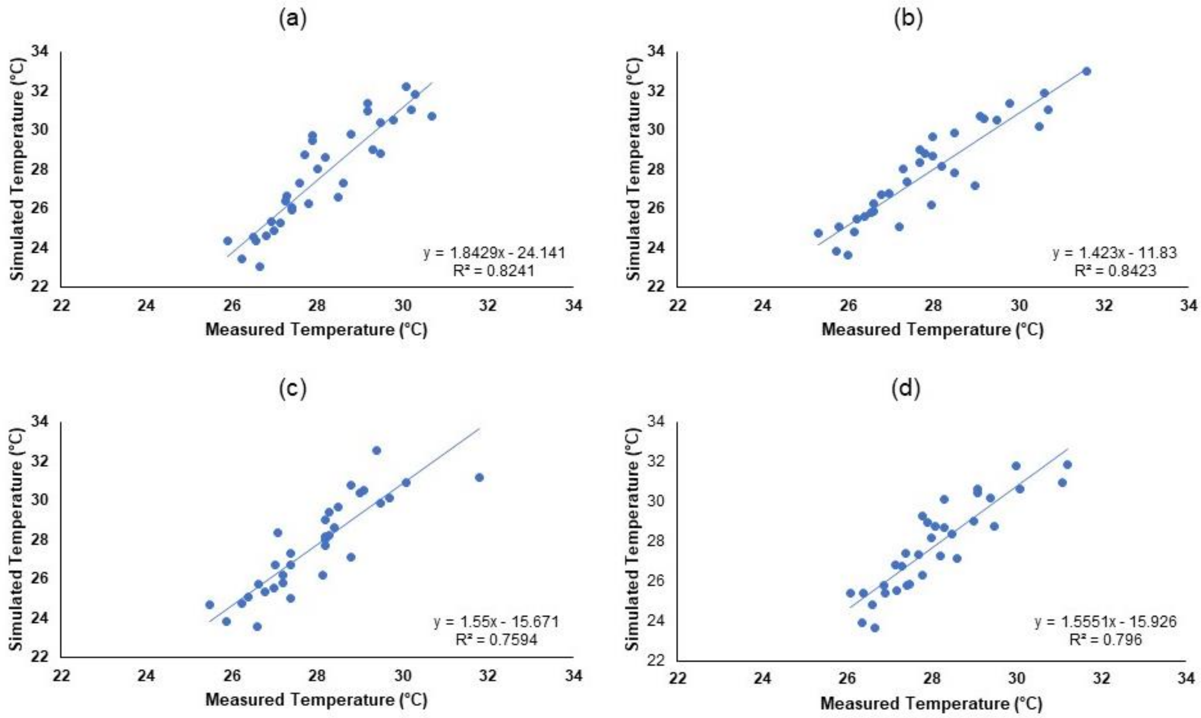


Figure 22: Correlation Air temperature measured/ simulated for 08-10.08.2021 (a. Zone 1 b. Zone 2 c. Zone 3 d. Zone 4)

Table 12: Validation of the model using RMSE / MBE

Zones	Zone 1	Zone 2	Zone 3	Zone 4
RMSE	1.61	1.19	1.39	1.28
	5.72%	4.26%	4.96%	4.55%
MBE	- 0.44	- 0.05	- 0.30	- 0.32
	- 1.56%	- 0.16%	- 1.06%	- 1.15%

According to ASHRAE Guideline 14, a simulation model is considered calibrated if it exhibits certain criteria. Specifically, the Mean Bias Error (MBE) should not exceed 10%, and the Root Mean Square Error (RMSE) should not exceed 30% when the calibration is performed using hourly data. It's worth noting that these criteria are crucial for ensuring the accuracy of the model's predictions.

While some previous research, such as (Sodoudi et al., 2018) et (Hien et al., 2012a), has conducted validation by running simulations for 48 hours and using air temperature as a parameter. We opted for a more rigorous approach by validating the model over 72 hours. This extended validation period enhances the precision of the model's predictions, as it allows for a more comprehensive assessment of its performance over a longer time frame.

It's also worth mentioning that the criteria for model accuracy, as defined by ASHRAE Guideline 14, have been adopted in various other studies as well. These studies, including those by (Ali-Toudert et al., 2005b),(Emmanuel and Fernando, 2007), and (Yang et al., 2013), have recognized the importance of adhering to these accuracy measures to ensure the reliability and applicability of simulation models in the field of building and environmental analysis.

3.3. Calculation process of PET Index:

3.3.1. Biomet

We conducted PET calculations using the ENVImet software, which allowed us to assess the thermal comfort conditions in a specific environment. The primary determinants in these calculations were mean radiant temperature (Tmrt) measured in degrees Celsius, as emphasized in the work of (Yung-Chang Chen and Matzarakis, 2014b). Additionally, we considered wind speed, measured in meters per second, and air temperature, measured in degrees Celsius, following the insights provided by (A. Matzarakis, 2018).

It's worth noting that relative humidity (RH) was included in our analysis, although it was found to have a relatively weak impact on PET, as reported by (Fröhlich and Matzarakis, 2016b). To evaluate the overall thermal comfort, we utilized a human energy balance equation that aligns with the Munich Energy Balance Model for Individuals (MEMI) developed by (P. Höppe, 1999). This equation allowed us to assess the thermal conditions more comprehensively, taking into account the interplay of these critical factors in determining PET.

$$M + W + R + C + E_{SK} + E_{RE} + E_{SW} + S = 0 \tag{3}$$

M: metabolic heat production	**E_{SK}:** latent heat (skin)
W: mechanical work	**E_{RE}:** latent heat (respiratory system)
R: fluxes of radiation	**E_{SW}:** latent heat sweating
C: sensible heat	**S:** heat storage

The ENVI-met software simulates atmospheric parameters and uses the BIO-met tool to calculate the Physiological Equivalent Temperature (PET) comfort index. This index is used to evaluate the thermal comfort of a space based on the simulated atmospheric parameters. The receiver is placed at the measurement point to obtain PET values corresponding to the actual space. After simulating the baseline conditions for the four zones, the 13 mitigation scenarios are also simulated. The PET results are classified into nine categories of thermal perception, ranging from very cold to very hot. After performing a CFD simulation using ENVI-met software and calculating PET using BIO-met in the targeted area, we analyzed the main results at a specific point of reference using the LEONARDO tool within ENVI-met. We generated then visual maps of PET at the height of 1.40m for all scenarios in the four designated zones at 12:00 pm.

3.3.2. IPCC Scenarios:

Using the same methodology followed for the calculation, this is carried out for all the following scenarios:

1989: The average global temperature was relatively stable, but since then, it has increased significantly, rising by 0.8 to 1.2 degrees Celsius compared to pre-industrial levels. This rise in temperatures has led to an increase in extreme weather events such as heat waves and intense precipitation.

2021: The reference scenario, also known as the contemporary scenario, is based on the year 2021 in our case. It describes the current trends in greenhouse gas emissions and human activities without any interventions to reduce them. It reflects a continued use of fossil fuels and other practices that generate emissions, thus contributing to climate change. This scenario is important for assessing the potential impacts of climate change and how trends would evolve in the future according to different scenarios.

2050 et 2090 en RCP 4.5: The RCP 4.5, or "Representative Concentration Pathway 4.5", is a greenhouse gas emission scenario employed by the Intergovernmental Panel on Climate Change (IPCC) for projecting future climate changes. It depicts a scenario wherein greenhouse gas emissions reach their peak in the mid-21st century and subsequently decrease gradually due to the implementation of policies and technologies aimed at curbing emissions. RCP 4.5 is typically viewed as an intermediate scenario in terms of the extent of efforts to reduce emissions compared to more extreme scenarios like RCP 8.5.

2050 et 2090 en RCP 8.5: The RCP 8.5, short for "Representative Concentration Pathway 8.5", represents one of the greenhouse gas emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). This scenario envisions a future where greenhouse gas emissions continue to rise without significant restriction, resulting in an atmospheric concentration of carbon dioxide (CO_2) reaching 936 ppm by 2100. This would lead to a significant increase in global temperature, exceeding pre-industrial levels by up to 4.8°C or more by the end of the century. Such a temperature rise would have serious consequences for natural and human systems.

3.4. Creation Algorithm:

In the course of our analyses, we developed a predictive model, denoted as Equation P, for hourly and annual forecasts of the Physiological Equivalent Temperature (PET). This model is based on specific days of measurement and relies on simulated outcomes. Essentially, Equation P is established by focusing on PET averages across all scenarios for the years 1989, 2020, 2050, and 2090 at four designated measurement points. The step-by-step construction of this equation (Figure 24) is elaborated in recurring stages:

Initially, we computed PET averages for the years 1989, 2020, 2050, and 2090 across all scenarios through a data simulation process. The resultant equations, incorporating novel variable forms (correction factors), amalgamate all previous scenario equations to form a singular, comprehensive prediction formula.

Subsequently, we assessed the prediction equation's accuracy using the Root Mean Squared Error (RMSE). The analysis indicated a preference for the first equation for overall predictions across diverse emission scenarios. As a result, a mathematically generated algorithm was formulated based on the chosen prediction equation from the validation process. Consequently, a precise validation equation displaying the lowest RMSE value was extracted from the initial prediction equation. The table analysis provides a detailed insight into predicting the Physiological Equivalent Temperature (PET) for various hours of the day in 2090. PET, which gauges the temperature experienced by the human body considering various meteorological factors, is estimated using intricate mathematical models.

Each prediction is based on a specific third-degree (cubic) equation, defined as follows:

$$y = ax^3 + bx^2 + cx + d$$

where a, b, c, and d are specific coefficients for each equation, and x represents a relevant meteorological variable. For example, for the prediction at 1:00, the equation is :

$$y = -0.805x^3 + 6.52x^2 - 15.655x + 26.295$$

The model's accuracy is evaluated using two statistical measures. The Root Mean Square Error (RMSE), measuring the average squared deviation between predicted and actual values, reaches 96.80%. The RMSE formula is defined as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

where n is the number of observations, yi is the observed values, and ŷi is the predicted values.

Likewise, the mean bias error (MBE), measuring the average of the absolute deviations between the predicted values and the actual values, stands at an impressive 99.30%. The MBE formula is defined as follows:

$$MBE = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i|}{n}$$

Adding an equation for converting years into decimals, denoted as the "Year Conversion Equation," brings an additional dimension to the analysis. This linear equation is expressed as:

$$y = 0{,}0299x - 58{,}39$$

where x represents the entry year, in addition, a binary-to-decimal conversion equation, denoted as 'From Binary to Decimals,' These conversion equations allows transforming input values into formats more suitable for subsequent calculations.

Lastly, the determination coefficient (R2) of 0.9953 underscores the model's outstanding alignment with real-world data. Calculated as the square of the correlation coefficient between predicted and observed values, the R2 indicates that the model accounts for approximately 99.53% of the variance in the data.

The predictive model relies on third-degree polynomial equations for PET estimations across 24 hourly intervals. Each equation is tailored for a specific hour, capturing the nuanced variation of PET during the day. By using averages from the four reference years (1989, 2020, 2050, 2090), the model incorporates long-term trends and climatic scenarios to ensure robustness against future uncertainties.

The use of correction factors integrates scenario-specific equations into a unified prediction model. This methodology enhances the model's generalization ability across diverse emission scenarios and meteorological variations. The RMSE value of 96.80% indicates that the model's predictions are close to observed values, with minimal error. The low bias (MBE of 99.30%) confirms that the model does not systematically overestimate or underestimate PET values. Together, these metrics validate the reliability of the model for long-term forecasting.

The inclusion of the Year Conversion Equation simplifies input processing, allowing for easier integration of chronological data into the polynomial equations. Binary-to-decimal conversion equations facilitate compatibility with computational frameworks that rely on binary inputs.

The R^2 value of 0.9953 indicates that the model explains nearly all variability in the PET data. This high explanatory power is critical for ensuring confidence in the predictions.

In practical terms, the hourly predictions can guide urban planners and policymakers in designing urban spaces, such as shading structures, green areas, and ventilation pathways, to optimize thermal comfort. The integration of diverse climatic scenarios equips policymakers with data-driven insights for adaptive strategies in the face of climate change. Moreover, providing accurate thermal comfort forecasts helps individuals and communities prepare for extreme weather conditions. Nonetheless, the model has some limitations. Its reliance on historical and simulated data may introduce biases if unforeseen climatic phenomena occur. Furthermore, its applicability outside the specified region and season requires additional validation.

In conclusion, the comprehensive information presented in the table, encompassing prediction equations, precision metrics, and conversion methodologies, provides a thorough grasp of PET modeling for the year. These particulars facilitate a comprehensive evaluation of expected thermal comfort based on projected meteorological conditions. The detailed analysis confirms the model's robustness while highlighting potential avenues for refinement and application in urban resilience planning.

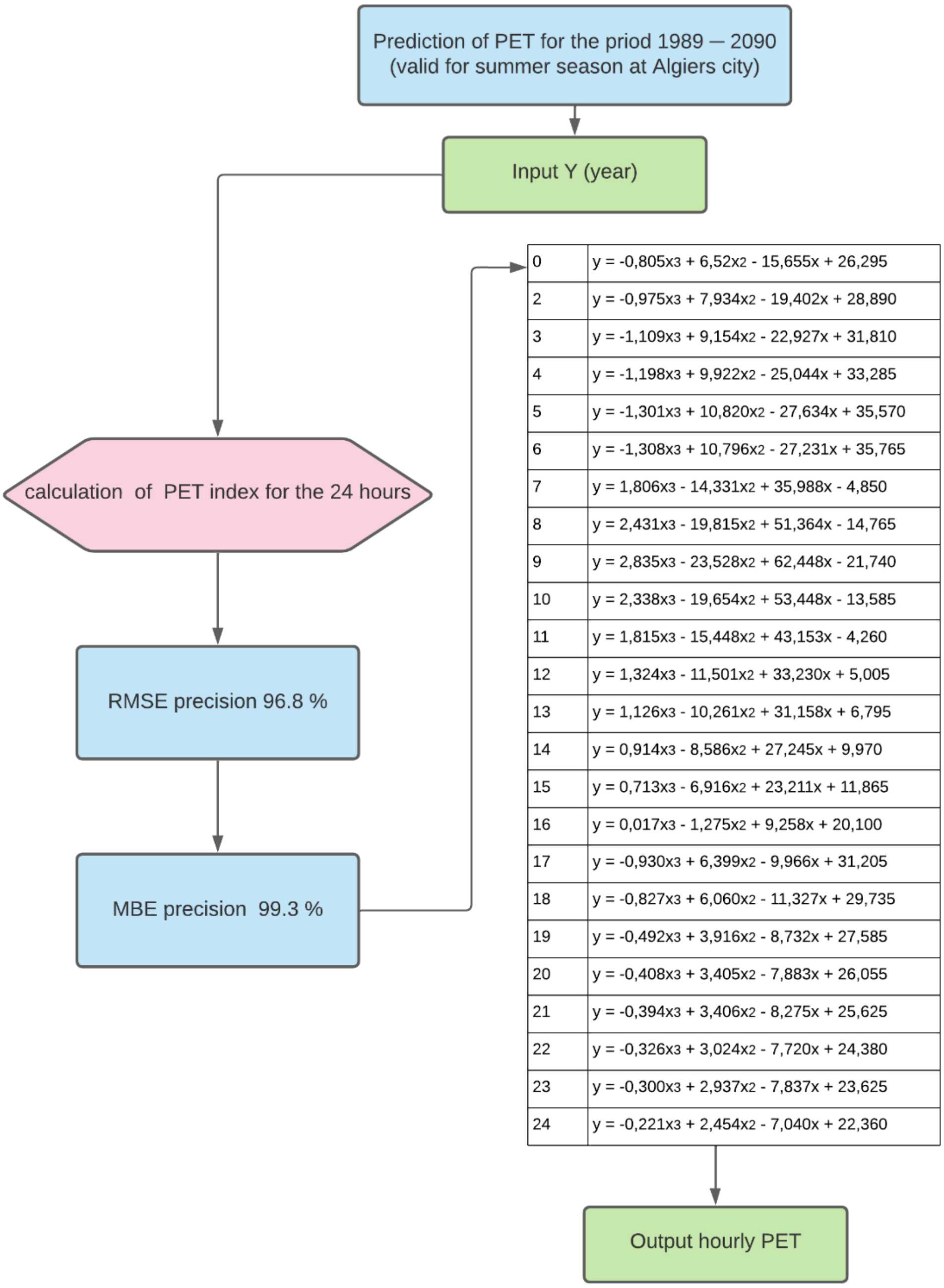


Figure 23: Algorithm generation

- **Error metrics :**

The detailed analysis of performance metrics provides significant insights into the model's robustness, particularly in its ability to predict the Physiological Equivalent Temperature (P.E.T). The Root Mean Square Error (RMSE), derived from the mean squared difference between observed (A) and predicted (B) values, is reported as 0.759. This metric is crucial as it quantifies the overall precision of the model. The RMSE formula, expressed as the square root of the mean of squared deviations, is: $RMSE = \sqrt{\frac{\sum(A-B)^2}{n}}$ where "n" represents the number of observations.

Similarly, the Mean Bias Error (MBE), defined as the average of the differences between observed and predicted values, indicates a slight average underestimation with a value of $MBE = \frac{\sum(B-A)}{n}$, The formula for MBE is crucial for understanding the model's tendency Py to deviate from actual values and for refining predictions.

The error percentages, expressing the Root MeaDn Square Error (RMSE) (2.84%) and MBE (-0.06%) in terms of percentage relative to actual values, add a significant dimension to the analysis. These values provide a relative assessment of errors, allowing a more intuitive understanding of the impact of deviations.

Regarding the Physiological Equivalent Temperature (P.E.T), the variances identified through these metrics play a crucial role in minimizing prediction errors. Negative and positive variances reveal the model's tendency to underestimate or overestimate PET, crucial information for adjusting model parameters to optimize performance. A detailed temporal analysis also highlights specific moments where adjustments may be necessary, contributing to targeted improvement of the model's accuracy. In summary, these metrics and analyses play an essential role in the evaluation and continuous improvement of the PET prediction model, ensuring accurate and reliable performance.

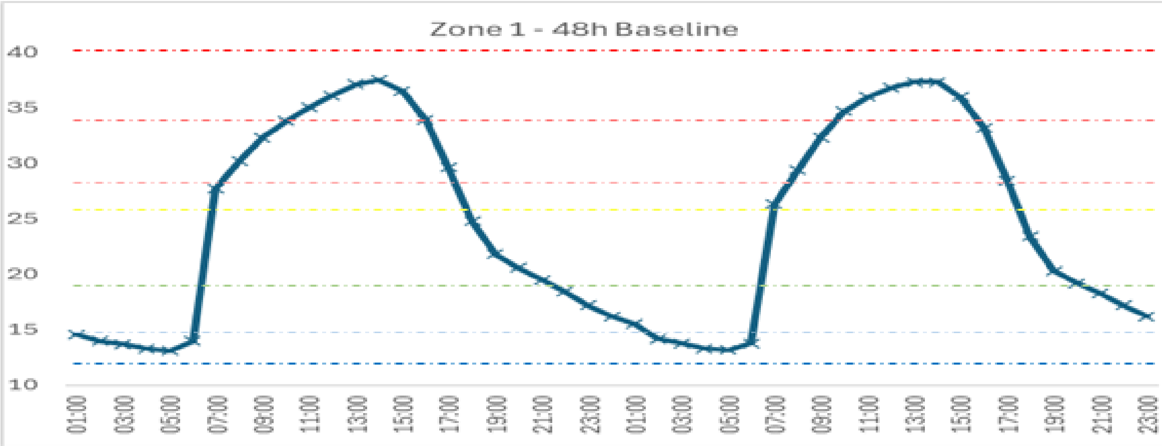
3.5. Results Visualisation:

We will present the results of our study using several graphical representations to enhance clarity and accessibility. A Climate Scenario Table will group the climate scenarios for four areas, color-coded to reflect heat stress levels for the years 1989, 2021, 2050 (average and pessimistic), and 2090 (average and pessimistic). Radar Charts will track changes in physiological equivalent temperature over time for each area. Boxplots will show the dispersion and variability of data for each area in each key year. An Algorithmic Project Plan Diagram will outline the steps of the algorithm used to generate the climate data. Finally, a Summary Table of Results will synthesize the average results produced by the algorithm for the four zones. These visualizations will provide a comprehensive and accessible overview of thermal stress evolution across the studied areas.

4 Results:

4.1. Future Climatic scenarios:

A. Zone 1:



(a)

Time	1989		Baseline - 2021		2050 Mid		2050 WS		2090 Mid		2090 WS	
	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th
00:00		17,5		16,2		17,2		18,5		19,2		22,7
01:00	16,4	16,6	14,6	15,5	16,3	16,4	16,1	18,1	16,5	19,0	19,9	22,0
02:00	16,5	15,6	14,0	14,2	15,8	15,4	15,7	17,3	15,9	18,4	19,9	21,4
03:00	17,0	15,1	13,7	13,8	15,5	14,9	15,4	16,8	15,6	18,5	19,7	21,0
04:00	17,1	14,1	13,3	13,3	15,1	14,4	15,1	16,4	15,2	18,4	19,5	20,6
05:00	17,5	13,7	13,1	13,2	14,9	14,1	15,1	15,9	14,9	18,5	19,5	20,6
06:00	18,1	14,4	14,0	13,8	15,9	15,2	16,2	16,7	15,9	19,1	20,4	21,3
07:00	18,7	29,0	27,7	26,3	23,9	23,1	28,8	26,6	28,7	21,2	25,7	26,9
08:00	19,3	30,8	30,2	29,4	27,4	27,2	30,1	28,3	31,2	25,2	30,3	30,5
09:00	20,1	32,9	32,3	32,3	31,0	31,1	33,8	32,1	33,6	30,2	35,8	33,6
10:00	22,5	34,1	33,8	34,7	33,3	33,9	36,0	34,8	35,7	35,8	38,8	36,2
11:00	25,1	32,7	35,0	36,0	35,4	36,1	37,8	36,8	37,6	38,4	40,2	38,1
12:00	27,8	30,8	36,1	36,8	36,9	37,7	38,6	38,5	38,7	37,6	40,9	38,8
13:00	28,7	30,6	37,1	37,3	38,3	38,8	39,2	39,9	39,4	37,0	41,3	40,4
14:00	29,4	29,6	37,5	37,3	39,2	38,8	39,3	40,3	40,2	35,6	42,3	40,7
15:00	28,8	27,6	36,5	36,0	38,7	38,3	37,7	39,7	40,0	31,9	38,8	39,7
16:00	28,1	26,1	33,9	33,2	37,1	36,6	35,3	37,2	38,2	28,7	35,5	37,7
17:00	26,7	22,9	29,6	28,4	34,1	32,2	31,6	32,5	34,5	25,3	32,2	34,7
18:00	23,7	20,8	24,8	23,4	28,3	26,6	27,3	27,3	28,8	23,9	29,1	30,1
19:00	22,3	19,3	21,8	20,3	23,3	22,2	24,4	22,8	23,8	22,7	27,1	25,6
20:00	21,2	18,4	20,6	19,2	22,0	21,0	23,1	21,8	22,9	22,4	26,6	24,0
21:00	20,4	17,6	19,5	18,3	20,7	19,9	22,0	20,8	21,8	21,6	25,4	22,9
22:00	19,3	16,5	18,4	17,2	19,5	18,8	20,8	19,7	20,9	21,3	24,6	21,7
23:00	18,4	15,6	17,2	16,2	18,4	17,9	19,7	18,8	20,0	20,7	23,7	20,7

	12 – 15	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal Comfort	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress Level	Moderate cold stress	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

(b)

Figure 24: PET Scenarios for Zone 1

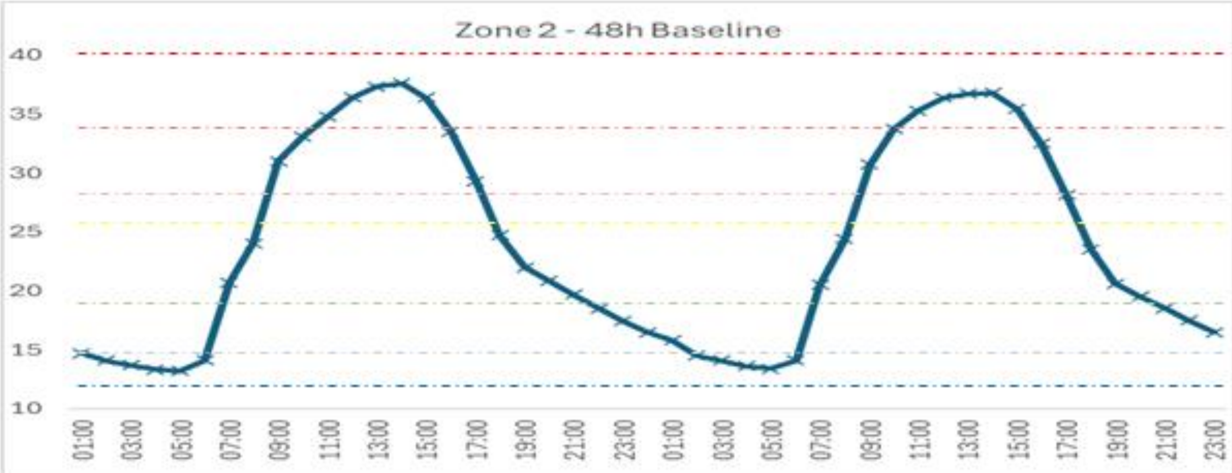
Figure 25 displays the Physiological Equivalent Temperature (PET) in measurement zone 1 from August 8 to August 9, 2021, across different scenarios: 1989, 2021, 2050, and 2090 in both normal and worst-case conditions. The analysis shows the evolution of temperatures throughout the day over multiple years.

Nighttime temperatures exhibit significant changes across the years and scenarios. In 1989, they were relatively cool, ranging from 16 to 17°C, with a low of 13.7°C on August 9. By 2021, the Baseline scenario saw a slight decline to around 13–14°C, causing moderate cold stress. The 2050 Mid scenario recorded a modest rise, reaching approximately 15°C with slight cold stress. In the 2050 Worst scenario, temperatures remained similar, mostly between 15 and 16°C, peaking at 18°C. The 2090 Mid scenario displayed a more pronounced increase, with temperatures around 15°C on August 8 and up to 18°C on August 9. Notably, the 2090 Worst scenario recorded significantly higher nighttime temperatures of 19 to 21°C, classified as neutral with no thermal stress.

Daytime temperatures show a dramatic rise across scenarios. In 1989, temperatures gradually increased from 18.7°C to a peak of 34.1°C on August 9, indicating moderate heat stress. The 2021 Baseline scenario continued this trend, reaching 37.5°C at midday, resulting in strong heat stress. In the 2050 Mid scenario, temperatures peaked at around 39.2°C at 14:00, indicating strong heat stress. The 2050 Worst scenario saw temperatures exceed 39°C from 13:00 to 14:00, peaking at 40.3°C, categorizing it as extreme heat stress. By 2090 Mid, temperatures surged to approximately 40°C at noon, denoting extreme heat stress from 10:00 to 13:00. The 2090 Worst scenario featured the highest temperatures, with extreme heat stress lasting six hours, peaking at 42.3°C from 11:00 to 14:00 on August 8 and again from 13:00 to 14:00 on August 9.

Evening and nighttime temperatures also demonstrate consistent trends. In 1989, temperatures dropped gradually from 22.3°C to 15.6°C, indicating slight cold discomfort. The 2021 Baseline scenario exhibited a similar pattern, remaining slightly higher at 24.8°C to 16.2°C. The 2050 Mid scenario kept comfort levels almost neutral, while the 2050 Worst scenario showed a slight increase to 24.4°C and 18.8°C. By 2090 Mid, nighttime temperatures reached around 21.3°C at 23:00. The 2090 Worst scenario recorded notably higher temperatures, nearing 24.6°C at 22:00, suggesting some discomfort due to heat.

B. Zone 2:



(a)

Time	1989		Baseline - 2021		2050 Mid		2050 WS		2090 Mid		2090 WS	
	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th
00:00		17,6		16,5		17,5		18,7		19,4		22,8
01:00	16,3	16,7	14,7	15,8	16,3	16,8	16,1	18,2	16,5	19,2	19,5	22,1
02:00	16,4	15,8	14,1	14,5	15,8	15,8	15,7	17,5	15,8	18,6	19,5	21,5
03:00	16,8	15,3	13,7	14,1	15,5	15,3	15,4	17,0	15,6	18,7	19,3	21,1
04:00	16,9	14,3	13,3	13,6	15,1	14,8	15,2	16,6	15,2	18,4	19,1	20,6
05:00	17,4	14,0	13,2	13,4	15,0	14,5	15,1	16,1	14,9	18,6	19,1	20,6
06:00	18,0	14,7	14,1	14,1	16,0	15,5	16,2	16,9	15,9	19,2	20,2	21,4
07:00	18,6	21,6	20,7	20,5	22,0	21,9	22,4	22,8	22,1	21,3	24,4	25,8
08:00	19,2	24,9	24,0	24,4	25,9	26,1	25,8	25,9	25,2	24,8	28,0	29,6
09:00	20,0	31,5	31,0	30,7	29,6	29,8	32,7	31,0	32,4	29,6	34,8	33,0
10:00	22,6	33,4	33,1	33,7	32,7	33,1	35,4	34,1	35,1	35,1	38,2	35,7
11:00	25,4	32,6	34,8	35,3	35,2	35,6	37,7	36,2	37,4	37,6	40,0	37,6
12:00	28,3	31,2	36,4	36,4	37,3	37,4	38,9	38,2	39,0	37,3	41,1	38,6
13:00	29,0	31,0	37,3	36,7	38,6	38,3	39,4	39,3	39,5	36,6	41,5	39,9
14:00	29,8	30,0	37,6	36,8	39,4	38,4	39,4	39,8	40,2	35,3	42,1	40,3
15:00	29,0	27,9	36,4	35,4	38,5	37,6	37,7	39,1	39,6	31,8	38,8	39,2
16:00	28,2	26,2	33,5	32,5	36,7	35,7	35,0	36,4	37,6	28,7	35,3	37,1
17:00	26,8	23,1	29,3	28,1	33,5	31,6	31,3	32,0	33,9	25,4	32,0	34,3
18:00	23,7	21,0	24,7	23,5	27,7	26,4	27,3	26,9	28,0	24,0	28,9	29,6
19:00	22,3	19,4	22,0	20,6	23,5	22,4	24,4	23,0	23,9	22,9	26,9	25,7
20:00	21,2	18,5	20,8	19,5	22,2	21,3	23,1	22,1	23,0	22,5	26,4	24,3
21:00	20,4	17,8	19,7	18,5	21,0	20,2	22,1	21,1	21,9	21,7	25,3	23,1
22:00	19,4	16,7	18,5	17,5	19,8	19,2	21,0	20,0	21,1	21,4	24,5	22,0
23:00	18,5	15,8	17,4	16,5	18,6	18,2	19,9	19,1	20,2	20,8	23,6	21,0

	12 – 15	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal Comfort	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress Level	Moderate cold stress	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

(b)

Figure 25:PET Scenarios for Zone 2

Figure 26 shows the physiological equivalent temperature (PET) data for measurement zone 2 across different years and climate scenarios from August 08 to August 09, 2021. The years examined are 1989, 2021, 2050, and 2090, including both normal and extreme climate scenarios for the 2050s and 2090s.

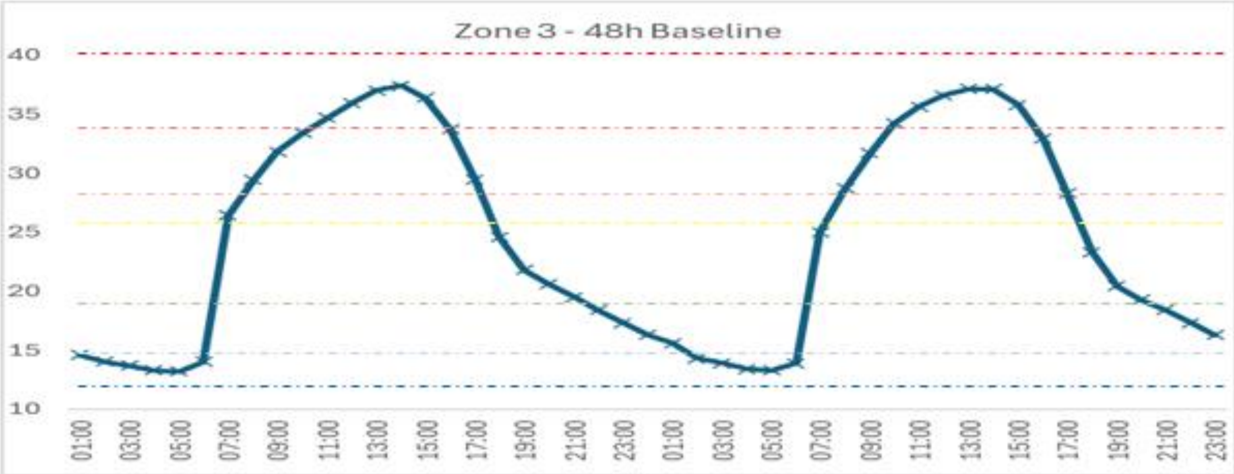
Night Period (01:00 to 06:00): In 1989, nights were relatively cool, with temperatures ranging from 14.0°C to 18.0°C, corresponding to mild cold heat stress. By 2021, early morning temperatures dropped to between 13.2°C and 16.5°C, indicating a moderately cool heat stress range. In the 2050 scenario, temperatures increase to 14.5°C to 17.5°C, shifting to slightly warm heat stress. For the 2090 scenarios, temperatures range from 14.9°C to 19.4°C, maintaining low to neutral heat stress.

Daytime Period (07:00 to 18:00): On August 8, 2021, daytime temperatures range from 18.6°C to 29.0°C, while August 9 sees a range from 21.6°C to 33.4°C, characterized by moderate heat stress. By 2050, temperatures rise significantly from 21.9°C to a peak of 39.4°C at 2 p.m., with mild heat stress persisting until 4 p.m. The extreme climate scenario for 2050WS shows slightly higher temperatures, reaching 39.8°C at the same time. In 2090, temperatures increase further, peaking at 40.2°C and leading to extreme heat stress during the day.

Evening Period (19:00 to 00:00): In 2021, evening temperatures are primarily in the neutral heat stress range, while the 2050 scenario shows a gradual decline but remains neutral. By 2090, evening temperatures drop from 23.9°C to 20.2°C, corresponding to a stress-free thermal comfort zone.

In the 2090 WS scenario, nights become significantly warmer, with temperatures reaching up to 22.8°C, allowing for thermal comfort. During the day, strong heat stress is observed from 9 a.m. to 4 p.m., with peak temperatures of 42.1°C on August 8.

C. **Zone 3:**



(a)

Time	1989		Baseline - 2021		2050 Mid		2050 WS		2090 Mid		2090 WS	
	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th
00:00		17,6		16,3		17,3		18,6		19,3		22,7
01:00	16,4	16,6	14,6	15,6	16,3	16,6	16,1	18,1	16,5	19,0	19,8	22,0
02:00	16,5	15,7	14,0	14,3	15,8	15,6	15,7	17,4	15,9	18,5	19,8	21,4
03:00	17,0	15,1	13,7	13,9	15,5	15,0	15,4	16,9	15,6	18,6	19,5	21,0
04:00	17,0	14,1	13,3	13,4	15,1	14,5	15,2	16,5	15,2	18,4	19,3	20,6
05:00	17,5	13,8	13,2	13,3	14,9	14,2	15,1	15,9	14,9	18,5	19,4	20,6
06:00	18,0	14,5	14,0	13,9	15,9	15,2	16,2	16,8	15,9	19,1	20,4	21,3
07:00	18,6	27,8	26,4	25,0	23,1	22,7	27,7	25,5	27,5	21,2	24,9	26,4
08:00	19,2	30,1	29,4	28,7	26,8	26,8	29,5	27,8	30,4	25,2	29,6	30,2
09:00	20,0	32,4	31,8	31,7	30,5	30,6	33,3	31,7	33,1	30,0	35,3	33,3
10:00	22,5	33,7	33,4	34,2	33,0	33,6	35,6	34,4	35,4	35,4	38,4	35,9
11:00	25,1	32,4	34,7	35,6	35,1	35,8	37,5	36,4	37,3	37,9	39,8	37,8
12:00	27,9	30,8	35,9	36,6	36,8	37,5	38,4	38,3	38,5	37,5	40,7	38,7
13:00	28,7	30,6	37,0	37,1	38,3	38,6	39,1	39,7	39,3	36,9	41,1	40,3
14:00	29,4	29,6	37,4	37,1	39,0	38,6	39,1	40,1	40,0	35,6	42,3	40,6
15:00	28,8	27,6	36,4	35,8	38,6	38,1	37,6	39,5	39,8	31,9	38,7	39,5
16:00	28,1	26,0	33,7	32,9	37,0	36,3	35,2	36,9	37,9	28,6	35,4	37,4
17:00	26,7	22,9	29,4	28,3	33,8	32,0	31,3	32,3	34,2	25,3	32,0	34,5
18:00	23,7	20,8	24,6	23,3	27,8	26,4	27,2	27,0	28,4	24,0	29,0	29,8
19:00	22,3	19,3	21,8	20,4	23,3	22,2	24,4	22,9	23,8	22,8	27,0	25,6
20:00	21,2	18,4	20,6	19,3	22,0	21,1	23,1	21,9	22,9	22,4	26,5	24,1
21:00	20,4	17,6	19,5	18,4	20,8	20,0	22,0	20,9	21,8	21,7	25,3	23,0
22:00	19,4	16,5	18,4	17,3	19,6	18,9	20,9	19,8	21,0	21,3	24,6	21,8
23:00	18,4	15,7	17,3	16,3	18,4	18,0	19,8	18,9	20,1	20,8	23,6	20,8

	12 – 15	15 – 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal Comfort	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress Level	Moderate cold stress	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

(b)

Figure 26: PET Scenarios for Zone 3

The data presented in Figure 27 illustrates the Physiological Equivalent Temperature (PET) in measurement zone 3 for various years and climate scenarios from August 08 to August 09, 2021. The years under consideration are 1989, 2021, 2050, and 2090, encompassing typical and extreme climate scenarios for the 2050s and 2090s.

1989 Scenario: During the nighttime period from 00:00 to 07:00, temperatures range from a low of 13.8°C at 05:00 on August 9th to a high of 18.0°C early on August 8th, generally experiencing slight cold stress. In the daytime (07:00 to 18:00), temperatures follow a rising and then descending pattern, starting at 18.6°C at 07:00 on August 8th. From 08:00 to 11:00, temperatures reach neutral comfort levels, followed by moderate heat stress from 12:00 to 17:00. On August 9th, temperatures peak at 33.7°C at 10:00, then decline but remain at moderate heat stress until 14:00. From 15:00 to 16:00, slight thermal stress occurs, transitioning to neutral comfort from 17:00 to 18:00. Evening temperatures decrease from 23.7°C at 18:00 to 18.4°C at 23:00 on August 8th, and from 20.8°C to 15.7°C at 23:00 on August 9th, resulting in generally neutral and slightly cool thermal comfort in the evenings.

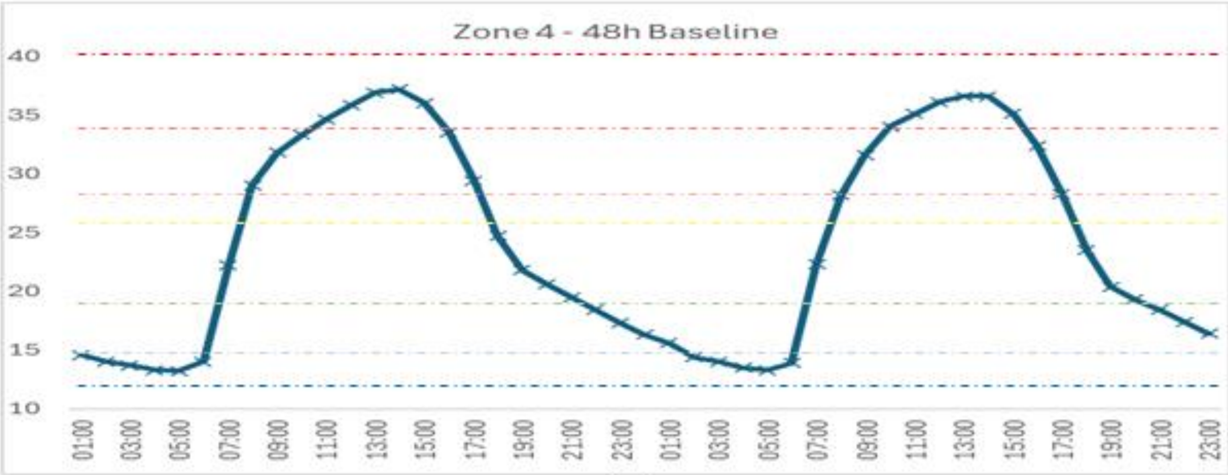
2021 Baseline Scenario: In this scenario, nighttime temperatures from 00:00 to 06:00 are cooler, averaging around 13.5°C, inducing moderate cold stress. Daytime temperatures show a notable increase in thermal stress compared to 1989, with high stress recorded from 10:00 to 15:00, peaking at 37.4°C at 14:00. Temperatures begin to decrease after 15:00, achieving thermal comfort at 18:00, with readings of 24.6°C on August 8th and 23.3°C on August 9th. Evening temperatures vary between neutral thermal stress and slight cold stress, ranging from 21.8°C to 16.3°C.

2050 Scenario: In 2050, temperatures primarily induce slight heat stress, occasionally reaching moderate stress. Nighttime temperatures drop to a low of 14.2°C at 05:00. Daytime temperatures increase until 14:00, peaking at 39°C, with strong thermal stress from 11:00 to 16:00. In the evening, from 19:00 to 23:00, temperatures remain in the neutral thermal zone, ranging from 18°C to 23.3°C. In the 2050WS scenario, temperatures are slightly higher, with a minimum of 15.2°C during the early hours and a peak of 40.1°C at 14:00, maintaining extreme stress levels. Evening temperatures are comparable to the 2050 scenario, with differences of only 0.9°C for minimums and 1°C for maximums.

2090 Scenario: In 2090, nighttime temperatures range from 14.9°C to 19.3°C, mostly within a slightly cool range, occasionally reaching moderate cold stress. Daytime temperatures rise from 27.5°C at 07:00 on August 8th to a peak of 40°C at 14:00, with strong thermal stress observed from 11:00 to 17:00. Evening temperatures gradually decrease from 28°C at 20:00 to 23°C at 23:00, mostly remaining in the neutral thermal stress zone.

In summary, the data highlights increasing thermal stress levels from 1989 to 2090, with significant changes in both nighttime and daytime temperatures across different scenarios. The progression indicates a shift from neutral and slightly cold thermal comfort towards predominantly higher heat stress levels in future scenarios.

D. Zone 4 :



(a)

Time	1989		Baseline - 2021		2050 Mid		2050 WS		2090 Mid		2090 WS	
	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th	08th	09th
00:00		17,5		16,3		17,4		18,6		19,3		22,7
01:00	16,3	16,6	14,6	15,6	16,2	16,6	16,1	18,1	16,4	19,0	19,6	22,0
02:00	16,4	15,7	14,0	14,4	15,7	15,6	15,7	17,4	15,8	18,5	19,6	21,4
03:00	16,9	15,2	13,7	14,0	15,4	15,1	15,4	16,9	15,6	18,5	19,4	21,0
04:00	16,9	14,2	13,3	13,5	15,1	14,6	15,1	16,5	15,1	18,4	19,2	20,6
05:00	17,4	13,9	13,2	13,3	14,9	14,3	15,0	16,0	14,9	18,5	19,2	20,6
06:00	18,0	14,6	14,0	13,9	15,9	15,3	16,1	16,8	15,8	19,1	20,2	21,3
07:00	18,6	23,4	22,2	22,3	22,6	22,3	23,6	23,9	23,3	21,2	24,5	26,0
08:00	19,2	29,7	29,0	28,2	26,4	26,5	29,1	27,4	30,1	25,0	29,3	29,8
09:00	20,0	32,3	31,8	31,6	30,5	30,4	33,2	31,5	33,1	29,9	35,4	33,1
10:00	22,6	33,6	33,3	34,0	33,0	33,4	35,6	34,2	35,3	35,2	38,3	35,7
11:00	25,4	32,5	34,6	35,1	35,0	35,3	37,3	36,0	37,1	37,4	39,7	37,6
12:00	28,2	31,0	35,8	36,1	36,7	37,0	38,3	37,8	38,3	37,1	40,6	38,4
13:00	28,9	30,9	36,9	36,6	38,1	38,1	39,0	39,2	39,1	36,6	41,0	39,8
14:00	29,6	29,9	37,2	36,6	38,8	38,1	39,0	39,5	39,8	35,3	40,8	40,1
15:00	28,9	27,8	36,0	35,1	38,2	37,3	37,4	38,8	39,3	31,9	38,5	39,0
16:00	28,0	26,3	33,5	32,4	36,6	35,7	34,9	36,3	37,5	28,7	35,0	37,0
17:00	26,6	23,0	29,4	28,3	33,7	31,8	31,3	32,1	34,1	25,3	31,8	34,3
18:00	23,5	20,8	24,7	23,5	28,0	26,6	27,1	27,1	28,5	23,9	28,8	29,9
19:00	22,2	19,3	21,8	20,4	23,3	22,3	24,3	22,9	23,8	22,7	26,9	25,7
20:00	21,1	18,4	20,6	19,3	22,0	21,1	23,0	21,9	22,9	22,4	26,4	24,2
21:00	20,3	17,6	19,5	18,4	20,8	20,0	22,0	20,9	21,8	21,6	25,2	23,0
22:00	19,3	16,5	18,4	17,4	19,6	19,0	20,8	19,9	21,0	21,3	24,5	21,9
23:00	18,4	15,7	17,3	16,4	18,4	18,0	19,8	18,9	20,0	20,7	23,5	20,9

	12 – 15	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal Comfort	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress Level	Moderate cold stress	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

(b)

Figure 27 : PET Scenarios for Zone 4

Figure 28 illustrates the Physiological Equivalent Temperature (PET) in measurement zone 4 for various years and climate scenarios from August 8, 2021, to August 9, 2021. The years considered are 1989, 2021, 2050, and 2090, encompassing typical and extreme climate scenarios for the 2050s and 2090s.

1989 Scenario: Between midnight and 7:00 AM, nighttime temperatures range from a minimum of 13.9°C at 5:00 AM on August 9 to a maximum of 18.6°C on August 8, with "Slight cold stress" observed during this period. From 7:00 AM to 6:00 PM, temperatures generally rise, with higher averages on August 9 (28.9°C) compared to August 8 (25.5°C). Moderate heat stress occurs from 12:00 PM to 4:00 PM on August 8 and from 8:00 AM to 2:00 PM on August 9, peaking at 33.6°C. Temperatures decline to a neutral range between 6:00 PM and 10:00 PM on August 8 and 5:00 PM to 7:00 PM on August 9, followed by slight cold stress, with evening temperatures reaching 15.7°C.

2021 Scenario: The 2021 scenario shows cooler nighttime temperatures than in 1989, with a minimum of 13.2°C recorded at 5:00 AM on August 8. A "Moderate cold" thermal stress is noted between 1:00 AM and 6:00 AM, contrasting with the "Slightly cool" classification in 1989. Daytime temperatures rise from 7:00 AM to 2:00 PM, peaking between 34°C and 37.2°C around midday, resulting in "Strong heat stress." The evening sees a transition from neutral thermal stress to "Slightly cool" conditions. Overall, nighttime temperatures in 2021 are lower by an average of 0.8°C, while daytime temperatures are higher by 3.6°C compared to 1989.

2050 Scenario: In the 2050 scenario, there is a reduction in cold-related thermal stress at night, with only 3 hours of "Moderate cold stress" on August 8 and 9, compared to 11 hours in 2021. Nighttime temperatures reach a minimum of 14.3°C, slightly above the 15.0°C recorded in the 2050 WS scenario. Daytime temperatures peak at 38.8°C between 11:00 AM and 4:00 PM, leading to pronounced heat stress. The evening sees temperatures transitioning from "Moderate heat stress" to "Neutral," with improved nighttime comfort compared to previous scenarios.

2090 Scenario: In 2090, particularly in the Mid-range and worst-case (RCP 8.5) scenarios, a global increase in temperatures significantly impacts nighttime conditions, shifting from moderate cold stress to a neutral range. The 2090 Mid scenario features generally slightly cool nighttime temperatures, with only 1 hour of moderate cold stress and 3 hours of neutral thermal stress. Daytime peaks reach 39.8°C, coinciding with strong heat stress from 10:00 AM to 5:00 PM. Comparatively, the 2090 WS scenario boasts the most comfortable nighttime conditions, with minimal thermal stress during the evening. However, it also records the highest daytime temperatures, peaking at 41°C on August 8 at 1:00 PM, which is notably higher than both the 2090 Mid and the 2021 scenarios.

Overall, the analysis indicates a trend of increasing temperatures and changing thermal stress conditions over the decades, highlighting the significant impacts of climate change on outdoor thermal comfort.

4.2. PET Evolution during all the studied periods

In this segment, we will explore the variations in Physiological Equivalent Temperature (PET) across different scenarios in the four study zones at various times of the day. The analysis will be visually represented using radar charts and boxplots for the following scenarios: 1989, 2021, 2050 Midrange scenario, 2050 worst-case scenario, 2090 Midrange scenario, and 2090 worst-case scenario.

4.2.1. *Zone 1:*

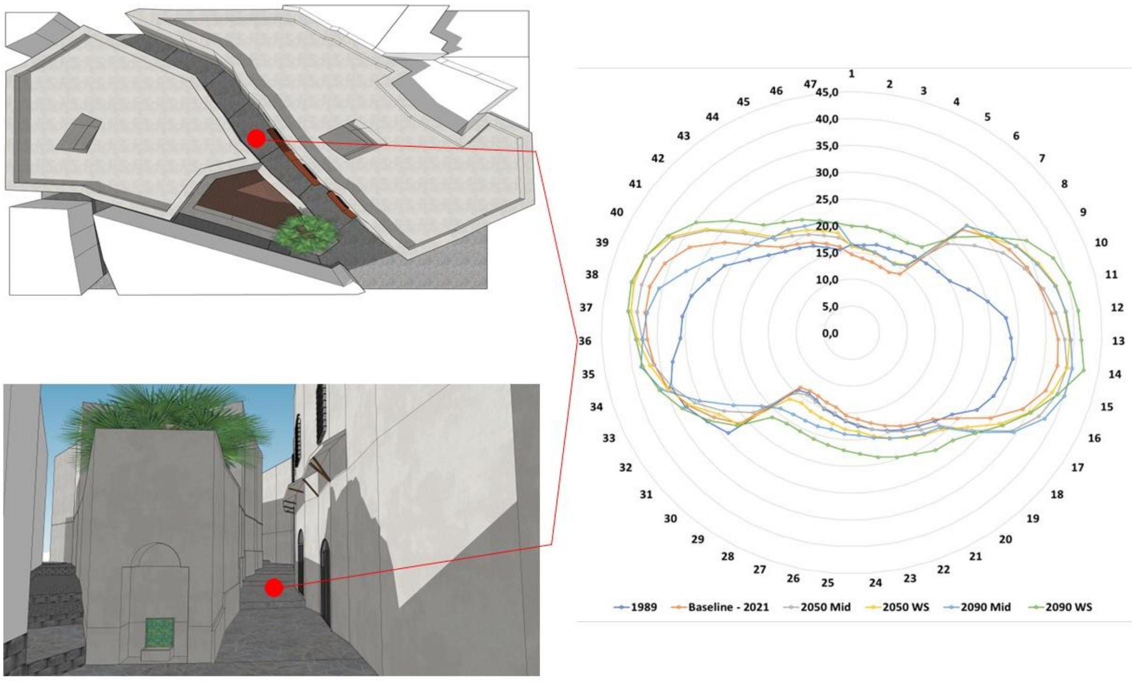
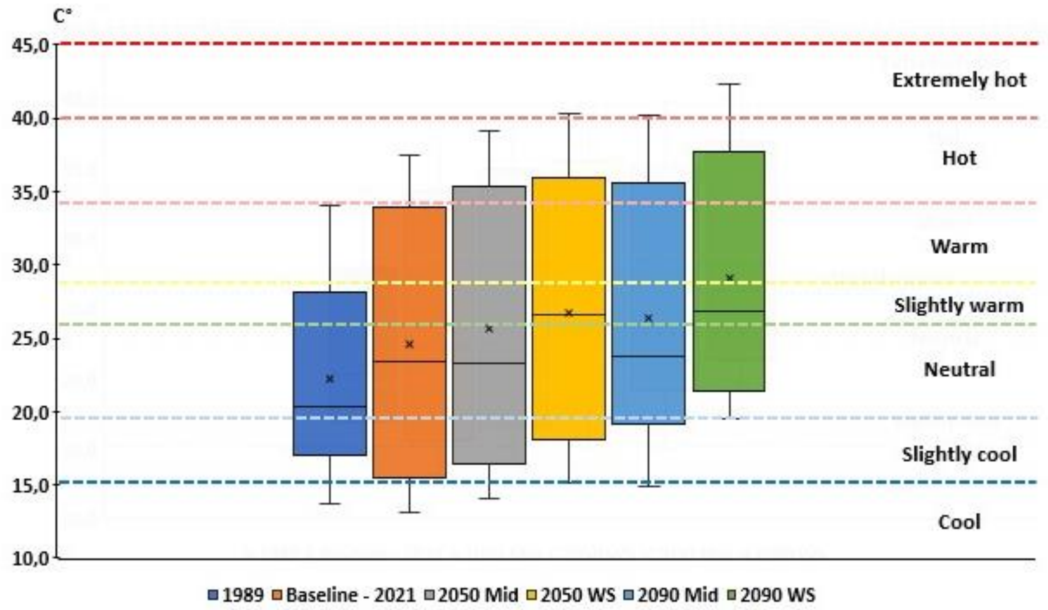


Figure 28: Zone 1 Radar Temperature of PET Temperatures Across Scenarios



	1989	2021	2050 Mid	2050 WS	2090 Mid	2090 WS
Maximum temp	34,1	37,5	39,2	40,3	40,2	42,3
Average Temp	22,2	24,6	25,7	26,7	26,4	29,1
Minimum Temp	13,7	13,1	14,1	15,1	14,9	19,5
Average temperature difference	5,2	8,3	8,1	8,0	7,4	7,0

Figure 29: Zone 1 Maximum, Average, and Minimum Temperatures and Box Plot Analysis

Examining figures 29 and 30 reveals notable differences in temperature outcomes across various scenarios. The temperature variations in contemporary and future scenarios surpass those observed in 1989. Specifically, the mean temperature difference for August 8th and 9th in 1989 is 5.2°C, with maximum and minimum temperatures of 34.1°C and 13.7°C, respectively. In contrast, the 2021 scenario shows an average difference of 8.3°C, with maximum temperatures reaching 37.5°C and minimums of 13.1°C.

For the 2050 scenarios, both the Mid and WS versions exhibit similar temperature differences of 8.1°C and 8.0°C, respectively. However, the average temperature for the 2050 WS scenario is 1°C higher (26.7°C) than that of the standard 2050 scenario (25.7°C), with maximum temperatures peaking at 39.2°C for 2050 and 40.3°C for 2050 WS.

In the 2090 scenarios, temperature differences are less pronounced, measuring 7.4°C for 2090 and 7.0°C for 2090 WS. However, the average temperatures differ significantly, with 2090 at 26.4°C and 2090 WS at 29.1°C, resulting in a 2.7°C variance. Notably, the 2090 WS scenario exhibits a difference of over 7°C from the 1989 average and 4.5°C from the 2021 average.

4.2.2. Zone 2:

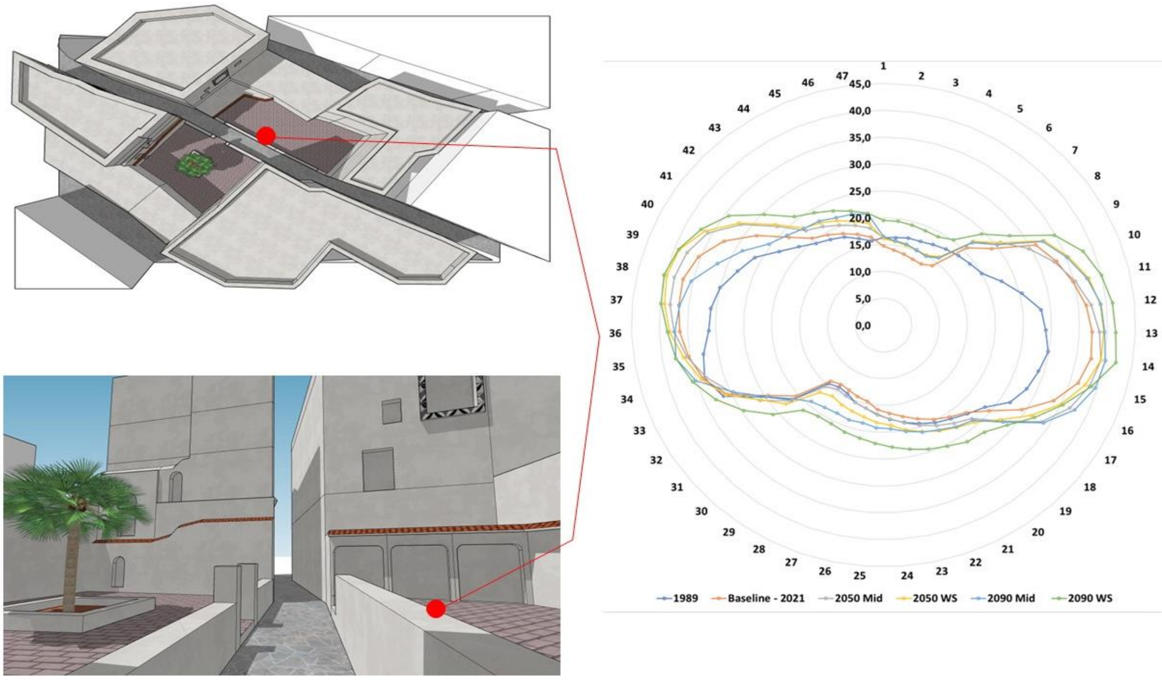
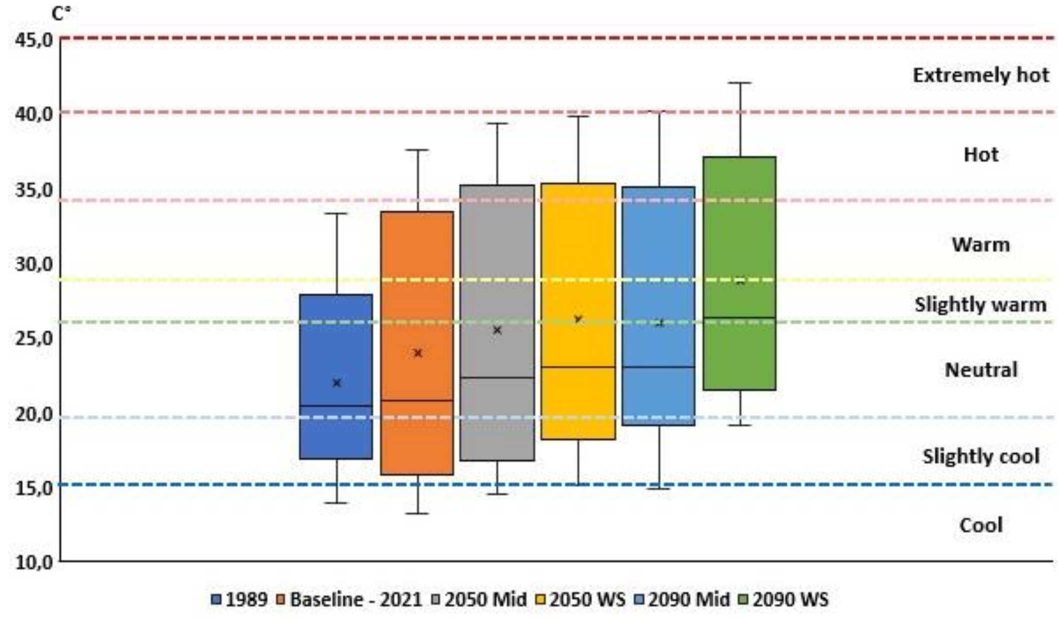


Figure 30: Zone 2 Radar Temperature of PET Temperatures Across Scenarios



	1989	2021	2050 Mid	2050 WS	2090 Mid	2090 WS
Maximum temp	33,4	37,6	39,4	39,8	40,2	42,1
Average Temp	22,0	24,0	25,5	26,3	26,0	28,8
Minimum Temp	14,0	13,2	14,5	15,1	14,9	19,1
Average temperature difference	5,0	7,8	7,8	7,8	7,1	6,9

Figure 31 : Zone 2 Maximum, Average, and Minimum Temperatures and Box Plot Analysis

In Zone 2 presented in the figure 31 and 32, there is a noticeable shift in average high and low temperatures, as well as temperature variation across different scenarios. In 1989, average daytime maximum temperatures were 27.5°C, with an average temperature of 22°C and a daily temperature difference of 5.0°C. In subsequent scenarios (2021, 2050 Mid, and 2050 WS), the average temperature difference increases to 7.8°C, while maximum temperatures rise to 37.6°C, 39.4°C, and 39.8°C, respectively. The average temperatures show a clear upward trend, with the 2050 WS temperatures being +4.25°C compared to 1989, +2.3°C compared to 2021, and +0.8°C compared to 2050 Mid.

In the 2090 scenarios, the average temperature deviation decreases to 7.1°C for 2090 Mid and 6.9°C for 2090 WS. However, maximum temperatures are notably higher, with a +1.9°C increase for 2090 WS compared to 2090 Mid and +2.3°C compared to 2050 WS. Compared to the contemporary scenario, this results in a 4.5°C difference in maximum temperature and a 4.8°C difference in average temperature.

4.2.3. Zone 3

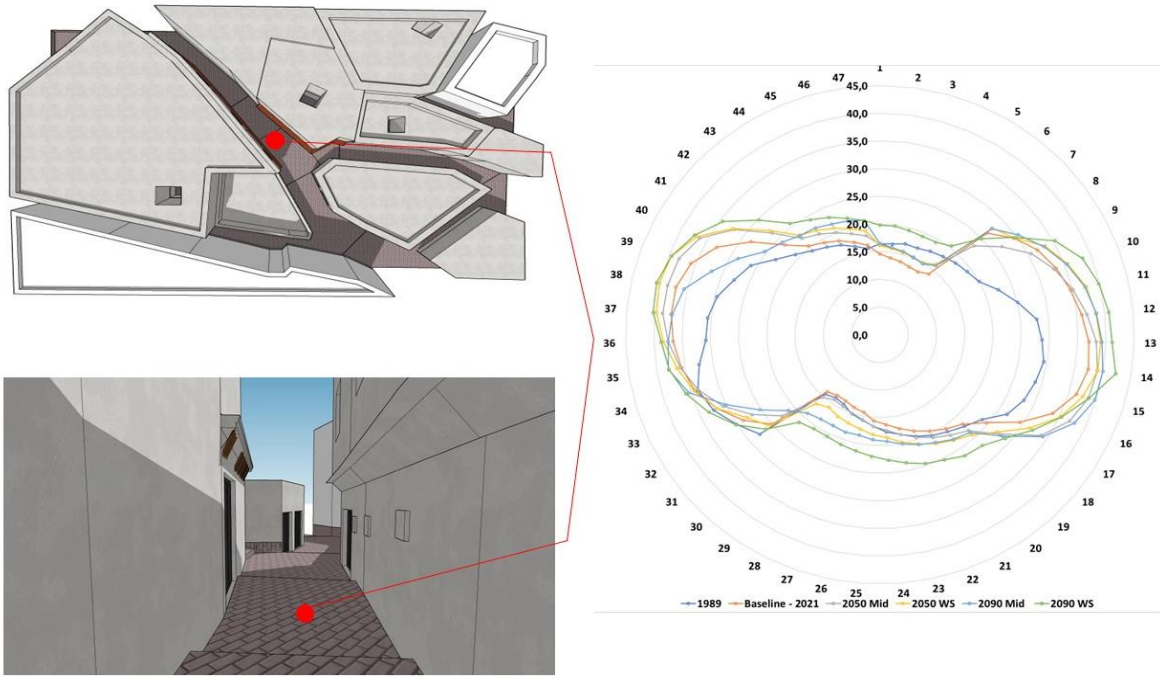
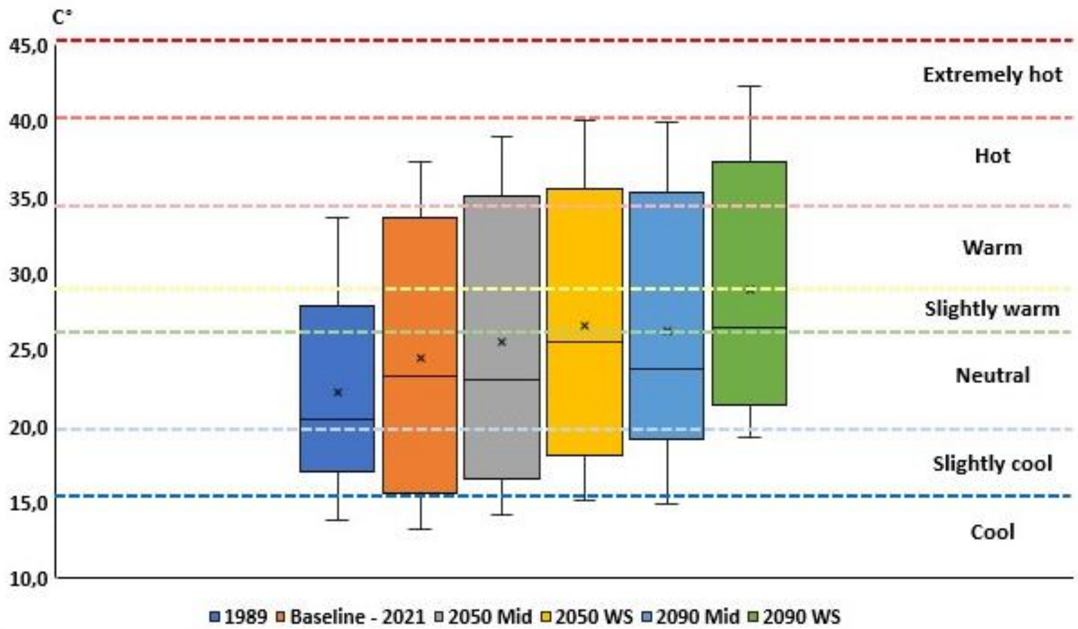


Figure 32: Zone 3 Radar Temperature of PET Temperatures Across Scenarios



	1989	2021	2050 Mid	2050 WS	2090 Mid	2090 WS
Maximum temp	34,1	37,5	39,2	40,3	40,2	42,3
Average Temp	22,2	24,6	25,7	26,7	26,4	29,1
Minimum Temp	13,7	13,1	14,1	15,1	14,9	19,5
Average temperature difference	5,2	8,3	8,1	8,0	7,4	7,0

Figure 33: Zone 3 Maximum, Average, and Minimum Temperatures and Box Plot Analysis

The results shown in Figures 33 and 34, in Zone 3, are characterized by houses on both sides forming a corridor, fluctuations in temperatures over the years are represented in graphs and radar displays. Notably, the 2021 scenario shows higher maximum and minimum temperatures compared to 1989, with these trends increasing over time.

Beginning with the 1989 scenario, the average daily temperature difference is 5.2°C, with an extreme maximum temperature of 33.7°C and an average high of 27.6°C. The minimum temperature recorded is 13.8°C.

In contrast, the 2021 scenario presents an average daily temperature difference of 8.1°C, with a maximum temperature of 37.4°C and a minimum of 16°C. The 2050Mid and 2050WS scenarios show average differences of 8.0°C and 7.8°C, respectively. The minimum temperatures rise to 17.2°C in 2050Mid and 18.5°C in 2050WS. The average temperatures also increase, from 24.5°C in 2021 to 25.6°C in 2050Mid (+1.1°C) and further to 26.6°C in 2050WS (+1°C). The maximum temperatures continue this upward trend, reaching 39.0°C in 2050Mid and 40.1°C in 2050WS, representing increases of +1.1°C and +2.7°C compared to the 2021 scenario, respectively.

In the 2090Mid and 2090WS scenarios, daily average temperature variances are less significant, measuring 7.2°C and 6.9°C, respectively. The average maximum temperatures are 34°C for 2090Mid and 37.2°C for 2090WS, with extreme peaks of 42.3°C and 40°C. Average temperatures in 2090Mid show a slight decrease of -0.3°C compared to the 2050WS scenario at 26.3°C, while the 2090WS scenario indicates a temperature of 29°C.

Analyzing average differences reveals that the 2090WS scenario exhibits an increase of 6.8°C compared to 1989, 4.5°C compared to 2021, and increases of 3.4°C, 2.4°C, and 2.7°C compared to the 2050Mid, 2050WS, and 2090Mid scenarios, respectively.

4.2.4. Zone 4:

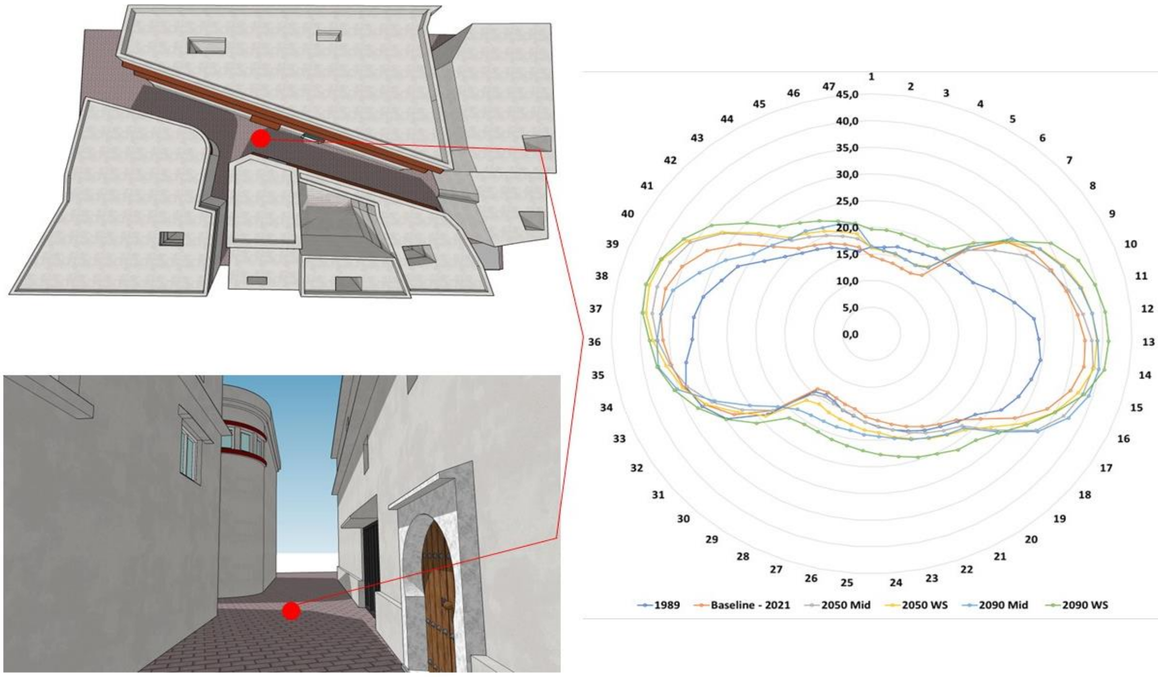
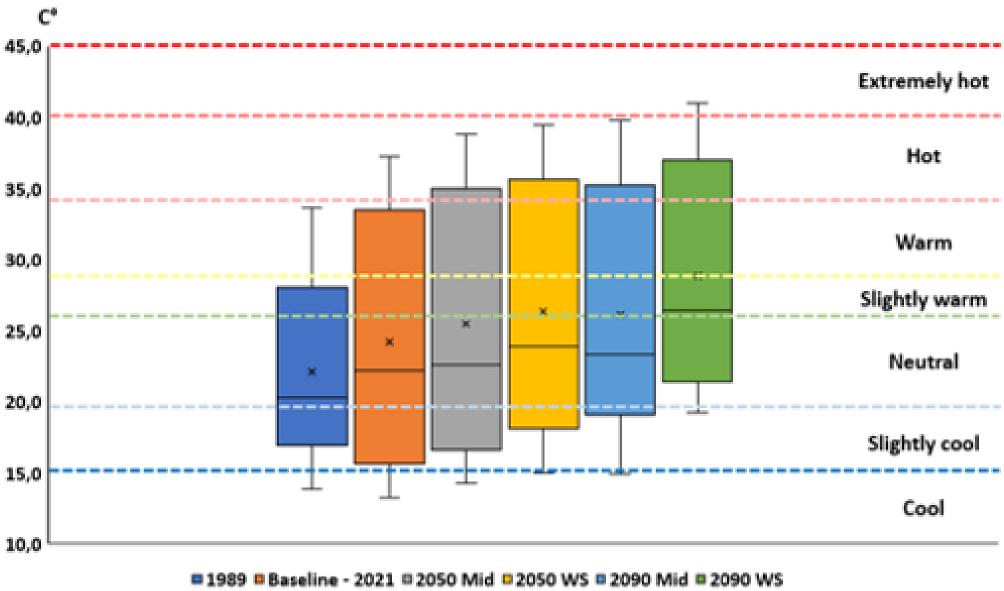


Figure 34 : Radar Temperature of PET Temperatures Across Scenarios



	1989	2021	2050 Mid	2050 WS	2090 Mid	2090 WS
Maximum temp	33,4	37,6	39,4	39,8	40,2	42,1
Average Temp	22,0	24,0	25,5	26,3	26,0	28,8
Minimum Temp	14,0	13,2	14,5	15,1	14,9	19,1
Average temperature difference	5,0	7,8	7,8	7,8	7,1	6,9

Figure 35: Zone 4 Maximum, Average, and Minimum Temperatures and Box Plot Analysis

In the results presented in Figures 35 and 36, we can see that in 1989, the recorded average temperature was 22.1°C, with a peak reaching 33.6°C and a minimum of 13.9°C. This resulted in a notable daily temperature fluctuation of 5.1°C, highlighting the variability in climate conditions during that year. By 2021, the average temperature increased to 24.2°C, reflecting a rise of 2.1°C compared to 1989. The maximum temperature rose to 37.2°C, a significant increase of 3.6°C, while the minimum temperature was slightly lower at 13.2°C, a decrease of 0.7°C from 1989. This period also saw the daily temperature fluctuation expand to 8°C, indicating a substantial increase in variability over the three decades.

In the mid-century scenario for 2050 (2050Mid), the average temperature is projected to rise to 25.5°C, indicating a continuous increase of 1.3°C from 2021. This scenario anticipates a maximum temperature reaching 38.8°C, which is an increase of 1.6°C compared to 2021, with an average temperature fluctuation of 7.9°C. In the worst-case scenario for 2050 (2050WS), the average temperature is expected to be even higher, at 26.3°C, marking an increase of 0.8°C from 2050Mid. The daily temperature fluctuations are similar in both 2050 scenarios, with 2050Mid at 7.9°C and 2050WS at 7.8°C, indicating consistent variability.

By 2090, the mid-century scenario (2090Mid) predicts an average temperature of 26.1°C, with a maximum temperature of 39.8°C, continuing the upward trend in maximum temperatures. Notably, the average temperature for 2090Mid is lower than that of the 2050WS scenario by 0.25°C, suggesting that temperature increases may be more pronounced in the earlier part of the century. The daily temperature differences are projected to be 7.2°C for 2090Mid and 6.8°C for 2090WS, indicating a trend toward reduced variability compared to earlier periods.

In the 2090WS scenario, the average temperature climbs to 28.8°C, representing an increase of 2.7°C compared to 2090Mid and 2.5°C compared to 2050WS. This rise underscores the persistent trend of increasing temperatures, emphasizing the importance of monitoring climate change impacts over time.

4.3. Algorithm data generation:

Table 13: PET Predictions from 2000 to 2090

Time	PET / Year									
	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090
01:00	14,9	14,6	14,6	15,0	15,5	16,1	16,6	16,9	16,8	16,2
02:00	14,6	14,0	14,0	14,4	15,0	15,6	16,1	16,4	16,2	15,5
03:00	14,6	13,8	13,7	14,0	14,6	15,3	15,8	16,2	16,0	15,3
04:00	14,3	13,5	13,3	13,6	14,2	14,9	15,5	15,8	15,7	14,8
05:00	14,5	13,5	13,2	13,4	14,0	14,7	15,3	15,6	15,4	14,5
06:00	15,2	14,2	14,0	14,3	15,0	15,7	16,3	16,6	16,4	15,4
07:00	22,5	23,8	24,3	24,1	23,6	23,0	22,7	23,0	24,1	26,3
08:00	22,5	23,8	24,3	24,1	23,6	23,0	22,7	23,0	24,1	26,3
09:00	27,5	30,4	31,7	31,9	31,4	30,6	30,1	30,2	31,4	34,2
10:00	29,3	32,0	33,4	33,8	33,6	33,1	32,8	33,0	34,0	36,3
11:00	31,0	33,4	34,8	35,4	35,4	35,2	35,1	35,4	36,3	38,1
12:00	32,7	34,8	36,1	36,7	36,9	36,9	37,0	37,2	37,9	39,2
13:00	33,5	35,7	37,1	37,9	38,2	38,3	38,3	38,4	38,8	39,7
14:00	33,9	36,0	37,5	38,3	38,8	39,1	39,2	39,3	39,7	40,3
15:00	32,8	34,9	36,4	37,4	38,0	38,4	38,7	39,0	39,3	39,9
16:00	30,7	32,3	33,7	34,9	35,9	36,7	37,2	37,6	37,8	37,8
17:00	27,3	28,2	29,5	30,9	32,2	33,5	34,4	34,8	34,7	33,8
18:00	23,5	23,9	24,7	25,7	26,7	27,7	28,5	28,9	28,8	28,2
19:00	21,7	21,6	21,9	22,2	22,7	23,2	23,6	23,9	24,0	23,7
20:00	20,6	20,5	20,7	21,0	21,4	21,9	22,3	22,7	22,9	22,9
21:00	19,6	19,5	19,6	19,8	20,2	20,7	21,1	21,5	21,7	21,8
22:00	18,6	18,4	18,4	18,7	19,0	19,5	20,0	20,4	20,8	21,1
23:00	17,6	17,3	17,3	17,5	17,8	18,3	18,8	19,3	19,8	20,2
00:00	16,7	16,4	16,3	16,5	16,8	17,2	17,7	18,3	18,9	19,5

	12 – 15	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal Comfort	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress Level	Moderate cold stress	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

The comprehensive analysis of thermal comfort from 2000 to 2090 presented in the table 13 reveals noteworthy trends across different time intervals, employing the Physiological Equivalent Temperature (PET) for classification.

Nocturnal Period (00:00 - 07:00): There is a subtle increase in temperatures over the years. In 2000, the PET at midnight is 16.7°C, rising to 19.5°C by 2090. These values consistently fall within the "Cool to Slightly Cool" range, indicating progressively warmer nights while maintaining an overall sense of comfort.

Daytime Period (08:00 - 18:00): A substantial temperature surge is observed during the daytime. At noon in 2000, the PET is recorded at 32.7°C, escalating to 39.2°C by 2090. This range transitions from "Moderate heat stress" to "Strong heat stress," highlighting hotter afternoons and a potential impact on thermal comfort.

Evening Period (18:00 - 00:00): Temperatures slightly increase, with the PET at 23.5°C in 2000, rising to 28.2°C by 2090. These values fall within the "Warm to Hot" range, indicating warmer evenings while still maintaining a comfortable atmosphere.

The analysis indicates a coherent temperature evolution, with specific years such as 2030 and 2070 serving as significant milestones. It is crucial to consider these comfort ranges for a comprehensive understanding of climate change and to formulate adaptation strategies for human well-being.

Overall Trends: Algorithm-generated data shows in the Figure 3 a consistent upward trend, with maximum temperatures fluctuating from 33.9°C to 40.3°C between 2000 and 2090, reflecting a 3.6°C increase from 2000 to 2020. Average temperatures also rise from 22.9°C in 2000 to 26.7°C in 2090, with minimal nightly fluctuations.

Throughout the day, especially from 09:00 to 18:00, there is a noticeable increase in discomfort, transitioning from moderate to strong heat stress. Instances of intense heat stress rise from 4 to 8 hours between 2010 and 2090, implying a substantial potential for thermal discomfort during active hours in the upcoming decades.

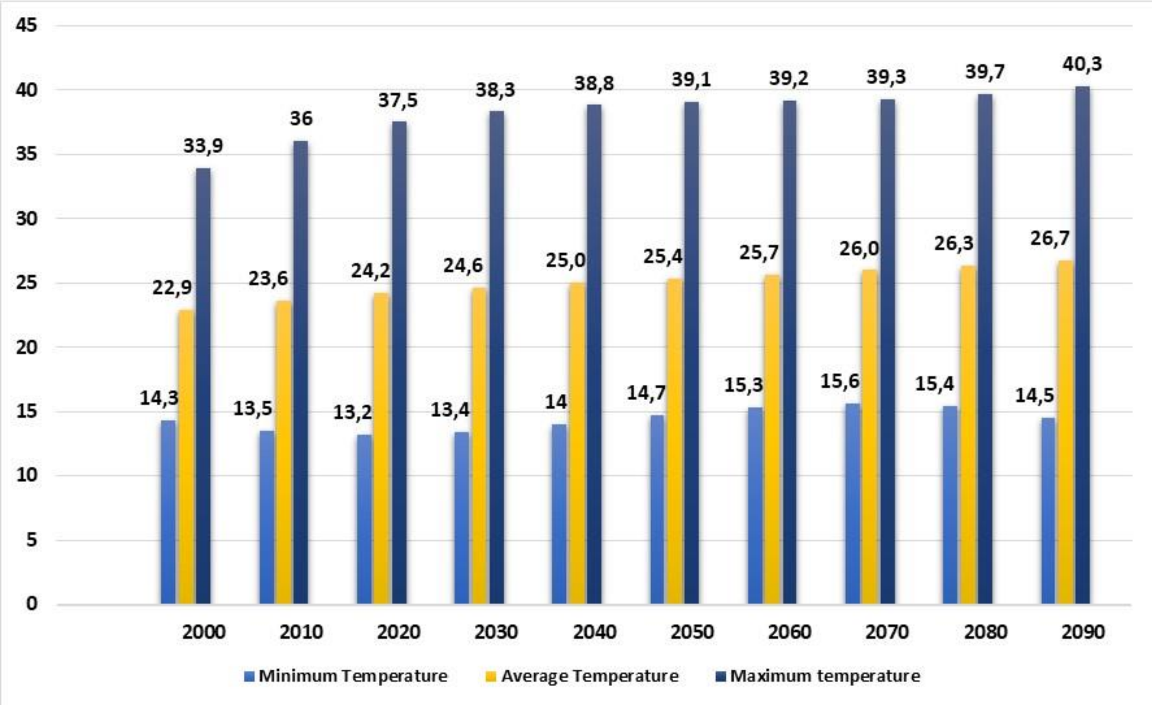


Figure 36 : Algorithm generation of Maximum, Average, and Minimum PET Temperatures.

5 Discussions

This study conducted a microclimatic analysis in a typical Mediterranean historic urban area to investigate the effects of climate change on outdoor thermal comfort. Specifically, it focused on how global warming predictions specific to Mediterranean climates and associated climate variations affect thermal comfort. The study assessed the impact of different climate scenarios across four zones using a combination of on-site measurements and Computational Fluid Dynamics (CFD) simulations, which were used to calibrate the model. Subsequently, the CFD Software ENVI-met was employed to conduct further simulations, specifically focusing on thermal stresses experienced during hot days across various timeframes: historical (1989), contemporary (2021), and future projections under Representative Concentration Pathways (RCP) 4.5 (for 2050 and 2090) as well as RCP 8.5, representing the most pessimistic scenario (for 2050 and 2090). Additionally, the software's BIO-met programs were used to compute the Physiological Equivalent Temperature (PET) index. In summary, the analysis of outdoor thermal comfort yielded significant findings regarding the impact of different climate scenarios on the studied urban fabric.

To summarize the simulation readings, the significant findings of the analysis of outdoor thermal comfort are listed:

5.1. Major findings and recommendations

With the ongoing progression of climate change, more intense and frequent overheating phenomena are anticipated. This study compares the Physiological Equivalent Temperature (PET) over two summer days (August 8-9) in 1989, 2021, 2050, and 2090 under normal and extreme scenarios. Nighttime and daytime temperatures are projected to increase, significantly impacting thermal comfort progressively.

5.1.1. Temperature Trends and Impacts

In 1989, nighttime temperatures averaged 16.7°C (minimum 13.7°C), providing moderate to slightly cold comfort. Daytime temperatures peaked at 34.1°C, with moderate heat stress observed throughout most of the day. By 2021, nighttime temperatures averaged around 14.8°C, resulting in moderate cold stress. Meanwhile, daytime temperatures reached a maximum of 37.5°C, indicating moderate to strong heat stress.

Looking ahead, projections for 2050 show nighttime temperatures increasing to approximately 16.2°C under the Mid scenario, slightly improving to mild cold comfort. The WS scenario anticipates nighttime temperatures averaging 17.2°C (peaking at 18.5°C), also indicating mild cold comfort. However, daytime temperatures are expected to rise significantly to 39.2°C in the Mid scenario and 40.3°C in the WS scenario, marking the onset of extreme heat stress.

By 2090, the Mid scenario predicts nighttime temperatures reaching 18.1°C, offering mild cold comfort, while daytime temperatures are expected to exceed 40°C for two hours, representing extreme heat stress. In the WS scenario, nighttime temperatures will range from 19.5°C to 22.7°C, ensuring neutral thermal comfort. However, daytime temperatures are projected to peak at 42.3°C, with up to six hours of extreme heat stress.

Overall, there is a clear trend of rising thermal stress levels over the years examined. Nighttime temperatures increased from 16.7°C in 1989 to 18.1°C in 2090 (Mid scenario), while daytime temperatures escalated from 34.1°C to 42.3°C during the same period. These escalating temperatures underscore the critical need for proactive adaptation strategies in urban planning to safeguard public health and enhance thermal comfort amidst worsening climatic conditions.

5.1.2. ***Comparative Analysis***

The findings align with studies by (Katavoutas et al., 2021) and (Orosa et al., 2014), which reveal significant increases in thermal stress over time. The Santorini study highlights a substantial rise in heat stress conditions during summer, paralleling the observed escalation in daytime temperatures and stress levels from 1989 to 2090. Orosa's research also underscores the impact of climate change on outdoor thermal comfort, noting that higher humidity and increasing temperatures contribute to extreme heat conditions and potential heat stroke risks. Both studies confirm the trend of escalating thermal stress under high-emission scenarios across different regions.

In contrast, (Kotharkar et al., 2021) and (Hansen et al., 2016) argue that regional variations and uncertainties in climate models could lead to different projections of thermal stress, suggesting that the general trend may not be uniform. They highlight potential overestimations of temperature increases and stress levels, indicating that the projected rise in heat stress conditions might be less severe than anticipated. These differing perspectives suggest that while an overall trend of rising thermal stress is observed, its intensity and regional variability may be more complex.

5.1.3. ***Long-term Climate Projections***

An analysis from 1989 to 2090 shows a significant increase in minimum, average, and maximum temperatures, indicating substantial climate warming. In 1989, temperatures ranged from 13.7°C to 34.1°C, with a daily temperature range of 5.2°C. By 2021, this range expanded to 8.3°C, with peak temperatures at 37.5°C and an average of 24.6°C, marking a 2.4°C increase from 1989.

Projections for 2050 continue this warming trend, with the Mid scenario forecasting an average temperature of 25.7°C (+1°C from 2021) and maximum temperatures reaching 39.2°C. The WS scenario for 2050 anticipates an average of 26.7°C (+2.1°C) and maximums of 40.3°C. Moving to 2090, while the daily temperature range slightly decreases (7.4°C for the Mid scenario and 7.0°C for the WS scenario), overall temperatures continue to rise. The Mid scenario predicts an average temperature of 26.4°C (+1.8°C from 2021), while the WS scenario forecasts a notable increase to an average of 29.1°C (+4.5°C).

These findings underscore the urgency for effective initiatives to mitigate the impacts of climate change, ensuring community resilience in the face of escalating challenges. Similar conclusions are drawn in studies by (Heaviside et al., 2017) and (Marx et al., 2021), which report a 50% increase in heat waves since the 1980s in certain regions.

5.1.4. ***Public Health and Urban Infrastructure***

Climate projections foresee significant increases in temperatures, especially during the daytime, with maximum temperatures already rising by 3.4°C between 1989 and 2021 and potentially increasing by 5.1°C to 8.2°C by 2090. This rise exposes populations to heat-related health risks, particularly among vulnerable groups such as the elderly and children. Historic cities like the Casbah of Algiers will also be affected, impacting the comfort of residents and tourists, necessitating nature-based techniques and passive cooling approaches while preserving heritage.

Urban infrastructure will require adaptation to these new thermal conditions, prompting investments in improved cooling systems and increased green spaces to mitigate urban heat islands. Developing and implementing robust adaptation strategies is essential to mitigate the negative impacts of rising temperatures and ensure a sustainable quality of life in changing urban environments.

*5.1.5. **Detailed Analysis of Temperature Trends (2000-2090)***

An analysis of minimum, average, and maximum temperatures from 2000 to 2090 reveals significant trends. Minimum temperatures started at 14.3°C in 2000, decreased slightly to 13.2°C by 2020, gradually increased to 15.4°C by 2080, and dropped slightly to 14.5°C by 2090. This pattern indicates slightly warmer nights over the long term despite intermediate fluctuations.

Average temperatures began at 22.9°C in 2000, increasing each decade to reach 26.7°C by 2090. This upward trend signifies ongoing daytime warming, likely associated with reduced thermal comfort. Maximum temperatures rose from 33.9°C in 2000 to 40.3°C by 2090, indicating a notable intensification of heat during the hottest parts of the day, potentially leading to more frequent and intense heatwaves.

These findings confirm the urgency of addressing climate change impacts and enhancing community resilience. The analysis aligns with studies by (Santamouris, 2020) and (Milner et al., 2019), which report projected temperature increases of 4 to 7°C in certain regions.

In contrast, studies by (McKitrick et al., 2023) and (Schmidt et al., 2014) Standard climate models may skew results due to assumptions about stationary error terms. Furthermore, discrepancies between model projections and actual observations indicate that models might predict greater warming than what has been observed. These contradictions emphasize the importance of a critical approach to interpreting climate data and projections.

The PET data analysis reveals alarming trends of climate warming over the decades. PET temperatures show substantial increases throughout the day, with significant warming early in the morning and sharp peaks by midday. For instance, at 07:00, PET rises from 22.5°C in 2000 to 26.3°C in 2090, and by 12:00, it increases from 32.7°C to 39.2°C. Afternoon hours exhibit the highest PET values, underscoring an intensification of thermal stress during the hottest parts of the day.

Moreover, early morning and nighttime periods are not immune to warming. At 00:00, PET increases from 16.7°C in 2000 to 19.5°C in 2090, while at 22:00, it rises from 18.6°C to 21.1°C, indicating a trend toward warmer nights that could disrupt sleep and nocturnal well-being.

These quantified data confirm a concerning reality: PET temperatures are steadily rising, necessitating robust adaptation strategies to mitigate health impacts and enhance comfort as climates become increasingly warmer and unpredictable (Fahmy et al., 2020b) .

5.1.6. Policy recommendations

Given the projected rise in temperatures and thermal stress, it is crucial to update urban heat management standards and building codes to ensure climate resilience. Policy recommendations should focus on integrating green infrastructure, such as green roofs and walls, and using heat-reflective materials, especially in historic areas, to reduce urban heat island effects. Additionally, creating cooling zones and shaded spaces in urban areas will help protect vulnerable populations from extreme heat. The implementation of comprehensive heat action plans, along with the adoption of passive cooling technologies, should be prioritized to manage the increasing temperatures. These policy measures are essential to mitigate the impacts of climate change, promote sustainable urban development, and safeguard public health.

5.2. Strengths and limitations of the study

This study bridges two crucial research domains: urban heritage and microclimate analysis. While previous research on traditional urban fabrics has largely focused on the effects of urban geometry or building materials on thermal comfort (Ben Ratmia et al., 2023; Krüger et al., 2011b; Matallah, 2015), studies on microclimates and climate change have primarily concentrated on modern urban areas, often overlooking traditional urban settings (Ahriz et al., 2019; Elnabawi and Hamza, 2019; Shooshtarian et al., 2020) . Few studies have examined how climate change impacts microclimates in traditional urban forms, which differ from modern cities in density, aspect ratios, and building materials, as well as in adaptation solutions. This research helps fill an important gap by addressing the influence of climate change on thermal comfort in traditional urban morphologies over the long term.

The study aims to establish a streamlined methodology for assessing outdoor thermal comfort over extended periods, providing decision-makers and urban planners with tools to develop effective mitigation strategies. It also evaluates the effectiveness of various nature-based solutions in historical cities, considering global climate scenarios, including the severe IPCC RCP 8.5 projections.

The methodology combines field measurements, computational fluid dynamics (CFD) simulations, and post-processing with Algorithm P, which consolidates PET results across scenarios to create a "Global PET." This metric establishes comfort thresholds, assisting in the selection of optimal mitigation strategies. This framework could be applied to other traditional urban areas, such as Fatimid Cairo (Egypt), the Historic City of Toledo (Spain), the Medina of Tunis (Tunisia), and the Centro Storico of Naples (Italy), aiming to enhance comfort and address overheating in Mediterranean climates.

Using a high-resolution model with a 1 m x 1 m x 1 m grid, this study improves the precision of outdoor thermal comfort assessments in historical contexts. Additionally, the simulations use a high-precision temporal model with a 2-second time step, surface data iteration of 15 seconds, wind iteration of 450 seconds, and radiation iteration of 300 seconds. Model calibration involved 72 hours of air temperature data validation through hourly mean bias error (MBE) and root-mean-square error (RMSE). Over 564 hours of microclimate data were gathered, resulting in 24 PET values across six study zones—an approach surpassing the typical 20–48-hour validation in similar studies (Hien et al., 2012b; Taleghani et al., 2015c).

The study's limitations include its exclusive focus on hot periods and heat waves; expanding the analysis to additional seasons would provide a more comprehensive view of mitigation in varying conditions. Additionally, Algorithm P's PET calculations have been validated only in Mediterranean climates, requiring further investigation in other regions where localized coefficients could enhance Global PET accuracy. Finally, the simplified model lacks detailed building data, suggesting that a finer-scale urban model could improve accuracy. Future research could expand on this study's contributions by integrating a broader range of mitigation strategies and conducting sensitivity analyses to explore diverse adaptation solutions in traditional urban fabrics.

5.3. Implication on practice and future work

- **Implication:**

This study assesses thermal comfort in the historic Casbah of Algiers by examining the impact of different climate scenarios on thermal comfort across four study areas. It quantifies the warming effect and its implications for comfort under each scenario (1989, 2021, 2050, and 2090 for both normal climate scenario 4.5 and the worst-case RCP 8.5 scenario), providing crucial insights for urban rehabilitation in the context of climate change. The algorithm developed can aid in setting deadlines for urban design and restoration of the historic fabric, providing results for every 10 years. Prioritizing outdoor thermal comfort as a key focus for neighborhood rehabilitation, particularly in the Casbah, integrating these findings into Casbah's urban renewal can mitigate thermal stress in Mediterranean climates. It is recommended that OGEBC establish a climate and environmental studies unit to serve as a legal mediator between environmental and heritage concerns.

- **Future work:**

Although research on outdoor thermal comfort and future climate scenarios in historic cities lags behind that in modern urban environments, recent studies have significantly enhanced this field. Nevertheless, there is a pressing need to further these investigations. Historic sites pose unique challenges and specific limitations regarding available thermal mitigation strategies. Therefore, developing advanced mitigation strategies and testing various combinations of adaptive solutions is crucial. Special emphasis should be placed on revitalizing dilapidated buildings through the integration of nature-based solutions. Comprehensive research is required on the use of specific Mediterranean plants to improve cooling, taking into account topographical variations and soil properties. Establishing local urban climate models based on measured climate data from historic areas can greatly enhance the accuracy of thermal comfort assessments. It is also critical to study adaptation strategies in response to future climate scenarios induced by climate change. Research on outdoor thermal comfort, utilizing innovative approaches such as real-time monitoring for urban climate analysis, is scarce yet essential. Additionally, sensitivity analyses are necessary to identify key parameters influencing thermal comfort in the urban canyons of historic cities. Future research efforts should focus on multi-objective optimization that integrates thermal comfort, thermal mitigation strategies, energy efficiency, and economic considerations.

6 Conclusion

The study aims to develop a process for landscape and urban designers to enhance outdoor thermal comfort in traditional cities with a Mediterranean climate through an early design approach in historic urban areas. This interdisciplinary initiative integrates knowledge from urban planning, landscape design, architecture, and building material science to assess the impact of global warming scenarios on outdoor thermal comfort.

Specifically, the research investigates the evolution of heat stress levels in the Casbah of Algiers by analyzing six climatic scenarios across four study areas. The methodology combines empirical and numerical modeling techniques to create a high-resolution model with a grid size of 1 m × 1 m × 1 m, enabling an accurate assessment of the Physiological Equivalent Temperature (PET) in heatmaps with a precise level of detail of 1m² per area. This approach includes field measurements, remote sensing, and advanced modeling techniques, such as real-time monitoring, Computational Fluid Dynamics (CFD) simulations, and biometeorological calculations. As a result, a predictive model called Equation P was developed, which computes hourly and annual PET forecasts based on specific measurement days and simulated results.

The findings indicate a significant increase in thermal stress over time, with daytime temperatures projected to rise from 34.1 °C to 42.3 °C (24%) and nighttime temperatures from 16.7 °C to 18.1 °C (8.4%). This underscores the necessity for proactive adaptation strategies in urban planning to mitigate the impacts of extreme thermal conditions on public health and comfort. The data reveal a clear trend toward rising average temperatures and an increase in the frequency and severity of hot days, highlighting the urgent need for effective initiatives to enhance community resilience. Projections for 2050 and 2090 further emphasize the potential intensity of future climate conditions, making robust adaptation strategies essential.

To prepare for and prevent future heat waves and adverse climate scenarios, detailed examinations of urban morphology have proven highly effective in creating cooling effects. Additionally, nature-based solutions play a crucial role in enhancing thermal comfort, offering substantial cooling benefits. Future research should focus on identifying the most effective nature-based solutions and mitigation strategies in urban environments, particularly their impact on outdoor thermal comfort. The insights gained could guide decision-makers in Mediterranean contexts, improving the urban fabric and enhancing the livability of outdoor spaces. Furthermore, these results can be applied to other traditional urban areas with similar climates.

VI. From Climate Change Impact Analysis to the Integration of Nature-Based Solutions for Pedestrian Thermal Comfort in a Mediterranean Climate

The analyses conducted in Part 03 highlighted the significant impact of climate change on outdoor thermal comfort, particularly in the historic districts of the Casbah of Algiers. The evaluation of IPCC climate scenarios 4.5 and 8.5 for 2050 and 2090 allowed for the characterization of the evolving trends of microclimatic parameters, directly affecting pedestrian comfort conditions. Simulations performed with ENVIMET demonstrated a progressive increase in the Physiological Equivalent Temperature (PET), associated with a rise in periods of extreme thermal stress.

Results indicate that, depending on the studied scenarios, maximum perceived temperatures could increase by 3 to 5°C by 2050 and up to 7°C by 2090 in certain neighborhoods. The intensity and duration of extreme thermal stress periods would also increase, with temperatures exceeding critical thresholds for more than six hours per day during summer. The most exposed urban spaces are those with low vegetation coverage and a high level of impervious surfaces, exacerbating the urban heat island effect.

The study relied on four measurement points representative of the morphological diversity of the Casbah of Algiers:

Zone 1: A narrow urban canyon with poor ventilation and a sky view factor of 0.18.

Zone 2: An open square exposed to direct solar radiation with a sky view factor of 0.56.

Zone 3: A tree-lined street with moderate vegetation coverage and a sky view factor of 0.24.

Zone 4: A mineralized public space with little natural shade and a sky view factor of 0.29.

These measurement points helped identify the most vulnerable areas and analyze the potential effectiveness of thermal mitigation interventions.

This advanced modeling, coupled with the developed predictive algorithm, provides a crucial projection tool for anticipating the intensification of urban thermal stress and guiding future urban planning strategies. However, identifying these climatic and microclimatic trends is only the first step in the process of adapting urban spaces. It is necessary to translate this knowledge into concrete actions to reduce the impact of heatwaves and improve outdoor thermal comfort, particularly in areas where historical heritage imposes strict architectural intervention constraints.

How can Nature-Based Solutions be effectively implemented to improve thermal comfort while respecting historical heritage constraints?

In this context, Part 04 explores the integration of Nature-Based Solutions (NBS) to optimize outdoor thermal comfort in the Mediterranean climate. These solutions, such as vegetation implementation, green roofs and walls, and the use of high-reflectance materials, represent effective mitigation strategies against the urban heat island effect. The goal is to demonstrate how a combined approach to these different levers would not only limit the temperature variations recorded in Part 03 but also ensure thermal resilience adapted to the historic context of the Casbah of Algiers.

Preliminary studies suggest that increasing vegetated surfaces in public spaces by 20 to 30% could reduce perceived temperatures by 2 to 4°C during the summer period. Additionally, integrating green roofs and walls, coupled with the use of high-reflectance materials, would limit heat absorption and enhance nighttime thermal radiation, thereby reducing urban temperatures more uniformly.

The four measurement points defined in Part 03 will be reused to assess the effectiveness of NBS. Simulations will compare scenarios with and without intervention to quantify the impact of each strategy.

This new stage of research is thus part of a sustainable urban planning approach, reconciling heritage conservation and climate adaptation. By exploring the interactions between different NBS devices and their effects at the micro and macro urban scales, this section aims to provide an operational framework for urban planners and policymakers. The adopted approach will identify the optimal combinations of strategies, considering architectural and climatic constraints specific to each sector of the historic urban fabric.

Thus, building on the results of climate and thermal modeling from Part 03, Part 04 will propose a series of recommendations and planning scenarios incorporating NBS. These solutions aim to sustainably improve thermal comfort in urban areas while preserving the historical and architectural identity of the Casbah of Algiers. This multidimensional approach is a crucial step toward reducing the effects of climate change and designing more resilient and inclusive cities.

PART 04 : Coupling of different nature base solutions for pedestrian thermal comfort in a Mediterranean climate [P2]

VII. PART 04 : Coupling of different nature base solutions for pedestrian thermal comfort in a Mediterranean climate [P2]

1 Introduction:

According to the United Nations report (2014), more than half of the world's population live in cities (54%), and this proportion is expected to increase (United Nations, 2014). Indeed, an increase of 1.2 million km² is estimated, tripling the urban land cover in 2030 (Seto et al., 2012). Thus, urbanization and global climate change are the two significant factors affecting cities' climate.

The consequences of Climate change will be very violent, especially in Southern Europe and North Africa. Where according to the Intergovernmental Panel on Climate Change (IPCC 2014), most of the population will be exposed to anthropogenic climate change in urban areas. These global change issues are risks changing the pace of life in cities and their populations. These changes come in different ways: Increased heat stress due to rising temperatures, Increased droughts, greater severity of storms, and heat-related mortality as the central issue (Kjellstrom and McMichael, 2013).

In this context of climate change, microclimate studies have been attracting more and more attention in recent years. Currently, urbanization faces many challenges regarding people’s livelihood and well-being. The effect of Urban Heat Islands can be extremely severe on human health. Thermal discomfort is one of the major causes negatively affecting human wellbeing. During the heatwave, which lasted four days in January 2009 in Melbourne, 374 excess heat-related deaths were recorded (Jamei et al., 2016b).

Thermal comfort gauges human well-being, reflecting contentment with the temperature surroundings. It involves factors influencing heat exchange between the body and the environment (Hoof, 2010). Outdoor thermal comfort pertains to human preferences in the external physical environment. Evaluation typically relies on subjective user surveys or objective methods, employing micro-meteorological measures, modeling, and simulations.

Urban outdoor thermal comfort is influenced by air temperature, wind speed, humidity, and radiation (Johansson et al., 2014). The urban landscape and form impact these factors, affecting human health, outdoor activities, and tourism. Outdoor space usage is linked to the thermal environment, emphasizing the importance of a conducive setting (Lai et al., 2019b; Lin et al., 2012; Nikolopoulou and Lykoudis, 2007b). A comfortable outdoor environment encourages extended outdoor stays, potentially saving energy compared to building cooling loads (Berardi, 2016; Kong et al., 2016). To mitigate global warming effects and enhance urban thermal comfort, tested adaptation strategies are crucial. Integrated tools, such as land use policies and modeling techniques, are needed for effective implementation (Evola et al., 2017).

Research has suggested changes in urban morphology (Charalampopoulos et al., 2013; He et al., 2020a; Johansson and Emmanuel, 2006b; Taleghani et al., 2015b) taking into consideration the effect of H/W ratio and Sky view factor (Ali-Toudert and Mayer, 2006b; He et al., 2015b; Krüger et al., 2011b), Orientation and geometry form of urban canyons (Deng and Wong, 2020; Johansson, 2006b; Nasrollahi et al., 2021). Others recommend the use of green, blue, and white surfaces (Liu et al., 2021; Lobaccaro and Acero, 2015; Taleghani, 2018a), vegetation, and the shading effect (Gómez et al., 2004; Hwang et al., 2015; Lin et al., 2010b; Yu and Hien, 2006), or modern and innovative materials (Jacobson and Ten

Hoeve, 2012; Rosso et al., 2018c; Sailor, 1995; Santamouris, 2014). These strategies have been tested at different scales in different urban spaces in cities located in a wide range of climate regions. Nevertheless, studies on Heat-Mitigation Strategies in historical cities remain limited compared to modern cities and urban public spaces, as demonstrated in a review of the type of urban spaces used in the thermal-comfort studies (Nasrollahi et al., 2020).

Pedestrians have generally experienced viable outdoor thermal comfort in historic cities with a significant shading effect in the streets (Darbani et al., 2022), which allowed them to perform different activities in urban spaces (Markham, 1942). Indeed, the high and heavy walls provide more shading and heat storage, leading to lower surface temperatures (Ali-Toudert et al., 2005b). However, Historic cities are not immune to global warming and overheating (Bigio, 2014) and are weakened by the problems of changing land uses after their degradation. It is becoming urgent to integrate the development of historical cities into territorial projects and make it possible to readapt degraded or abandoned historic districts to contemporary urban life (UN Habitat, 2008).

Despite studies dealing with the morphological and bioclimatic specificities of traditional urban fabrics and outdoor thermal comfort, their number remains reduced compared to studies in contemporary cities. Nevertheless, few studies (Evola et al., 2017; Laureti et al., 2018b; Rosso et al., 2018c; Su et al., 2022) investigated the effect of heat-mitigations strategies on outdoor thermal comfort in traditional urban morphologies, specifically in the Mediterranean climate, following an empirical approach using the Physiological Equivalent Temperature.

Therefore, this study is motivated by limited knowledge regarding the mitigation strategies scenarios in historical urban fabrics. Outdoor urban comfort is investigated through a validated empirical approach. Then, a series of simulations using the computational fluid dynamic software ENVI-MET. Specifically, the study considers the outdoor thermal comfort conditions in four subspaces of a complex urban morphology in a Mediterranean climate. The current study is based on the micro-meteorological parameters collected in situ during the measurement campaign to quantify comfort. Then, the thermal comfort index, “physiological equivalent temperature,” and the effect of different heat mitigation strategies in Mediterranean historical cities will be considered to answer the research questions.

This work provides a framework for urban designers and managers to consider when developing environmental strategies to renovate and improve the cities. It evaluates the current conditions and uses empirical and numerical methods to compare outdoor thermal comfort during a heatwave under various scenarios. The aim is to guide decision-making based on a comparative approach. More specifically, the following questions are answered:

What are the summer thermal comfort levels in the historical urban fabric?

To what extent can heat mitigation strategies improve outdoor thermal comfort within the Casbah of Algiers?

What impact does coupling nature-based solutions have on outdoor thermal comfort in the Mediterranean regions?

This study breaks new ground by exploring the effects of various nature-based solutions within the framework of traditional city design, investigating the impact of strategies such as urban form adjustments, vegetation planting, implementation of green roofs and walls, and the utilization of high-reflectivity materials. The research offers a multifaceted examination of their individual and combined efficacy. Moreover, it innovatively navigates the constraints of a historical district where interventions are heavily regulated, emphasizing the importance of balancing urban heat reduction with the preservation of cultural heritage. By analyzing nature-based solutions at both micro and macro levels, the study not only sheds light on their singular impacts but also delves into the complex interactions that occur when these strategies are combined. This comprehensive approach provides valuable insights into optimizing urban design for sustainability and resilience, particularly in contexts where historical preservation guidelines pose unique challenges to modern interventions.

This parameterization brings added value by examining the interactions between different parameters by coupling two-level scenarios. On the one hand, it looks at interactions between parameters within the same category (such as nature-based solutions or cool materials), and on the other hand, it combines the best-case parameters into a global scenario specific to each study area. This research significantly contributes to urban climatology and provides solutions specific to historic urban areas.

Our research focuses on reducing heat in historic urban areas in the Mediterranean region with a specific case study showcasing the use of narrow and shallow street corridors, local materials, and a low height-to-width ratio. This study is aligned with Sustainable Development Goal 11, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable. Our study supports this goal by promoting responsible intervention in ancient cities that preserve cultural heritage while leveraging their adaptability to address the vulnerability, providing a new approach to enhancing thermal comfort through nature-based solutions and urban design. This case study is a valuable resource for urban planners and architects working in similar environments.

Finally, the study has bridged the gap in understanding how heat reduction strategies affect traditional urban areas. The results can be extended to other historic cities with comparable urban structures, such as Fatimid Cairo (Egypt), the Historic city of Toledo (Spain), Medina of Tunis (Tunisia), and Medina of Fez (Morocco).

2 Literature review:

Recent studies on outdoor thermal comfort amid climate change and warming temperatures, particularly in cities, have increased. With summers becoming longer and more unbearable, understanding and addressing thermal comfort is crucial. This literature review examines over 120 publications from Scopus and the Web of Science, focusing on outdoor thermal comfort, mitigation strategies, and historic cities. The review prioritizes studies using objective measurements and CFD simulations between 2010 and 2022, excluding those with different approaches.

Table 14: Literature review 2

Global Outdoor thermal comfort studies			
City (Country)	**Köppen classification**	**Key findings**	**Reference**
De Bilt (Netherlands)	Cfb	This study treated the different urban forms "Singular, Linear, and the courtyard" in different orientations - The mean radiant temperature and wind velocity are mainly influenced by urban geometry. - The courtyard provides the most comfortable microclimate in the Netherlands in June compared to the other studied urban forms.	(Taleghani et al., 2015b)
Several cities	Af, Aw, BWh, BSk, Cfa, Cwa, Csa, Cfs, Ca, Dwa, Dfb.	- More than 165 human thermal indices have been developed to date. The following 4: "PET, PMV, UTCI, SET" are the most used external thermal perception studies. - The neutral range for the PET index differs from one climate to another (e.g., hot climates: 24 - 26°C; cold climate: 15 - 20°C); On the other hand, for the UTCI, the “no thermal stress” category is common to all climates (18 - 23 °C)	(Potchter et al., 2018b)
Several cities	General	- Outdoor spaces are important to sustainable cities because they contribute to urban liveability and vitality. -The different levels of assessment are "Physical, physiological, psychological and social." These depend on factors of objective influence (Morphology, microclimate, energy balance) and subjective (Preferences, expectation,...)	(Chen and Ng, 2012b)
Curitiba (Brazil)	Cfb	- This paper presents the relationship between urban morphology and changes in microclimate and air quality within a city center through two approaches: First, the results of in-situ measurements and comfort surveys, then urban climate simulations using the ENVI-met software. - The results demonstrated the influence of SVF on thermal comfort. Also, although there is a high correlation between the Tmrt and the Sky view factor, the latter pointed to a null correlation between the diurnal urban heat island and the SVF.	(Krüger et al., 2011b)

Studies on mitigation strategies			
Delft (Netherlands), Almeria (Spain), Portland (USA)	Af, Csa, Csb, Cfb, Cwb	- This study reviews the effect of different heat mitigation strategies on human thermal comfort in urban open spaces. - The mitigation strategies studied are vegetation in different forms (parks, trees, green roofs, and walls) and highly reflective materials (roof and ground level) the main findings of the study are: - Highly reflective materials reduce the air temperature in urban open spaces and increase the re-radiation of the sun to pedestrians. - Mean radiant temperature affects human thermal comfort more than the other meteorological variables - Vegetation is a better choice for improving thermal comfort at the pedestrian level.	(Taleghani, 2018a)
Several cities	Af, Aw, Bsh, BWh, BSk, Cfa, Cwa, Csa, Cfs, Ca, Dwa, Dfb.	- This paper reviews the cooling effects of the mitigation strategies "urban geometry, planting vegetation, cool surface, and bodies of water." - Reflective surfaces can increase values in summer by increasing the reflected solar radiation. -Compact spaces are more recommended than open spaces in hot climates because they provide a better urban thermal environment. - Urban geometry has the greatest effect on the thermal environment in summer, followed by vegetation and water bodies.	(Lai et al., 2019b)
N/A	N/A	- State of the art on the development and assessment of cool materials. The research is developed on the parameters: Cool roofing materials, cool paving materials, PCM-doped infrared reflective coatings, and thermochromic materials. Findings show that White cool coatings have superior thermal performance.	(Santamouris et al., 2011)

		The developed colored materials have a higher near-infrared reflectivity than conventional materials of the same color and, therefore, have a higher overall solar reflectance effect.	
Several cities	Af, BWh, Cfa, Csa, Cwa, Cwb,	This article reviews studies on pedestrian-level urban greening and geometry in improving city thermal comfort. Parameters considered in this study are urban geometry through its different ways of application (Aspect ratio, Street orientation, Sky view factor, and local and neighborhood scale) and urban greening (Street trees, urban parks) and what are the stages of urban planning for the application of each. The correct choice of type, form, and density of vegetation to produce a positive thermal effect during summers and winters depends on the seasonal conditions of the region.	(Jamei et al., 2016b)
Studies on outdoor thermal comfort in traditional cities			
Avola (Italy)	Csa	- The study examines the outdoor thermal comfort in dense and old neighborhoods, which are often neglected in UHI research. A combination of field measurements and numerical simulations was needed for this study. - The study found that the UHI effect in the old city of Palermo is significant, with temperature differences up to 6°C. - The factors contributing to these neighborhoods' UHI effect are high population density, limited green spaces, and a high percentage of impervious surfaces.	(Evola et al., 2017)
Rome (Italy)	Csa	- This paper investigates the effects of climate change and global warming on urban historical areas in Rome while evaluating possible mitigation strategies that can be implemented. - The study is based on in-situ measurements and simulations to assess the thermal comfort in historical areas of Rome, -It was found that the urban density, high reflectivity of the materials used in the buildings, and the few existing green spaces make these areas vulnerable to overheating.	(Laureti et al., 2018b)

		- The proposed mitigation strategies are increasing the reflectivity of surfaces, increasing the number of green spaces, and building retrofits.	
Rome (Italy)	Csa	The paper study the effects of innovative material on the thermal comfort of pedestrians in historical urban canyons using combined field measurements and numerical simulations, focusing on two urban canyons: - First, traditional building materials (masonry and plaster) - Second, with innovative materials (reflective surfaces). - The Predicted Mean Vote (PMV) and Mean Outdoor-to-indoor Temperature Difference (MOCI) were used as thermal comfort indexes for this study - PMV values (-0.2 to +0.2) for the canyon with innovative materials (reflective surfaces) are more comfortable for pedestrians compared to the canyon with traditional materials (+0.5 to +1.5).	(Rosso et al., 2018c)
Biskra (Algeria)	BWh	- This study investigates the potential effects of climate change on outdoor thermal comfort in an arid region using a numerical model. - The approach used is based on the Perceived Temperature index (PT), using simulation software ENVI-met and calculation model RayMan. - The study results indicate a gradual increase in PT index values, beginning from 2020 and gradually elevating to 2080 during the hot season. - The difference in PT index averages at the hot season between 2020 and 2050 was (+5.9 °C), and 2080 (+7.7 °C) - Global warming could significantly increase the average temperature in the hot season, making the outdoor spaces in the arid region less comfortable and less available.	(Matallah et al., 2021d)

3 Methodology:

A conceptual framework of the study is developed that summarizes and visualizes the research methodology of this paper. As shown in Figure 38, the conceptual study framework is based on three methods: combining the literature review, In-situ measurement of microclimatic data, and numerical simulations. The presentation of the model consists of the literature review, selection criteria, and measurement campaign. This was followed by creating the model for the 4 study areas by characterizing the urban geometry and building properties to calibrate the simulated model with the real model. Then, the application of the preselected adaptation and mitigation scenarios and the calculation of the PET Index in the different scenarios. Finally, a comprehensive analysis of the results will be conducted in the data post-processing section.

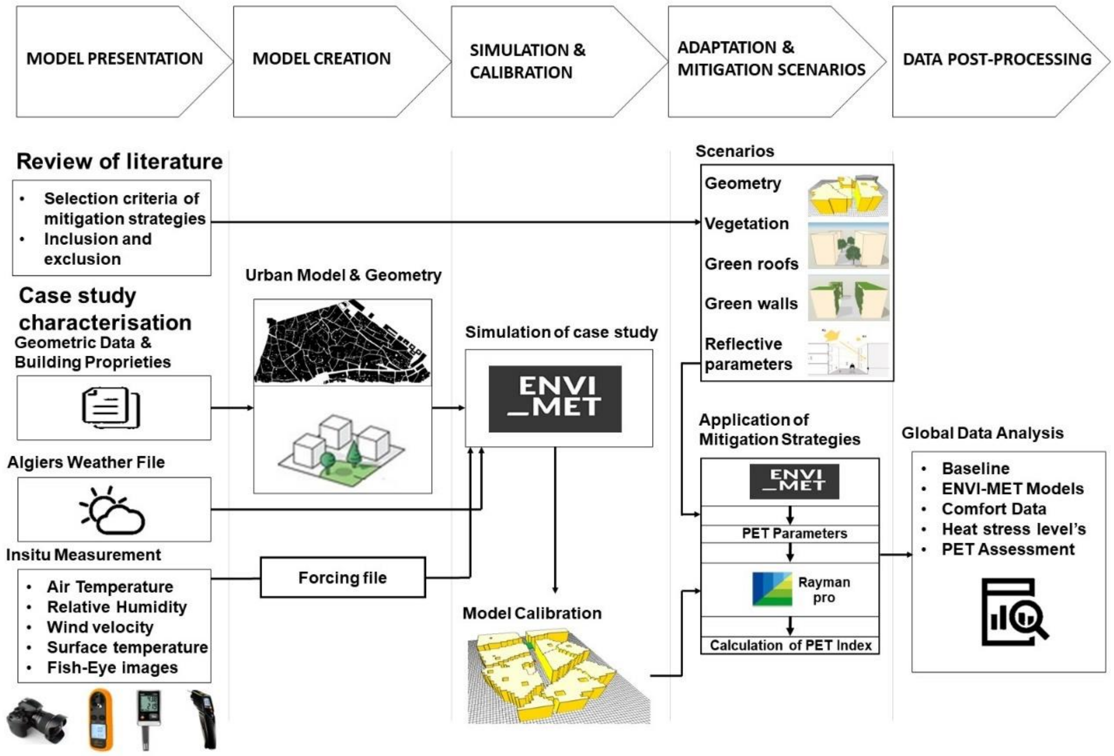


Figure 37: Study conceptual framework

3.1. Model presentation:

3.1.1. Algiers weather

Algiers' Casbah, situated at 36°47'00" N and 3°03'37" E, stands atop a 107 m high hill in Algeria. Positioned in the Mediterranean, a climate change hotspot (Giorgi and Lionello, 2008; Lionello et al., 2012), Algiers experiences notable summer warming and altered precipitation (Gatto et al., 2021). Over the past 30 years, "Algiers 603900" recorded 1440 heating degree days (HDD) and 956 cooling degree days (CDD). Algiers falls under the Warm Mediterranean Climate "CSA," characterized by scorching summers with an average high of 35°C and occasional peaks at 42°C. Winters see temperatures ranging from 0°C to 6°C.

3.2. Model creation & simulation:

ENVI-met, a three-dimensional non-hydrostatic microclimate model, is utilized for microclimatic analysis in urban planning and landscape architecture. Employing fluid dynamics and thermodynamics principles, it simulates interactions among buildings, soil, vegetation, and air to enhance air quality and mitigate the heat island effect. With a grid resolution of 0.5 to 10 meters and a time-step of 1–5 seconds, it offers high spatial resolution, making it a prominent choice for urban microclimate assessment (Taleghani et al., 2015b). Recognized for its holistic urban-scale approach, ENVI-met calculates detailed parameters, including Air temperature, relative humidity, wind speed, and mean radiant temperature, which is crucial for studies like calculating PET (Huttner and Bruse, 2008).

ENVI-met's calculation of Tmrt considers direct and diffuse short-wave irradiances and long-wave radiation fluxes from the ground, building surfaces, and the atmosphere (Ali-Toudert and Mayer, 2007b). Widely validated and reputable, ENVI-met stands as a dynamic simulation tool for microclimate simulations and outdoor thermal comfort assessment (Tsoka et al., 2018). In our study, we specifically focus on the four main parameters for PET calculation (Matallah et al., 2021b).

3.2.1. Modeling on ENVI-met:

The four study areas were modeled using the "SPACES" workspace in ENVI-met. Starting first with the model location and geographic coordinates, the degree of rotation of north. And details of the geometry of the model (Table 16) such as the dimension of the grids along the axes (X, Y, Z) and the size of the grid's cell in meters. Following this, The 2D drawings were done based on existing plans in bmp formats. According to the existing data, building materials, heights, vegetation, and soil were chosen. Through ENVI-met's "DB Manager" tool, The creation of traditional materials for walls and roofs was carried out, as demonstrated in the building material section of Table A1.

It is important to note that, in order to achieve grid-independent solution validation, we followed the modeling recommendations of Prof. Bruse, who suggested adding 5 to 10 empty cells along the model boundaries to ensure a more accurate model and precise airflow movements (Shinzato et al., 2019). In our case, we added 10 cells on each side.

We employed a 60-minute interval for output data in our model, covering building data, radiation, soil, and vegetation data. Regarding time steps, our model operates through the following sequence:

- Time step T0 (2s) - Time step T1 (2s) - Time step T2 (1s).

Concerning update timing, we relied on the default values provided by the software:

Plant processes: 600s ; Surface Data: 30s ; Radiation and Shadows: 600s ; Flow field: 900s

Hence, we can determine the number of iterations as follows:

$$\boldsymbol{Number\ of\ iterations} = \frac{\text{Simulaion Time Step}}{\text{Update interval}} \tag{1}$$

3.2.2. Meteorological parameters forcing:

Regarding the microclimatic parameters, the full forcing option was selected. The meteorological data were used based on CSV files and entered on ENVI-met's full forcing manager settings. We should indicate that CSV data files contained all meteorological parameters measured in sites. Our meteorological data entries cover the period of the in-situ data collection "From 5th to 11th August 2021".

3.2.3. Simulation of case study

The start of simulation time was set up before sunrise, ensuring stable conditions (Shinzato et al., 2019) based on the microclimatic measurement files. The total simulated time was 72h, set from 00:00 am (08.08.21) to 11:59 pm (10.08.21). The first hours of the model run were discarded to avoid any model spin-up effects (Tseliou et al., 2022).

In the outputs, the four main parameters "Ta. HR. Va and Tmrt" were used to calculate the outdoor thermal comfort index. The (PET) is one of the most common indices (Potchter et al., 2018b) and is certificated by the German VDI-Guidelines 3787 to assess the urban scale's thermal comfort. The shared dataset (Arrar et al., 2023) summarizes all the output data.

The calculation of the PET comfort index was performed with the BioMet ENVI-met add-on tool. The BioMET calculates the thermal indices by summarizing the impact of some ENVI-met atmospheric outputs using the simulated values of the hourly Tair (◦C), humidity (RH%), mean radiant temperature (Tmrt, °C), and wind speed (WS, m/s) (Tseliou et al., 2022).

3.3. Model Calibration:

In this study, the ENVI-met model's accuracy was assessed through a comparison of measured and simulated data, with a focus on validating the simulations against ASHRAE guideline 14 limits. Calibration criteria included adherence to neighborhood models and metrics evaluation using Root Mean Square Error (RMSE) and Mean Bias Error (MBE) (Attia et al. 2021). The RMSE gauges the simulation model's ability to capture variability in measured data, while the MBE provides a nondimensional measure of overall bias error over a known time resolution (Attia et al., 2021). Validation specifically targeted "air temperature" parameters, following a 72-hour duration simulation, in line with Taleghani's recommendation (Taleghani et al., 2014b). Figure 41 and 42 summarizes the validation outcomes for the four zones.

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (Sim_i - Obs_i)^2} (\%) \quad (2)$$

$$MBE = \frac{1}{n} \cdot \sum_{i=1}^{n} (Sim_i - Obs_i) \ (\%) \quad (3)$$

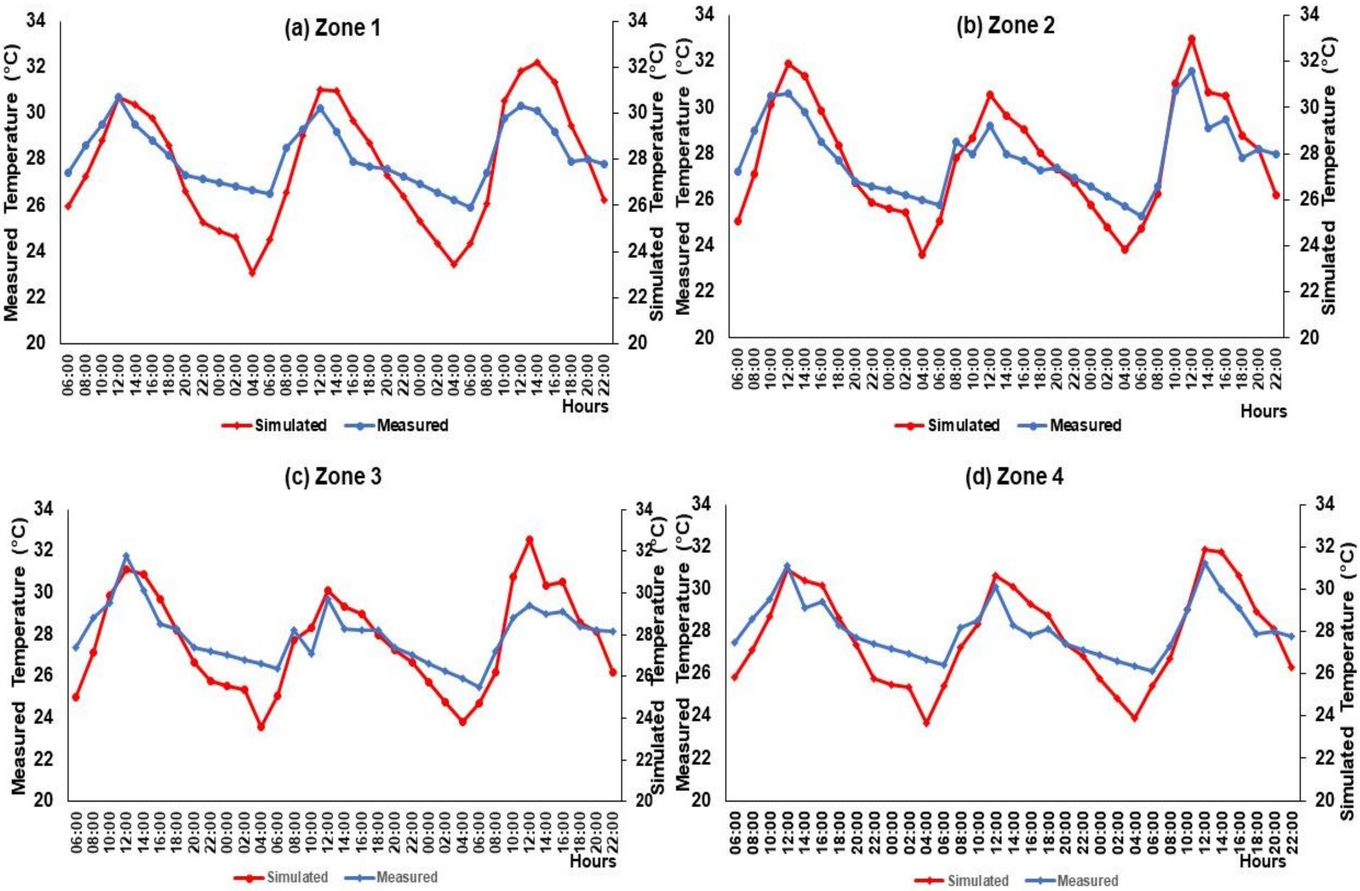
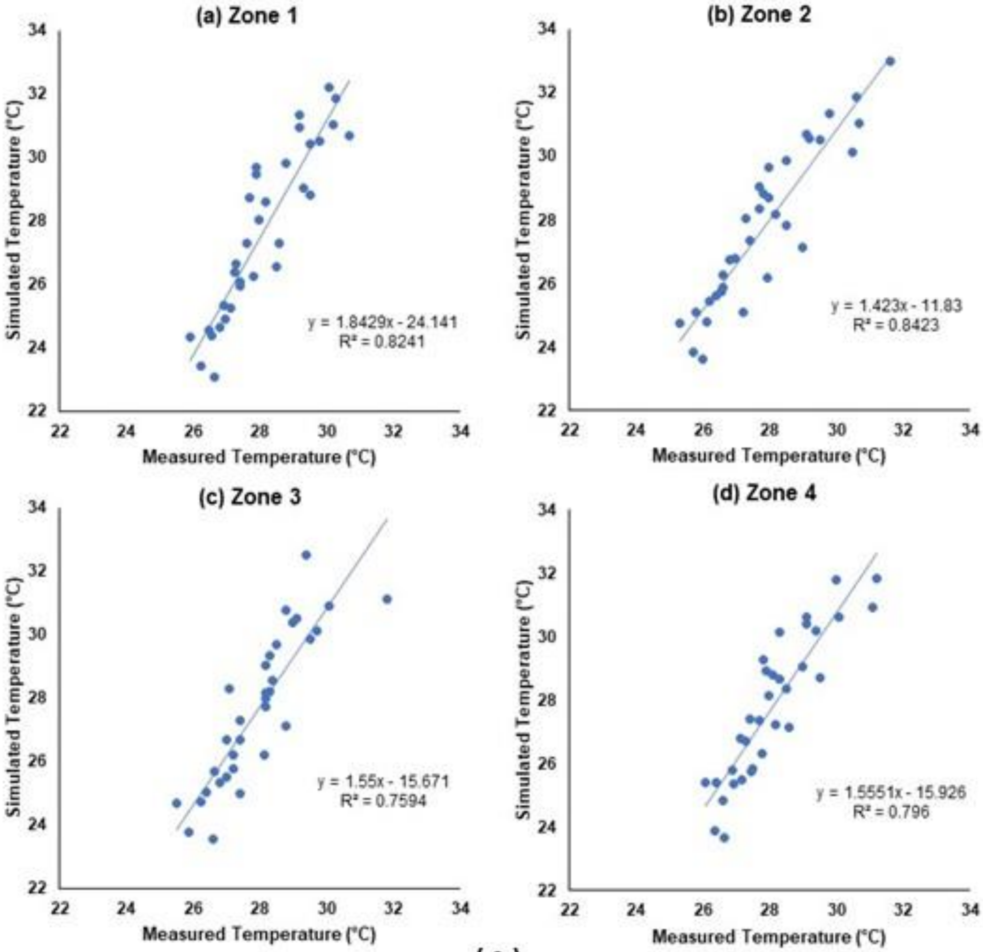


Figure 38: Validation measured/ simulated for 08-10.08.2021(a. Zone 1 b. Zone 2 c. Zone 3 d. Zone 4)



(A)

Zones	Zone 1	Zone 2	Zone 3	Zone 4
RMSE	1.61	1.19	1.39	1.28
	5.72%	4.26%	4.96%	4.55%
MBE	- 0.44	- 0.05	- 0.30	- 0.32
	- 1.56%	- 0.16%	- 1.06%	- 1.15%

(B)

Figure 39: A. Correlation Air temperature measured/ simulated for 08-10.08.2021 (a. Zone 1 b. Zone 2 c. Zone 3 d. Zone 4)

B. Validation of the model using RMSE / MBE

According to the ASHRAE Guideline 14, the simulation model is considered calibrated if it has an MBE that is not larger than 10%. (RMSE) is not larger than 30% when the Hourly data are used for the calibration. Although the literature review shows that the validation is carried out on a 48h simulation running using the air temperature parameter (Hien et al., 2012a; Sodoudi et al., 2018). The model was validated for 72 hours to improve its accuracy. These measures of model accuracy have also been used in other studies (Ali-Toudert, 2005; Emmanuel and Fernando, 2007; Yang et al., 2013).

3.4. Adaptation and mitigation scenarios

3.4.1. Mitigation scenarios

In this paper, the impact of various strategies on thermal-comfort improvement for pedestrians is thoroughly evaluated and compared for urban areas of the Casbah of Algiers. The paper presents four groups of strategies, namely "geometry, vegetation, green surfaces, and material parameters" in Figure 43, and different scenarios for each group. The specifics of how these strategies are applied in each study area are outlined in Table 17.

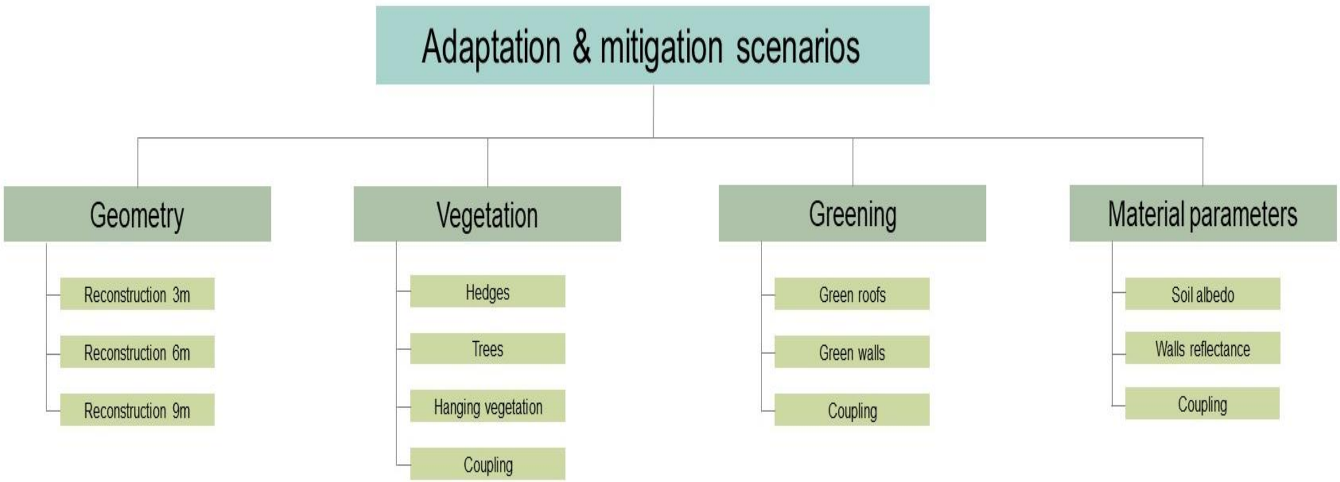


Figure 40: Adaptation and mitigation strategies selected in the study

3.4.2. Geometry

Urban geometry, particularly the arrangement of streets and buildings, significantly influences the thermal comfort of pedestrians. Research by (Santamouris, 2013b) and (Roshan et al., 2020b). Emphasizes the impact of urban canyons and their role in wind cooling potential, which can alleviate heat stress. The Andreou study (Andreou, 2013) underscores the substantial influence of solar radiation on thermal comfort, with a potential 10°C difference in predicted mean vote temperature (PET) between shaded and sun-exposed locations. Parameters like street orientation, building aspect ratio, and sky view factor, as highlighted by (Jamei et al., 2016b)., are crucial for determining canyon geometry.

In the context of our study, we aim to preserve the traditional aesthetic of the surrounding urban area while addressing vacant lots and ruined houses. The proposal suggests rebuilding using locally-sourced materials at varying heights—3, 6, and 9 meters. This strategy seeks to maintain the site's integrity, contributing to both urban sustainability and thermal comfort for residents.

3.4.3. Vegetation

Vegetation, highlighted by (Zölch et al., 2016), is vital for mitigating urban heat. Studies(Lai et al., 2019b; Nasrollahi et al., 2020; Shashua-Bar et al., 2011; Sodoudi et al., 2018) explore its impact on microclimates, emphasizing temperature reduction and wind influence. (Dimoudi and Nikolopoulou, 2003) Emphasize how urban vegetation alters air temperature, humidity, and wind patterns.

Street greenery not only offers physical and psychological comfort but is aesthetically valued (Klemm et al., 2015b) (Morakinyo et al., 2017) found that tree shade in urban canyons reduces surface and radiant energy during the day, enhancing nighttime comfort. Green canopies, as per (Fahmy et al., 2020c)., improve microclimates and cut energy consumption.

Given the limited vegetation in Algiers' Casbah, nature-based solutions are crucial for thermal comfort. The study proposes scenarios aligned with the historic fabric, such as Robinia/False Acacia rows, 2m high hedges, suspended vegetation at 5m, and a combination. Table 4 summarizes their arrangements, aiming to provide insights into sustainable urban planning in the Casbah.

3.4.4. Greening

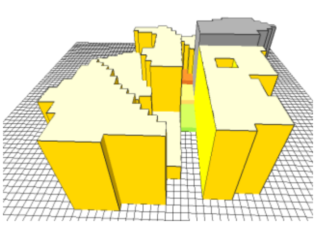
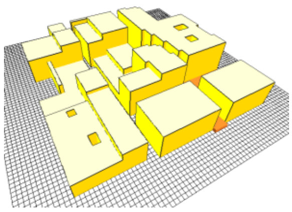
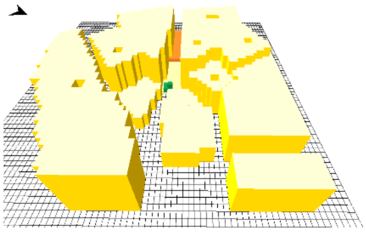
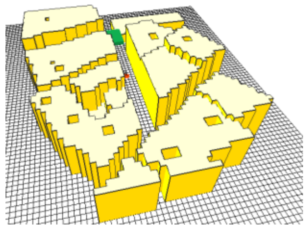
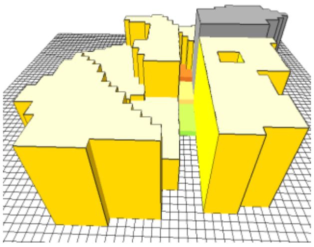
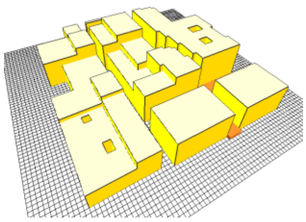
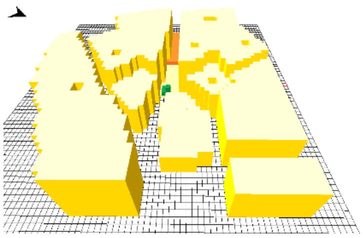
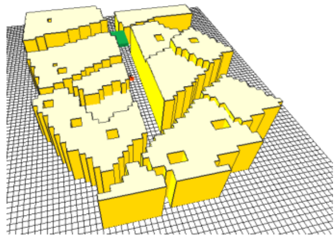
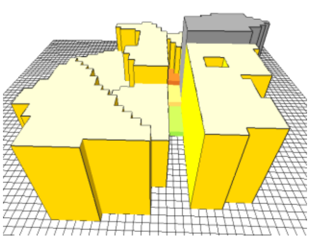
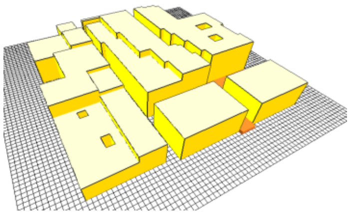
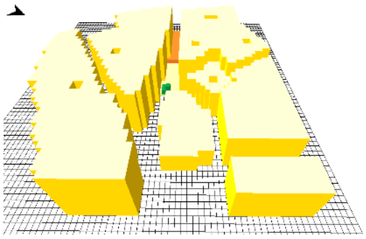
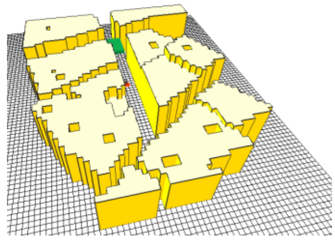
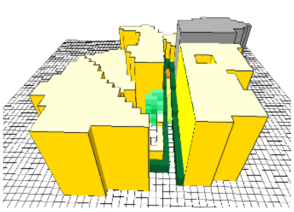
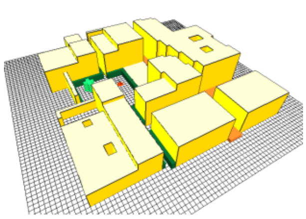
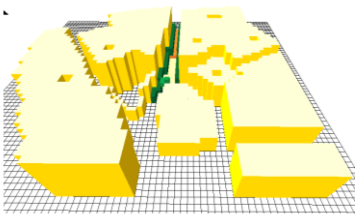
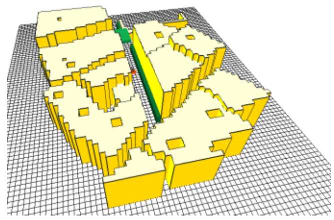
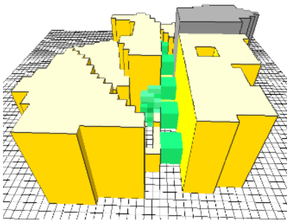
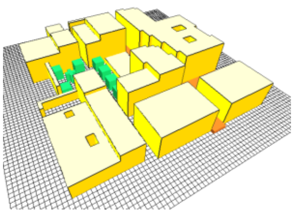
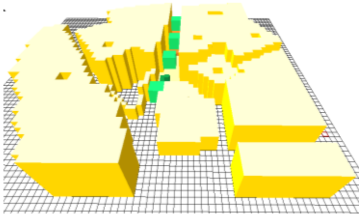
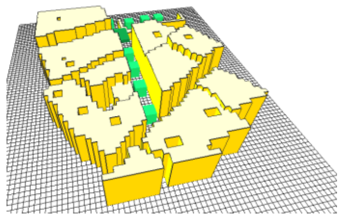
Among nature-based solutions strategies, greenery systems are considered one of the most appropriate sustainable solutions to resolve urban heat island-related issues (Besir and Cuce, 2018). Green roofs and walls are two examples of adding vegetation to urban canyons, especially as their impacts can be used to enhance the building performance in terms of energy efficiency and indoor and outdoor comfort (Manso and Castro-Gomes, 2015; Santamouris, 2014). Several studies have been conducted on the performance of greening built surfaces (Klemm et al., 2015a; Salata et al., 2017; Taleghani et al., 2014a), also knowing that Roofs account for nearly 20–25% of overall urban surface areas (Raji et al., 2015).

In the study, three greening scenarios are included to investigate their impact on the urban morphology of the four predefined zones. First, a case of green roofs at the level of the study area, then a scenario of green walls along the length of the urban canyon, and finally, study the effect of coupling the two strategies in the same scenario.

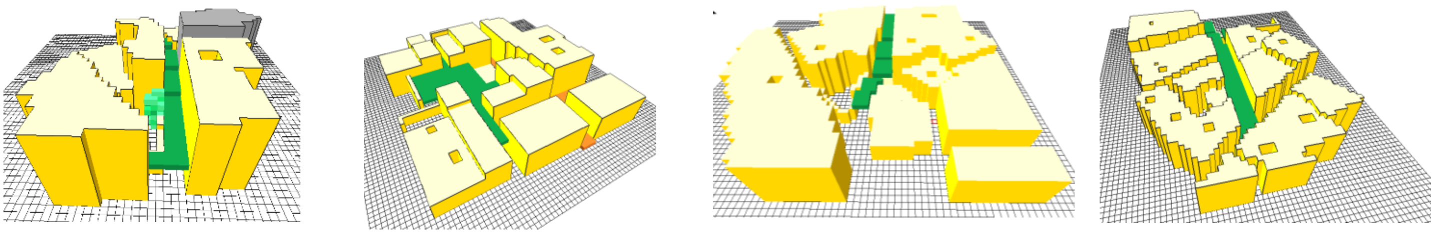
3.4.5. Material parameters

The Casbah of Algiers, characterized by dark gray pavements and white houses, is a prime candidate for mitigating urban heat through architectural strategies. Reflective materials, cool roofs, and urban greening have garnered attention for their potential to reduce indoor and outdoor overheating (Morini et al., 2018; Oleson et al., 2010; Synnefa et al., 2007) (Pisello, 2017). Highly reflective surfaces in urban canyons can efficiently reflect solar radiation, aiding in heat dissipation and alleviating urban heat islands (Mohajerani et al., 2017). Three scenarios are proposed to assess the impact on the Casbah: modifying soil albedo from 0.40 (Current) to 0.80, analyzing the effect of wall reflectance from 0.50 (Current) to 0.80, and exploring a combined scenario incorporating both strategies.

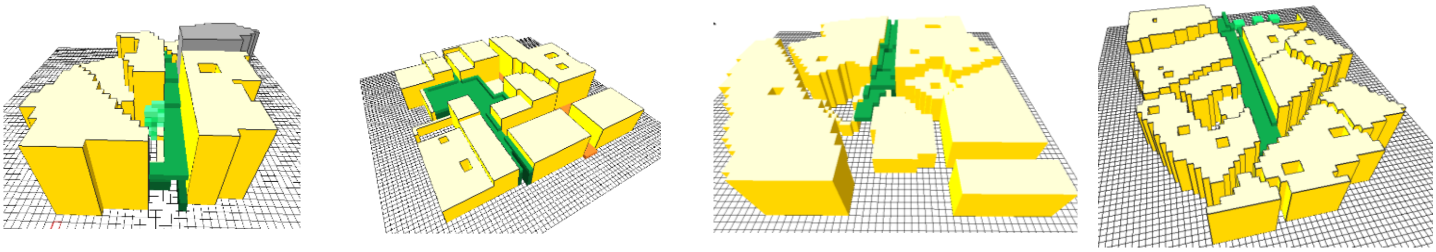
Table 15: Application of the mitigation scenarios in the four site locations

	Zone 1	Zone 2	Zone 3	Zone 4
		Géométrie		
Reconstruction 3m				
Reconstruction 6m				
Reconstruction 9m				
		Végétation		
Hedges				
Trees				

Hanging vegetation

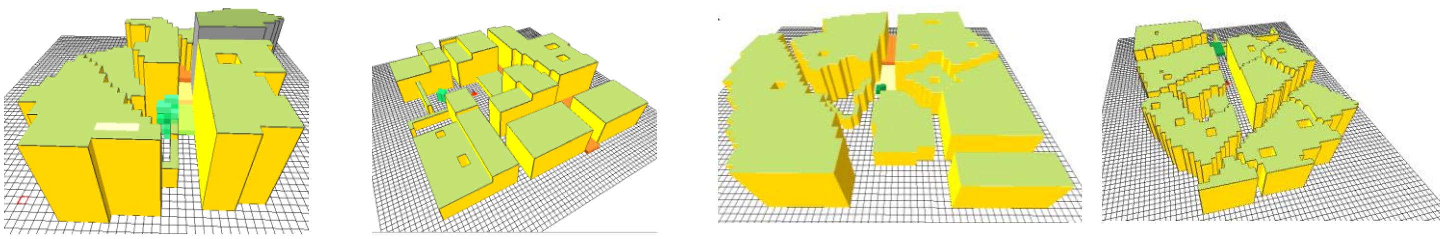


Coupling

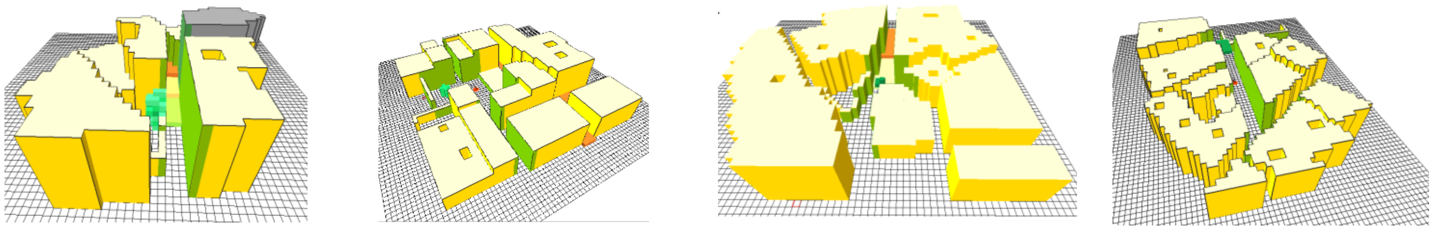


Greening

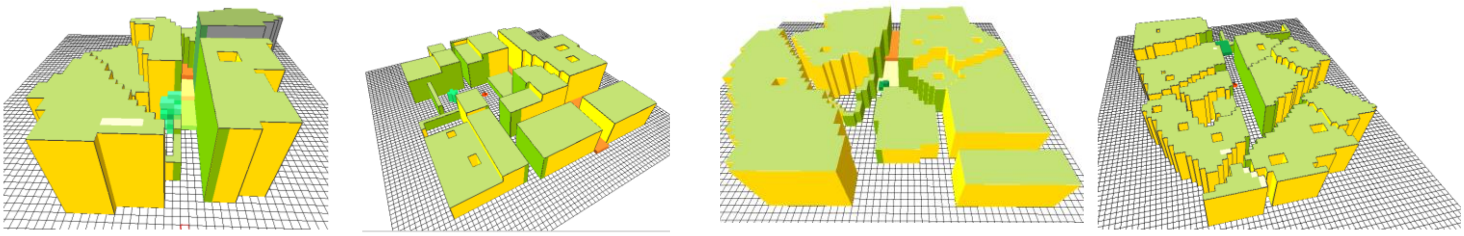
Green roofs



Green facades



Coupling



Material parameters

1.Soil albedo	Actual: 0.4 Proposed: 0.8	2. Walls reflectance:	Actual: 0.50 Proposed: 0.8	3. Coupling: Soil Albedo (0.8) and reflective walls (0.8)

3.4.6. Coupling scenarios

In this section, we define the best-case scenario for each of the four areas to simulate the PET Index. After simulating previous scenarios and analyzing the results for "Morphology, vegetation, greening, and materials parameters," we designed specific plans for each zone based on the optimal outcomes. A subsequent simulation incorporates the best-case strategies from each family. Figure 44 provides a concise overview of the scenario composition for each zone.

The coupled scenarios are, therefore, as follows:

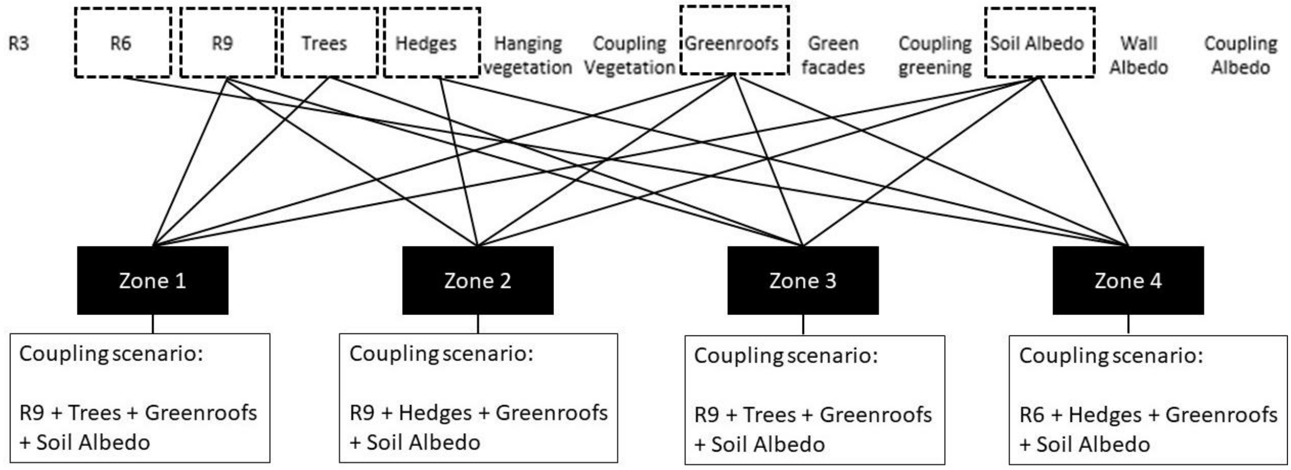


Figure 41: Composition of the best-case scenarios for the four zones

3.4.7. Calculation process of PET Index and heatmaps

The most critical factors of PET are the mean radiant temperature Tmrt (◦C) (Y-C Chen and Matzarakis, 2014), wind speed (m/s), and air temperature (◦C) (A. Matzarakis, 2018). Relative humidity RH (%) only shows a very weak impact on PET (Fröhlich and Matzarakis, 2016b). The overall thermal impact on PET is determined using a human energy balance equation based on the Munich Energy Balance Model for Individuals (MEMI) (3). (P. Höppe, 1999).

$$M + W + R + C + E_{SK} + E_{RE} + E_{SW} + S = 0 \qquad (4)$$

M: metabolic heat production

W: mechanical work

R: fluxes of radiation

C: sensible heat

ESK: latent heat (skin)

ERE: latent heat (respiratory system)

ESW: latent heat sweating

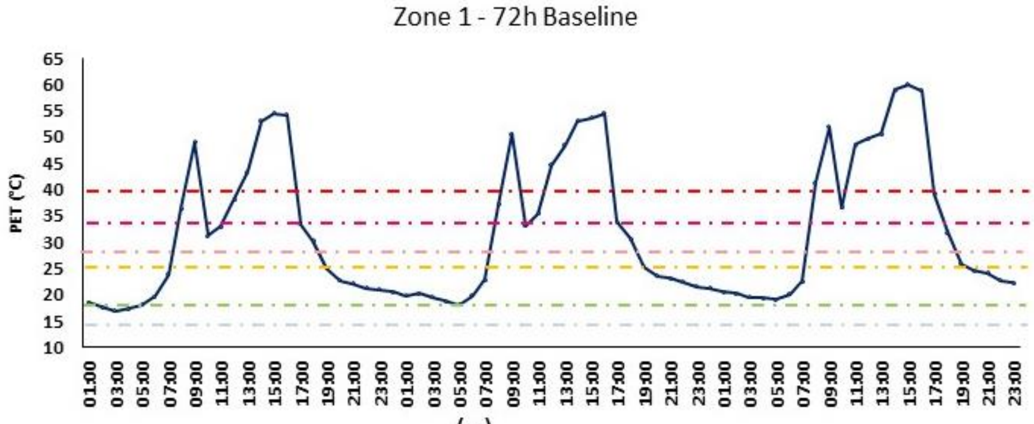
S: heat storage

ENVI-met simulated atmospheric conditions and used BIO-met to calculate the Physiological Equivalent Temperature (PET) for thermal comfort evaluation. Four zones underwent baseline and 13 mitigation scenario simulations. PET results were categorized into nine thermal perception levels. Using the LEONARDO tool, the main results at a specific point were analyzed, and visual PET maps at 1.40m height for all scenarios in four zones at 12:00 pm were generated.

4 Results:

4.1. What are the summer thermal comfort levels in the historical urban fabric?

Zone 1:



District	Days	PET 5:00 am	PET 8:00 am	PET 10:00 am	PET 12:00 pm	PET 3:00 pm	PET 5:00 pm	PET 8:00 pm	PET 10:00 pm
Zone 1	Baseline	19.1	41.3	36.5	49.8	59.9	39.2	24.6	22.8
	Rebuild 9m	17.3	34.9	31.5	34.6	56.3	33.7	23.0	21.3
	Trees	18.3	35.0	30.5	33.0	54.2	32.1	23.2	21.5
	Greenroofs	18.1	35.2	31.7	35.1	56.1	33.5	23.1	21.3
	Soil Albedo	18.1	35.2	31.8	34.9	56.0	33.4	23.0	21.3
	Coupling scenarios	17.4	34.6	30.5	32.7	55.0	32.1	23.0	21.3

	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal comfort	Slightly cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress level	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

(b)

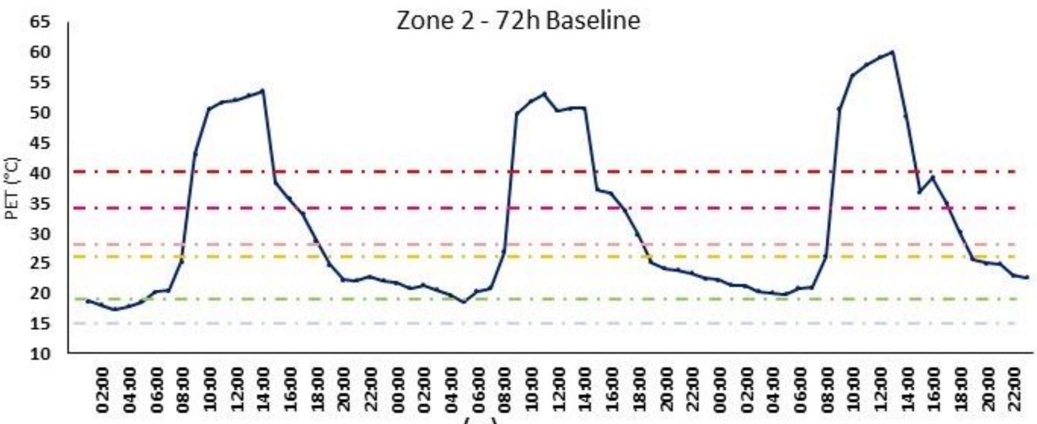
Figure 42: (a) 72h PET Values for the zone 1 from 08.08.2021 to 10.08.2021

(b) PET Values for the best-case scenarios in zone 1 on 10.10.2021

Figure 45 (a) shows the Physiological Equivalent Temperature (PET) in measurement zone 1 from 08.08.2021 to 10.08.2021. The baseline exhibits a repeating 4-phase pattern over the 3 days. PET values rise from 4:00 am to 9:00 am and 11:00 am to 4:00 pm. From 9:00 am to 10:30 pm, a decrease occurs due to solar radiation masking. Temperature drops from 5:00 pm to 3:00 am, with a decrease from 2:00 pm to 6:00 pm as solar radiation lessens. The highest values, reaching 59.9°C on 10.08, are at midday (3:00 pm). PET assessment reveals three comfort levels (Neutral, hot, extremely hot) in zone 1 during the period, aligning with Mediterranean climate standards (Potchter et al., 2018b).

Figure 8(b) illustrates discomfort from 8:00 am to 5:00 pm. In the baseline, heat stress peaks (> 40 °C) from 12:00 pm to 3:00 pm. Various scenarios reduce heat stress levels by nearly two levels compared to the baseline, but at 3:00 pm, heat stress remains extreme.

Zone 2:



(a)

District	Days	PET 5:00 am	PET 8:00 am	PET 10:00 am	PET 12:00 pm	PET 3:00 pm	PET 5:00 pm	PET 8:00 pm	PET 10:00 pm
Zone 2	Baseline	19.9	26.1	56.1	59.1	36.8	35.1	25.1	23.0
	Rebuild 9m	17.4	23.1	31.4	36.1	35.4	33.9	23.5	21.7
	Hedges	19.2	24.2	51.5	53.5	37.2	33.2	24.7	22.7
	Greenroofs	18.8	24.2	52.1	54.0	39.5	33.6	24.2	22.2
	Soil Albedo	18.8	24.3	52.2	54.8	42.9	33.6	24.0	22.0
	Coupling scenarios	18.6	23.8	30.9	35.2	33.8	32.8	24.3	22.7

	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal comfort	Slightly cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress level	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

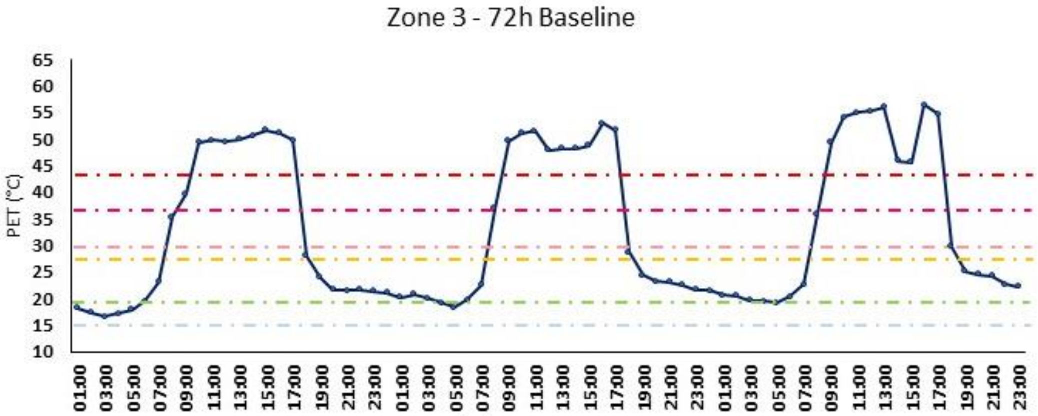
(b)

Figure 43: (a) 72h PET Values for the zone 2 from 08.08.2021 to 10.08.2021

(b) PET Values for the best-case scenarios in zone 2 on 10.10.2021

Figure 46 (a) depicts the Physiological Equivalent Temperature (PET) in measurement zone 2 from 08.08.2021 to 10.08.2021. Baseline graphs exhibit two phases daily: PET rises from 4:00 am to 1:00 pm, then decreases from 2:00 pm to 10:00 pm. Peak PET is 59.1°C at noon. Figure 9 (b) displays four comfort levels: Neutral, Slightly warm, Hot, and Extremely hot. Extreme discomfort (>50°C) is observed from 10:00 am to 12:00 pm. Strong heat stress (>34°C) occurs from 3:00 pm to 5:00 pm in the baseline. Reconstruction of deteriorated spaces notably improves comfort, reducing PET to 36°C outside the "Extreme heat stress" zone. Other scenarios lower midday PET by 6°C but still result in extreme heat stress.

Zone 3:



(a)

District	Days	PET 5:00 am	PET 8:00 am	PET 10:00 am	PET 12:00 pm	PET 3:00 pm	PET 5:00 pm	PET 8:00 pm	PET 10:00 pm
Zone 3	Baseline	19.3	36.0	54.2	55.4	55.7	54.6	24.5	22.6
	Rebuild 9m	17.7	34.0	48.7	49.2	51.5	50.7	23.0	21.3
	Trees	17.9	33.8	48.4	48.3	50.4	50.1	23.2	21.5
	Greenroofs	17.7	34.1	49.5	49.8	52.0	51.2	23.0	21.2
	Soil Albedo	17.7	34.1	49.2	49.8	52.1	50.8	23.0	21.2
	Coupling scenarios	17.7	34.0	49.2	49.3	51.3	50.7	22.9	21.3

	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal comfort	Slightly cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress level	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

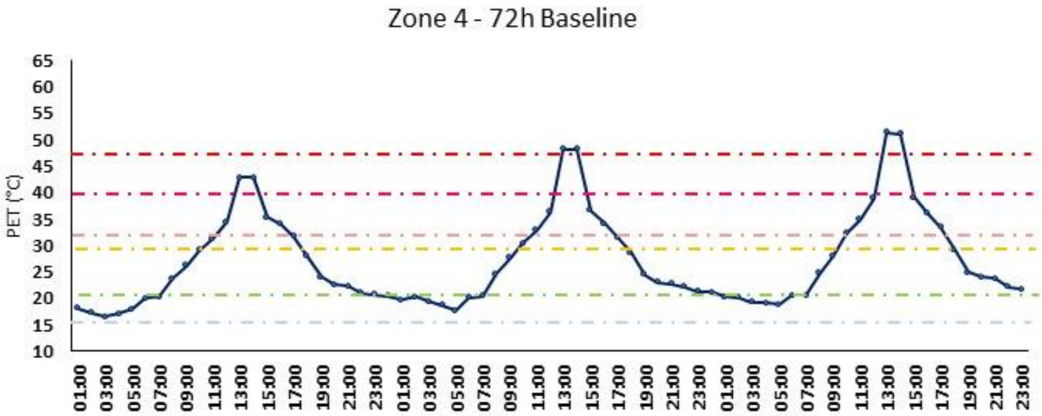
(b)

Figure 44: (a) 72h PET Values for the zone 3 from 08.08.2021 to 10.08.2021

(b) PET Values for the best-case scenarios in zone 3 on 10.10.2021

The graph for zone 47 (Figure 10) shows three distinct phases during the day, with an increase in PET values from 4:00am to 10:00am, a stable period from 10:00am to 5:00pm, and a decrease from 5:00pm to 10:00pm. This area is the most critical, with temperatures exceeding 52°C from 10:00am to 5:00pm, due to its E-W orientation and high H/W aspect ratio of 2.07. Figure 10(b) shows that this area experiences extreme discomfort (>40°C) all day long, with a particular heat stress (>54°C) from 3:00pm to 5:00pm in the baseline case. However, there is a rapid drop in temperature to a neutral level at 8:00pm. The proposed mitigation scenarios have a slight impact, reducing PET values by 6°C on average, but temperatures remain at an extreme level during the day.

Zone 4:



(a)

District	Days	PET 5:00 am	PET 8:00 am	PET 10:00 am	PET 12:00 pm	PET 3:00 pm	PET 5:00 pm	PET 8:00 pm	PET 10:00 pm
Zone 4	Baseline	18.9	24.8	32.2	39.0	39.1	33.5	24.1	22.1
	Rebuild 9m	17.8	23.2	29.6	35.3	36.8	32.3	23.1	21.2
	Hedges	18.1	23.0	28.8	34.2	35.4	31.3	23.6	21.7
	Greenroofs	17.8	23.3	29.7	35.3	36.9	32.3	23.0	21.1
	Soil Albedo	18.2	23.7	30.1	35.8	36.9	32.2	22.9	21.1
	Coupling scenarios	18.6	24.0	30.1	35.5	36.0	31.9	23.4	21.7

	15 - 19	19 - 26	26 - 28	28 - 34	34 - 40	> 40
Thermal comfort	Slightly cool	Neutral	Slightly warm	Warm	Hot	Extremely hot
Stress level	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

(b)

Figure 45: (a) 72h PET Values for the zone 4 from 08.08.2021 to 10.08.2021

(b) PET Values for the best-case scenarios in zone 4 on 10.10.2021

In Figure 48 , the baseline graph of Zone 4 shows a temperature increase from 4:00 AM to 1:00 PM, followed by a decrease from 2:00 PM to 11:00 PM. There are four thermal comfort levels during the day in this zone: slightly cool, neutral, warm, and hot. The area experiences strong heat stress from 12:00 PM to 3:00 PM and moderate heat stress at 10:00 AM and 5:00 PM. Hedges have the best cooling effect, reducing the temperature by almost 5°C and bringing the comfort level to a lower state.

4.2. Which mitigation parameters to considered in reducing thermal stress levels in the Mediterranean climatic zone?

The assessment of PET in the four zones, depending on the mitigation scenarios at 8:00am,12:00pm and 5:00pm, is illustrated in the next section (Figures 49 to 52). The best case is taken according to temperature improvements throughout the day.

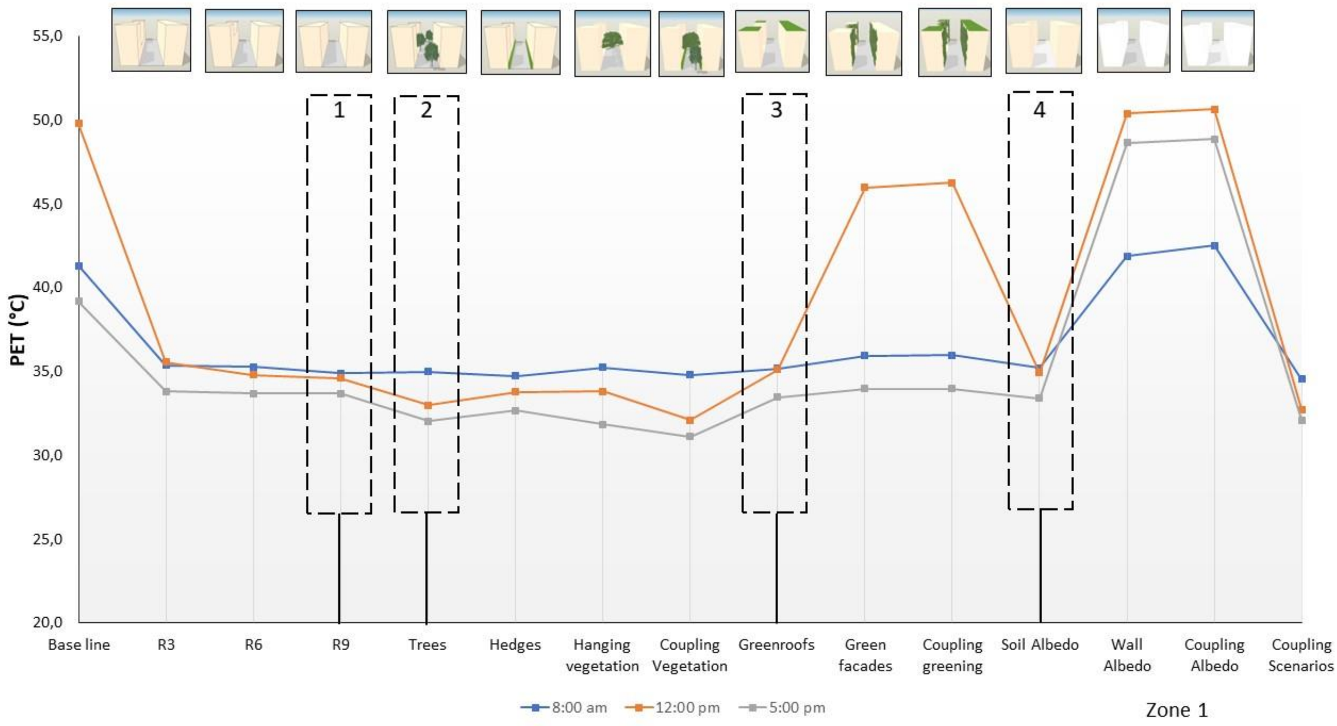


Figure 46: Mean cooling effect in zone 1 by different scenarios on 10.08.2021 at 8 a.m, 12 p.m, and 5 pm

Figure 49 illustrates diurnal PET variation for 14 scenarios in zone 1 at 8 am, 12 pm, and 5 pm PET values generally peak at 8 am, with 12 pm reaching 50.6 °C in "Coupling albedo." At 5 pm, the lowest value is 31°C in "Coupling vegetation" with trees, hedges, and hanging vegetation. Notably, PET is generally better at 5 pm for most scenarios, except those involving wall albedo due to iteration issues. Cooling effects vary at noon, with minimal differences between coupling and individual scenarios. Optimal configurations for zone 1, based on overall PET improvement, are "Rebuild 9m, trees, green roofs, and soil albedo."

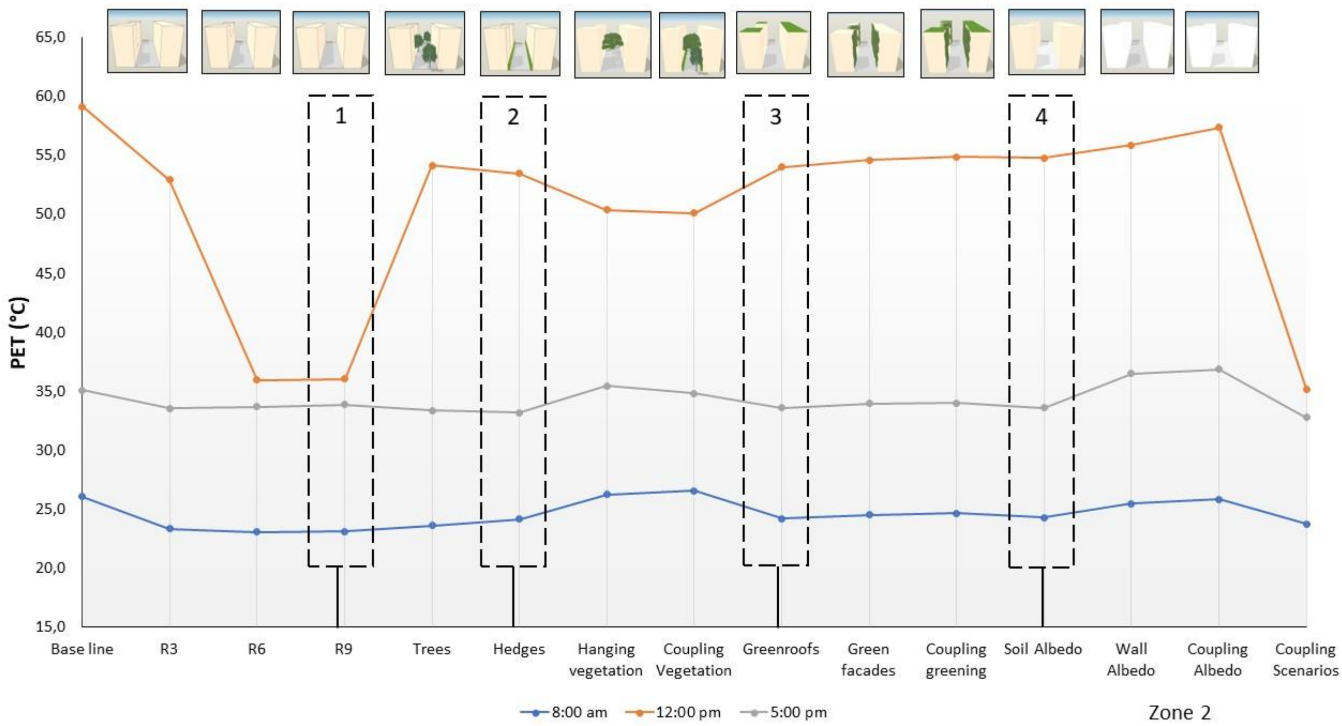


Figure 47: Mean cooling effect in zone 2 by different scenarios on 10.08.2021 at 8 a.m, 12 p.m, and 5 pm

Figure 50 shows PET variation at 8 am, 12 pm, and 5 pm in zone 2. The lowest PET is at 8:00 am in all scenarios. The highest average PET is at 12:00 pm, with coupling albedo reaching 57.7°C. The lowest temperature is in "rebuild 6" at 8:00 pm at 23.1°C. Cooling differences between scenarios are similar at 8:00 am and 5:00 pm but more noticeable at 12:00 pm Albedo and greening coupling scenarios don't outperform individual scenarios due to a single parameter impact, e.g., global coupling affected by rebuild 9m at 12:00 pm

Morphological scenarios have the greatest influence, improving PET by 23°C at 12:00 pm Among vegetation scenarios, "hanging vegetation" cools most at 12:00 pm, but "hedges" perform better overall. The best configurations for daily cooling in zone 2 are "Rebuild 9m," "hedges," "green roofs," and "soil albedo".

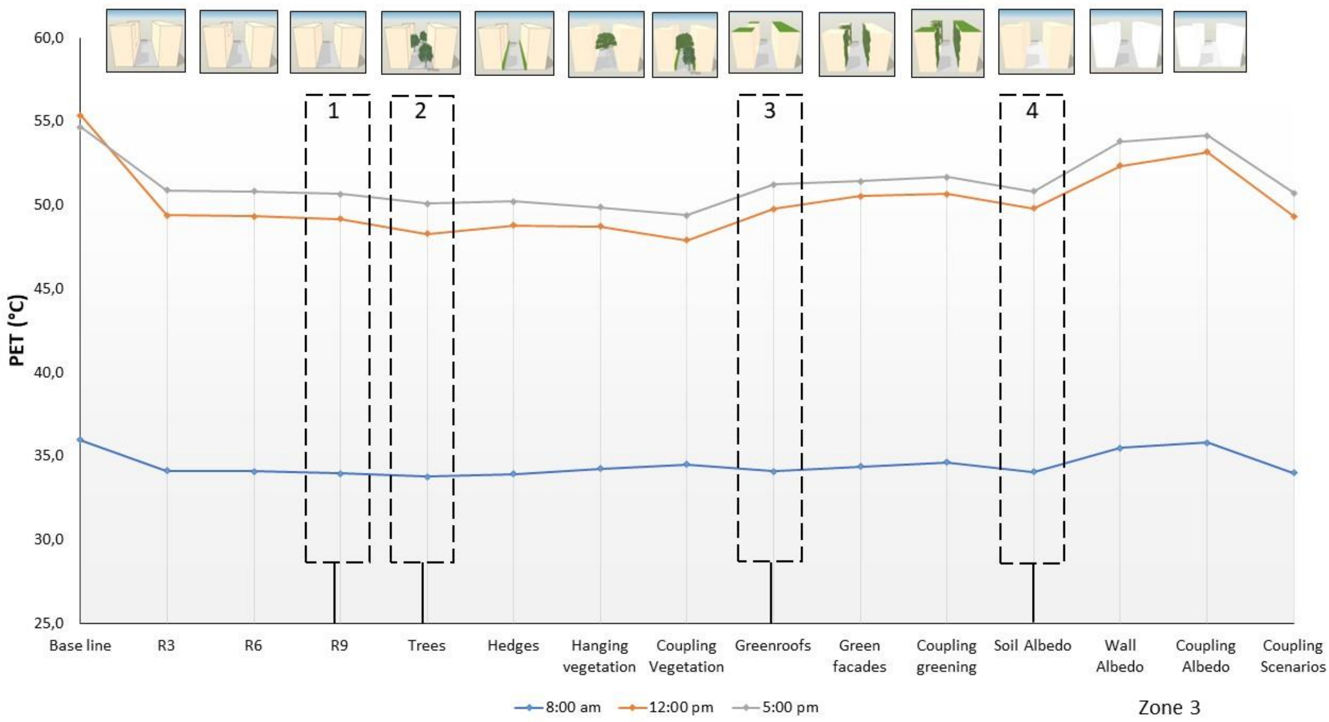


Figure 48: Mean cooling effect in zone 3 by different scenarios on 10.08.2021 at 8 am, 12 pm, and 5 pm

The PET values in Zone 3 show a similar pattern at different times (8 am, 12 pm, and 5 pm). The highest values occur at 5 pm The mitigation strategies have less impact in this zone compared to others. The most effective scenario for this zone is "Rebuild 9m" which has a cooling effect of 6.2°C at 12 pm The vegetation scenario (Coupling vegetation) has slightly better values than the Trees scenario. The best configuration for Zone 1 is "Rebuild 9m, Trees, Green-roofs, and Soil Albedo".

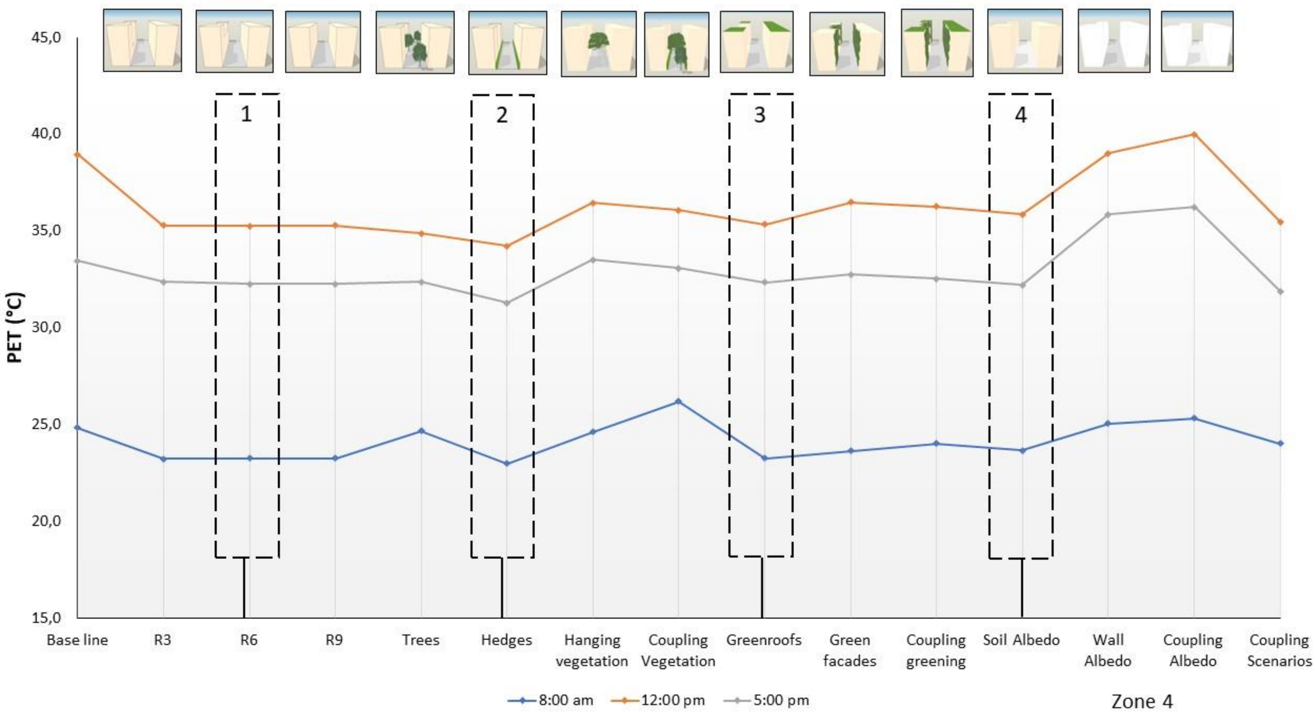


Figure 49: Mean cooling effect in zone 4 by different scenarios on 10.08.2021 at 8 a.m, 12 p.m, and 5 pm

The Physiological equivalent temperature (PET) of 14 scenarios in zone 4 is shown in Figure 52, with the diurnal variation at 8 am, 12 pm, and 5 pm The maximum PET values are observed at 12:00 pm in most scenarios, reaching 40°C in the "Coupling Albedo" configuration. The lowest temperature is recorded at 8 am at 23°C for the "Hedges" scenario. The "Hedges" scenario also exhibits the lowest temperatures at all three times. The cooling effects of the different scenarios are most prominent at midday (12 pm). Among the scenarios, the "Rebuild 6m," "Hedges," "Green-roofs," and "Soil Albedo" configurations provide the best cooling results during the day for zone 4.

4.3. To what extent can heat mitigation strategies improve outdoor thermal comfort within the Casbah of Algiers?

Table 18 shows the effects of different mitigation strategies on the PET values for the study areas. In this section, we will discuss the impact of the strategies on the case study.

4.3.1. Zone 1:

The 9m rebuild yields the best results, enhancing PET by 6.4°C at 8:00 am and 15.2°C at 12:00 pm, shifting heat stress from extreme to nearly moderate. Vegetation parameters (trees, hedges, hanging vegetation) show marginal impact versus trees alone, with a 0.9°C difference in PET at 12:00 pm (ΔT PETTrees = 16.8°C; ΔT PETCoupling vegetation = 17.7°C). The green roof is most effective, providing a 14.7°C cooling effect at 12:00 pm, mitigating heat stress from extreme to strong.

Materials strategy affects PET negatively. Increased wall reflectance induces a greenhouse effect, elevating PET by 9.4°C at 5:00 pm, attributed to the east-west street orientation and low sky view factor

(SVF=0.18). However, enhancing ground albedo by using a more reflective pavement reduces PET by 14.9°C at 12:00 pm

4.3.2. Zone 2 :

Zone 2, resulting from collapsed houses, faces critical conditions with high solar radiation and extreme thermal stress (PET 10 am = 56.1°C; 12 pm = 59.1°C). Reconstruction at 6m or 9m improves temperatures significantly by 25°C at 10 am and 23°C at 12 pm, eliminating thermal stress.

Efficient vegetation, specifically "Hedges and Coupled Vegetation," plays a crucial role. Hanging vegetation positively impacts noon temperatures (ΔT PET = 8.7°C) but has a slight negative effect in the morning/evening. Hedges (5.6°C) consistently cool the area, maintaining neutral thermal comfort in the morning/evening and reducing stress in the evening.

Greening strategies, including green roofs, show positive effects. Green roofs reduce temperatures by 2°C at 8 am and 5.1°C at noon, moderating stress levels at 5 pm Ground albedo is effective in reflecting radiation, resulting in temperature reductions at 12 pm (ΔT PETSoil.Albedo = 4.3°C) and 5 pm (ΔT PETSoil.Albedo = 1.5°C).

4.3.3. Zone 3 :

Severe heat stress in Study Area 3 occurs from 10:00 am to 5:00 pm, with PET values surpassing 50°C due to its East-West orientation and canyon aspect ratio (H/W: 2.07), magnifying solar reflections. Morphology and vegetation impact the area similarly. The R9 and tree scenarios lower temperatures by 2.0°C at 8:00 am, mitigating heat stress from strong to moderate. Despite a 6.2°C and 7.1°C cooling effect at noon, extreme heat stress persists. Evening temperatures drop significantly (8:00 pm to 10:00 pm), achieving neutral thermal comfort.

Green roof and soil albedo scenarios decrease PET values by 1.9°C at 8:00 am and 5.5°C at 12:00 pm, showing effectiveness. However, they don't alter the heat stress level, necessitating a more comprehensive, personalized mitigation study.

4.3.4. Zone 4:

Zone 4 is the most comfortable, with a peak temperature of 39°C from noon to 3 PM. Hedges offer the best comfort, cooling by 4.7°C at midday and 2.2°C in the evening. Morphological rehabilitation impacts temperature by 1.6°C in the morning and 3.7°C at noon, with similar results at 6m and 9m. Green roofs have the most significant impact, cooling by 3.6°C at noon, 1°C more than green facades or combined greening. Albedo changes in walls negatively affect comfort, increasing PET temperature by 2.8°C. Ground albedo changes positively impact comfort, reducing PET temperature by 3.1°C at noon and by 1.2°C at 8:00 am and 5:00 pm

Table 16: The effect of different mitigations strategies on PET values in the four zone of the study

Geometry scenarios									
		Zone 1		**Zone 2**		**Zone 3**		**Zone 4**	
▲▼	**Time**	**PET Baseline**	**ΔT PET**	**PET Baseline**	**ΔT PET**	**PET Baseline**	**ΔT PET**	**PET Baseline**	**ΔT PET**
S1 : R3	8:00 am	41,3	▲5,9	26,1	▲2,7	36,0	▲1,8	24,8	▲1,6
	12 :00 pm	49,8	▲14,2	59,1	▲6,2	55,4	▲6,0	39,0	▲3,7
	5 :00 pm	39,2	▲5,4	35,1	▲1,5	54,6	▲3,8	33,5	▲1,1
S2 : R6	8:00 am	41,3	▲6,0	26,1	▲3,0	36,0	▲1,9	24,8	▲1,6
	12 :00 pm	49,8	▲15,0	59,1	▲23,2	55,4	▲6,0	39,0	▲3,7
	5 :00 pm	39,2	▲5,5	35,1	▲1,4	54,6	▲3,8	33,5	▲1,2
S3 : R9	8:00 am	41,3	▲6,4	26,1	▲2,9	36,0	▲2,0	24,8	▲1,6
	12 :00 pm	49,8	▲15,2	59,1	▲23,1	55,4	▲6,2	39,0	▲3,7
	5 :00 pm	39,2	▲5,5	35,1	▲1,2	54,6	▲4,0	33,5	▲1,2

Vegetation scenarios									
		Zone 1		Zone 2		Zone 3		Zone 4	
	Time	**PET Baseline**	**ΔT PET**	**PET Baseline**	**ΔT PET**	**PET Baseline**	**ΔT PET**	**PET Baseline**	**ΔT PET**
S4 : Trees	8:00 am	41,3	▲6,3	26,1	▲2,4	36,0	▲2,2	24,8	▲0,1
	12 :00 pm	49,8	▲16,8	59,1	▲5,0	55,4	▲7,1	39,0	▲4,1
	5 :00 pm	39,2	▲7,1	35,1	▲1,7	54,6	▲4,6	33,5	▲1,1
S5 : Hedges	8:00 am	41,3	▲6,6	26,1	▲1,9	36,0	▲2,0	24,8	▲1,8
	12 :00 pm	49,8	▲16,0	59,1	▲5,6	55,4	▲6,6	39,0	▲4,7
	5 :00 pm	39,2	▲6,5	35,1	▲1,9	54,6	▲4,4	33,5	▲2,2
S6 : Hanging Vegetation	8:00 am	41,3	▲6,1	26,1	▼-0,2	36,0	▲1,7	24,8	▲0,2
	12 :00 pm	49,8	▲16,0	59,1	▲8,7	55,4	▲6,6	39,0	▲2,5
	5 :00 pm	39,2	▲7,3	35,1	▼-0,4	54,6	▲4,8	33,5	▼-0,1
S7 : Coupling vegetation	8:00 am	41,3	▲6,5	26,1	▼-0,5	36,0	▲1,5	24,8	▼-1,4
	12 :00 pm	49,8	▲17,7	59,1	▲9,0	55,4	▲7,5	39,0	▲2,9
	5 :00 pm	39,2	▲8,1	35,1	▲0,3	54,6	▲5,2	33,5	▲0,4

Greening scenarios									
		Zone 1		Zone 2		Zone 3		Zone 4	
	Time	PET Baseline	ΔT PET	PET Baseline	ΔT PET	PET Baseline	ΔT PET	PET Baseline	ΔT PET
S8 : Greenroofs	8:00 am	41,3	▲6,1	26,1	▲1,9	36,0	▲1,9	24,8	▲1,6
	12 :00 pm	49,8	▲14,7	59,1	▲5,1	55,4	▲5,6	39,0	▲3,6
	5 :00 pm	39,2	▲5,7	35,1	▲1,5	54,6	▲3,4	33,5	▲1,1
S9 : Green façades	8:00 am	41,3	▲5,4	26,1	▲1,5	36,0	▲1,6	24,8	▲1,2
	12 :00 pm	49,8	▲3,8	59,1	▲4,5	55,4	▲4,8	39,0	▲2,5
	5 :00 pm	39,2	▲5,2	35,1	▲1,1	54,6	▲3,2	33,5	▲0,7
S10 : Coupling greening	8:00 am	41,3	▲5,3	26,1	▲1,4	36,0	▲1,4	24,8	▲0,8
	12 :00 pm	49,8	▲3,5	59,1	▲4,3	55,4	▲4,7	39,0	▲2,7
	5 :00 pm	39,2	▲5,2	35,1	▲1,1	54,6	▲3,0	33,5	▲0,9

Albedo scenarios									
		Zone 1		Zone 2		Zone 3		Zone 4	
	Time	PET Baseline	ΔT PET	PET Baseline	ΔT PET	PET Baseline	ΔT PET	PET Baseline	ΔT PET
S11 : Soil Albedo	8:00 am	41,3	▲6,1	26,1	▲1,8	36,0	▲1,9	24,8	▲1,2
	12 :00 pm	49,8	▲14,9	59,1	▲4,3	55,4	▲5,5	39,0	▲3,1
	5 :00 pm	39,2	▲5,8	35,1	▲1,5	54,6	▲3,8	33,5	▲1,3
S12 : Wall Albedo	8:00 am	41,3	▼-0,6	26,1	▲0,6	36,0	▲0,5	24,8	▼-0,2
	12 :00 pm	49,8	▼-0,6	59,1	▲3,2	55,4	▲3,0	39,0	0,0
	5 :00 pm	39,2	▼-9,4	35,1	▼-1,4	54,6	▲0,9	33,5	▼-2,4
S13 : Albedo Coupling	8:00 am	41,3	▼-1,2	26,1	▲0,2	36,0	▲0,2	24,8	▼-0,5
	12 :00 pm	49,8	▼-0,8	59,1	▲1,7	55,4	▲2,2	39,0	▼-1,0
	5 :00 pm	39,2	▼-9,7	35,1	▼-1,8	54,6	▲0,5	33,5	▼-2,8

Coupling scenarios									
		Zone 1		Zone 2		Zone 3		Zone 4	
S14: Coupling scenarios	Time	PET Baseline	ΔT PET	PET Baseline	ΔT PET	PET Baseline	ΔT PET	PET Baseline	ΔT PET
	8:00 am	41,3	▲6,7	26,1	▲2,3	36,0	▲2,0	24,8	▲0,8
	12 :00 pm	49,8	▲17,1	59,1	▲ 23,9	55,4	▲6,1	39,0	▲3,5
	5 :00 pm	39,2	▲ 7,1	35,1	▲ 2,3	54,6	▲3,9	33,5	▲1,6

Figure A7 maps show urban configuration and solar radiation impact on PET values at 12:00 pm for four sites. Baseline and best-case scenarios, using a 1.40m cut plan for PET measurements, reveal urban morphology's notable effect. It increases shading, reducing overall stress from extreme to moderate in the studied canyon and surrounding zones on the four-zone morphology heatmap.

Trees and hedges notably decrease temperatures at measurement points. In zone 1, trees lower the temperature by 17°C, and in zone 3, by 7°C. This cooling extends to adjacent streets, as evident in the heatmap. Hedges also cool street canyons in zones 2 and 4. In zone 2, the street canyon stress level decreases, but the square center remains a hotspot. In zone 4, with an aspect ratio H/W=1.82, hedging reduces stress levels from strong to moderate, showing the highest cooling effect. Green roofs impact thermal comfort, reducing PET temperature by up to 14.7°C in zone 1, 5°C in zones 2 and 3, and 3.6°C in zone 4. Strategy effectiveness varies based on factors like building height, street width, and orientation.

Finally, the Soil Albedo strategy, replacing dark pavement with reflective material, reduces temperatures by 14.9°C in zone 1 and averages 4°C in other zones. Effectiveness depends on factors like solar radiation and street orientation, as seen in adjacent streets in zones 3 and 4. All scenarios can enhance microclimates at different scales.

5 Discussions

A microclimatic analysis was conducted in a typical Mediterranean historical urban fabric for this study. The effect of different mitigation scenarios in four zones was assessed through in-situ measurements. Subsequently, a series of simulations were applied to the models to analyze thermal stress during hot periods. The study is based on the numerical software CFD ENVI-met for the validation and simulation of the models. The software was also used with its BIO-met programs to calculate the PET index, as well as the generation of heatmaps.

To summarize the simulation readings, the significant findings of the analysis of outdoor thermal comfort are listed:

5.1. Major findings and recommendations

The study examined the cooling effects of nature-based solutions in the Casbah of Algiers, specifically focusing on vegetation, greening, and cool materials. Combining scenarios within the same category, such as different vegetation strategies, did not show significant differences compared to individual scenarios. The research tested these combinations at two scales, and the results indicated minimal variations in the PET (Physiological Equivalent Temperature) values at 12:00 pm For instance, the difference in PET for three vegetation variants and the best-case scenario was Z1.ΔPET = 0.9, Z2.ΔPET = 0.3, Z3.ΔPET = 0.4, and Z4.ΔPET = -2.3, as illustrated in figures 12 to 15.

These findings are in line with studies by Sodoudi and Kong (Kong et al., 2016; Sodoudi et al., 2018), which showed the relationship between the fragmentation of green areas and vegetation type. Similarly, the results showed that the cooling effect of green roofs was greater than that of coupling greening and that the cooling effect of soil albedo was greater than that of coupling albedo, with ΔPETGreen-roofs > ΔPETCoupling.Greening and ΔPETSoil.Albedo > ΔPETCoupling.Albedo.

Conversely, combining best-case scenarios doesn't significantly differ from isolated best-case scenarios, aligning with Salata's findings (Salata et al., 2017). Results indicate that one or two parameters mainly influence coupling scenarios. For instance, in Zone 1 and Zone 2, the impact of combined best scenarios is notably affected by tree scenarios, as seen in Figures 12 and 13. This supports Wang's conclusion (Wang et al., 2016b) that the combination of mitigation techniques is more effective in high-rise areas than in canyons.

Secondly, the impact ranking of mitigation techniques on pedestrian thermal comfort varies across different areas (Figure 7). Green roofs and soil albedo prove effective in all four zones, with varying cooling effects. However, in the studied subspaces, morphology and strategic vegetation have the most significant cooling impact. For instance, tree scenarios in Zone 1 and vegetation in Zones 3 and 4 exhibit better cooling effects compared to morphological reconstruction approaches. In Zone 2, reconstruction at 9m has the greatest effect, followed by suspended vegetation.

Thirdly, Figures 12 to 15 depict diurnal variations in the cooling impact of 14 scenarios at 8:00 am, 12:00 pm, and 5:00 pm Across all scenarios, mean cooling rises from 8:00 am to peak at 12:00 pm, then declines until 5:00 pm Rebuilding in Zone 2 yields the highest mean cooling at 12:00 pm (23.2°C). Cooling effects are more prominent during the day due to intense solar radiation, increased evapotranspiration, and shading. Post-sunset, north-south-oriented zones experience a faster cooling decline than east-west-oriented ones. Nighttime cooling persists in street canyons (Zones 1-3), albeit reduced without solar radiation or shading (PET ≈ 1.5°C).

Fourthly, In this study, three albedo scenarios were tested, and the results (Table 5) indicated that the scenario featuring high albedo soil and low albedo walls was the most effective, imparting significant cooling effects throughout the day, with peak effectiveness at 12:00 pm This scenario led to improvements of 14.9°C in Zone 1 and 5.5°C in Zone 3 for PET values. Increasing soil albedo proved to be a viable solution in the high-density canyons of the Casbah of Algiers, characterized by their aspect ratio H/W and dense building layout.

These findings corroborate previous research by (Xu et al., 2020), demonstrating that cool paving enhances outdoor thermal comfort in high-density urban areas. (Aboelata, 2021) similarly observed that cool paving can be beneficial in densely populated areas lacking open spaces. Notably, augmenting ground surface albedo contributes to a reduction in ground surface temperature, subsequently enhancing mean radiant temperature and PET (Andreou and Axarli, 2012b).

The wall albedo scenario, despite its reputation for cooling effects, showed less effectiveness and even had a negative impact on high aspect ratio urban canyons in zones 1 and 4. (Qin, 2015) demonstrated that the narrow width of the streets in the Casbah of Algiers, along with the aspect ratio H/W and facade heterogeneity, played a crucial role in this negative impact. Yang and Kondo's studies (Kondo et al., 2001; Yang and Li, 2015) suggested that increased facade heterogeneity led to higher surface temperatures due to elevated radiation reflection. These findings align with (Nazarian et al., 2019), indicating that the use of cool walls in Singapore's dense urban areas increased cooling requirements and decreased thermal comfort.

Furthermore, the coupling of high albedo materials for both walls and ground in a high aspect ratio urban canyon had a detrimental effect on cooling and thermal comfort. This combination increased reflectivity throughout the canyon's height, resulting in higher surface temperatures and reduced outdoor thermal comfort. Using high albedo materials in a closed, high aspect ratio microclimate is not advisable, as (Taleghani, 2018b) found that increasing albedo in a closed microclimate amplifies re-radiation towards the human body, decreasing thermal comfort.

Fifth, adding vegetation to urban areas through green roofs and walls was studied to determine its cooling effects. Both strategies were evaluated separately and in combination. The results in Table 5 indicate a strong cooling impact on all study areas. This was due to the evapotranspiration of foliage and the reduction of surface temperature, which also affected the Mean Radiant Temperature (Taleghani et al., 2014a).

The cooling impact of greening is consistent at 8:00 am and 5:00 pm, peaking at noon. Green roofs prove more effective than green facades, exhibiting slightly better cooling, particularly in Zone 1, with a 10.9°C difference at midday and an average 1°C difference in Zones 2, 3, and 4. Notably, green roofs excel in high aspect ratio street canyons (H/W Z1 = 4). However, Jamei's (Jamei and Rajagopalan, 2017) findings in Melbourne contradict, stating green roofs don't enhance the PET index for pedestrians.

Contrary to (Alexandri and Jones, 2008), this study reveals that, in traditional urban fabrics, green roofs have a superior cooling effect compared to green walls. In disagreement with (Zhang et al., 2017), the current research aligns with Alexandri et al., asserting that both green roofs and walls positively impact thermal comfort in hot and dry climates. Additionally, studies by (Castleton et al., 2010; Saadatian et al., 2013) affirm the energy-saving benefits of green roofs in buildings.

The thermal comfort of studied urban canyons, particularly in Zones 1 and 2 (Table 5), is significantly influenced by urban morphology, with cooling effects of 15.2°C and 23.1°C, respectively. Figure A7 illustrates how interventions in urban morphology can provide shading to adjacent streets. Reconstruction in deteriorated canyon areas notably cools streets crossing them (Zones 1, 3, and 4), reducing PET values to 15°C in Zone 2. This shading impact extends to streets parallel to the canyons, enhancing the cooling effect. Previous studies (Gong et al., 2019; Krüger et al., 2011b; Thorsson et al., 2011c) support the role of urban geometry in shading and outdoor thermal comfort.

Zone 3, experiencing the highest discomfort, is evident in Figure 10, with peak PET values reaching 55.4°C and 54.6°C at 12:00 pm and 5:00 pm, respectively. The latter's PET curve surpasses that of 12:00 pm, indicating sustained overheating. This is attributed to Zone 3's elevated height-to-width (H/W) aspect ratio of 2.07 and its east-west (E-W) orientation, leading to prolonged solar exposure and reduced shading.

Research by (Ali-Toudert and Mayer, 2006b; Chatzidimitriou and Axarli, 2017) emphasized the impact of factors like orientation, aspect ratio, and sky view factor on street canyon overheating. (Jamei et al., 2016b) highlighted urban geometry as crucial in microscale thermal behavior. Despite implemented mitigation strategies yielding a cooling effect of up to 7.1°C in Zone 3, they proved inadequate in alleviating thermal stress. Additional measures are imperative for enhancing conditions in this area.

This study recommends prioritizing the redevelopment of urban blocks in ruins for the most effective improvement in microclimates within historic Mediterranean urban areas. Modifying the urban morphology, particularly by restoring shading through the use of nature-based solutions like trees and hanging vegetation, is highly recommended for enhancing thermal comfort.

Mitigation strategies emphasize individual approaches like vegetation, greening, or albedo modification, discouraging combined scenarios for their complexity and limited cooling benefits. In Algiers' traditional Casbah, caution is urged against high albedo and cool materials on walls, favoring soil albedo modification in narrow canyons for more effective radiation reduction and continuous cooling.

Greening scenarios, particularly with green roofs, enhance overall thermal comfort in urban canyons, with higher resident acceptability than green walls. However, in zones with challenging orientations, openings, and aspect ratios, further specialized studies and techniques are needed to address residual thermal discomfort.

5.2. Strength and limitations of the study

The study in this paper brings together two crucial areas in the literature: urban heritage and microclimate studies. Previous studies on traditional urban fabrics have mostly focused on the impact of urban geometry or building materials on thermal comfort (Achour-Younsi and Kharrat, 2016b; Ali-Toudert et al., 2005b; Johansson, 2006b). Meanwhile, studies on microclimates and strategic mitigations are mostly conducted on current case studies in modern cities (He et al., 2015b; Shooshtarian and Rajagopalan, 2017b; Taleghani et al., 2015b). Few studies have explored the impact of nature-based solutions on microclimate in traditional urban fabrics, distinct from modern cities in terms of high density, aspect ratio, and building materials. The results of this research are significant as they contribute to filling the knowledge gap regarding the influence of mitigation strategies on thermal comfort in traditional urban morphology.

This study aims to evaluate the effectiveness of different Nature-based solutions in improving outdoor thermal comfort in historical cities. The approach includes field measurements and computational fluid dynamics (CFD) simulations. The results of this study can be applied to other similar traditional urban areas such as Fatimid Cairo in Egypt, the Historic City of Toledo in Spain, the Medina of Tunis in Tunisia, and the Medina of Fez in Morocco. This study represents a move towards enhancing comfort and addressing overheating issues in a hot Mediterranean climate, particularly in historical urban fabrics.

The study uses a high-resolution model, with a grid size of 1m x 1m x 1m, to assess the outdoor thermal comfort through different mitigation strategies in historical cities. This precision is an improvement compared to previous studies in the field, which used larger grid scales. This high-resolution model allows for greater accuracy in the results of the PET, which measures the outdoor thermal comfort with a precision of 1m.

The study uses a high-precision simulation model to assess outdoor thermal comfort and the impact of different mitigation strategies. It began with a calibration stage of 72 hours using air temperature data to validate the model. The calibration was based on hourly mean bias error (MBE) and root-mean-square error (RMSE). Sixty simulations were run for over 864 hours to gather microclimate data such as air temperature, relative humidity, air velocity, and mean radiant temperature. The results were calculated as 15 predicted mean vote (PET) values for each zone, totaling 60 PET values. This is a more in-depth approach than previous studies that were validated over 20-48 hours (Hien et al., 2012a; Sharmin et al., 2017b; Taleghani et al., 2015b) and provides a better understanding of the impact of mitigation strategies in traditional urban environments.

On the other hand, the study's limitations are that it only focuses on hot periods and testing during heat-wave days. Extending the duration would offer insights into mitigation strategies in both hot and cold periods. Minimal outdoor comfort improvement is seen at specific times (8:00 and 17:00 hrs), with significant enhancements mainly at noon, requiring further investigation. The study employs a simplistic model without building details; a more intricate model at a smaller urban scale is recommended. Mitigation strategies are constrained in the historic urban fabric, hindering complete transformation. To broaden the study, exploring diverse mitigation solutions and conducting sensitivity analyses is suggested.

5.3. Implication on practice and future work

5.3.1. Implication:

This study assesses thermal comfort in the historic Casbah of Algiers, examining the impact of mitigation strategies in four areas. It quantifies the cooling effect for each scenario, offering crucial insights for urban rehabilitation in the context of climate change. Urban design and historic fabric restoration, especially in the Casbah, should integrate findings for effective long-term planning. The OGEBC should establish a climate and environmental study department to serve as a legal mediator between environmental and heritage concerns. Implementing these insights in the urban renovation of the Casbah can mitigate thermal stress in Mediterranean climates.

5.3.2. Future work:

While studies on outdoor thermal comfort and mitigation in historical cities are limited compared to modern cities, recent research has contributed significantly. However, further work is essential.

Developing advanced mitigation scenarios and exploring diverse strategy combinations is crucial. Research on specific Mediterranean plants for cooling, considering varied topography and soil materials, is necessary (Mijani et al., 2020). Establishing local urban climate models with measured climatic parameters by placing stations in historic areas can enhance evaluation accuracy. Additionally, investigating potential future discomfort under climate change using future weather files is essential.

Outdoor thermal comfort studies based on land-surface temperature are scarce due to large-scale precision limitations in this region. This study employs a novel real-time monitoring approach for urban climate analysis. Conducting sensitivity analysis studies to identify key parameters in historical city urban canyons is important.

Future research should focus on multi-objective optimization, integrating thermal comfort, mitigation strategies, energy efficiency, and investment costs.

6 Conclusion

The study aims to develop guidelines for landscape and urban designers to enhance outdoor thermal comfort in traditional cities with a Mediterranean climate by using nature-based solutions in historic urban areas. This interdisciplinary effort combines knowledge from urban planning, landscape design, architecture, and building material science to assess the effects of mitigation strategies on thermal comfort. The study evaluates the evolution of heat stress levels in the Casbah of Algiers by analyzing 14 scenarios across 4 study areas. The research approach combines empirical and numerical modeling techniques that create a high-resolution model (1m x 1m x 1m grid size) for accurate analysis of the Physiological Equivalent Temperature (PET). The methodology includes real-time monitoring, Computational Fluid Dynamics (CFD) simulations, and biometeorological calculations to provide a novel approach to urban climate analysis.

The findings of the study indicate that combining different mitigation strategies does not result in a significant improvement in the cooling effect. Instead, the outcomes of coupling scenarios are mainly influenced by one or two parameters. The results showed that using cool pavements can enhance outdoor thermal comfort in densely populated urban areas by up to 14.9°C. However, increasing wall albedo negatively affects dense areas, as it increases solar radiation reflections and surface temperatures. Urban morphology is, for its part, the most effective strategy in terms of cooling effect. Indeed, the shading generated by the reconstruction of ruined plots greatly influences thermal comfort with a significant cooling effect. Future studies should investigate wider solutions spaces of mitigation combinations and the impact of climate change on outdoor thermal comfort. Overall, the study results may have significant implications for advising decision-makers in similar Mediterranean environmental contexts to improve the existing urban fabric, contributing to more liveability and vitality in outdoor areas. The findings of this study can be transferred to similar traditional urban fabrics in the Mediterranean climate.

7 Appendix A

Table A1: Construction material for models in ENVI-met software.

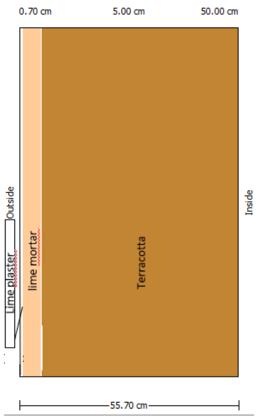
Construction material

Building material

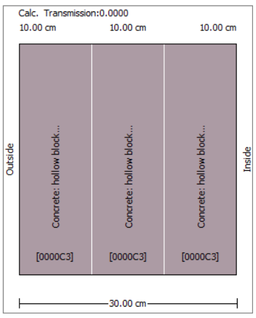
Walls:

- Created wall:

Terracotta;Lime mortar;Lime plaster



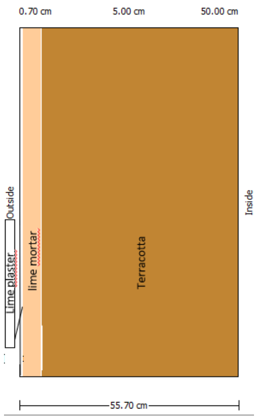
- Concrete wall (hollow block)



Walls:

- Created wall:

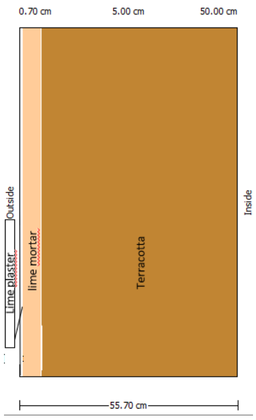
Terracotta;Lime mortar;Lime plaster



Walls:

- Created wall:

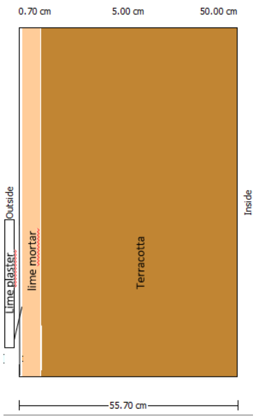
Terracotta;Lime mortar;Lime plaster



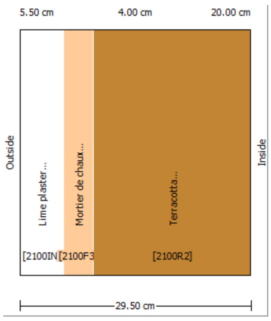
Walls:

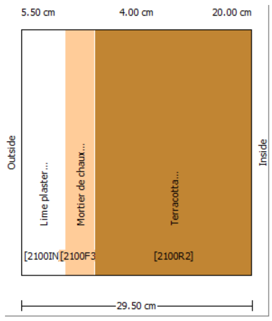
- Created wall:

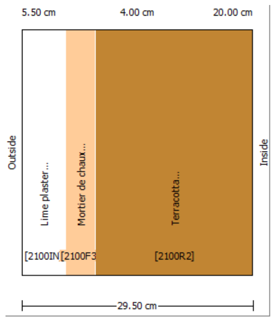
Terracotta;Lime mortar;Lime plaster

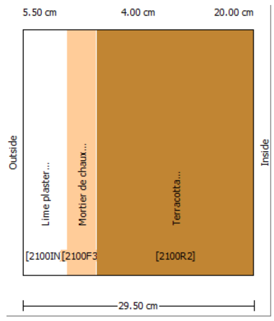


Roofs:	Roofs:	Roofs:	Roofs:
Created roof: Terracotta;Lime mortar;Lime plaster	Created roof: Terracotta;Lime mortar;Lime plaster	Created roof: Terracotta;Lime mortar;Lime plaster	Created roof: Terracotta;Lime mortar;Lime plaster









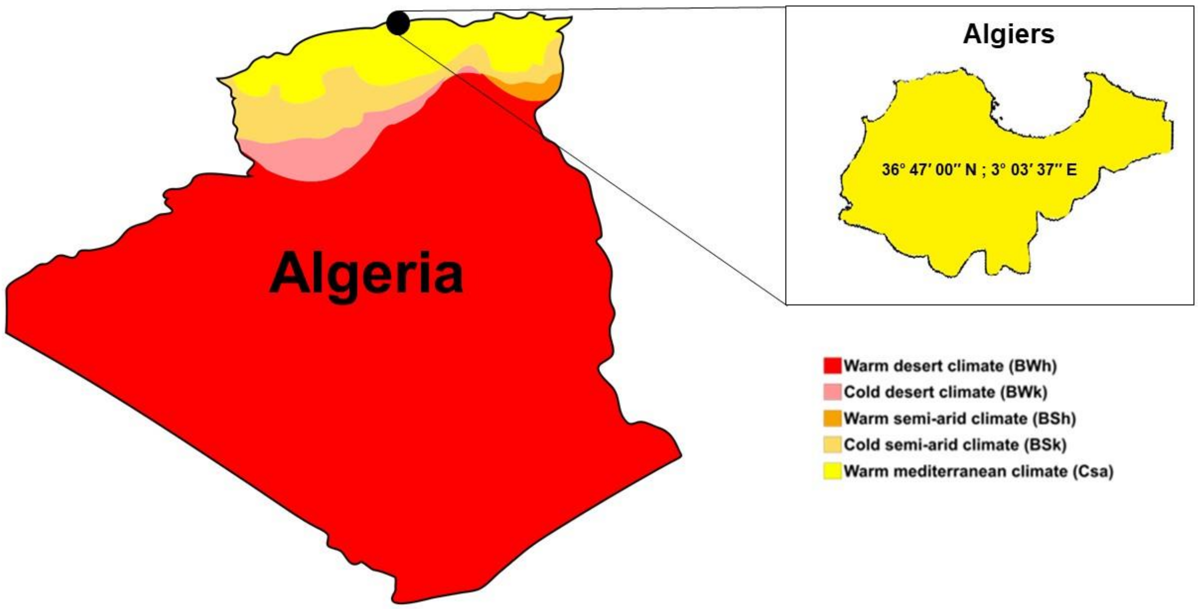


Figure A1: Algiers climatic classification

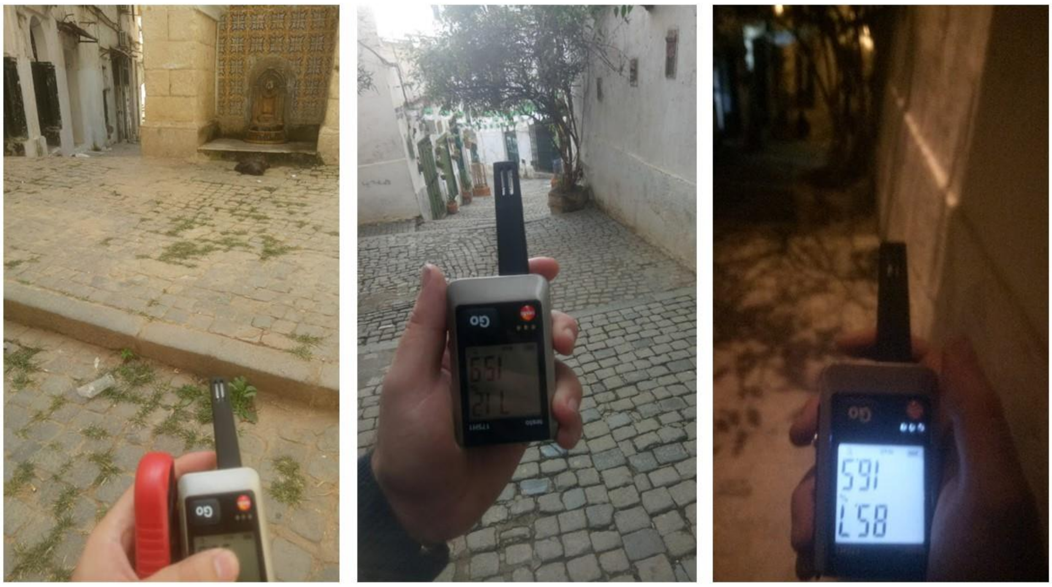


Figure A2: Measurement campaign

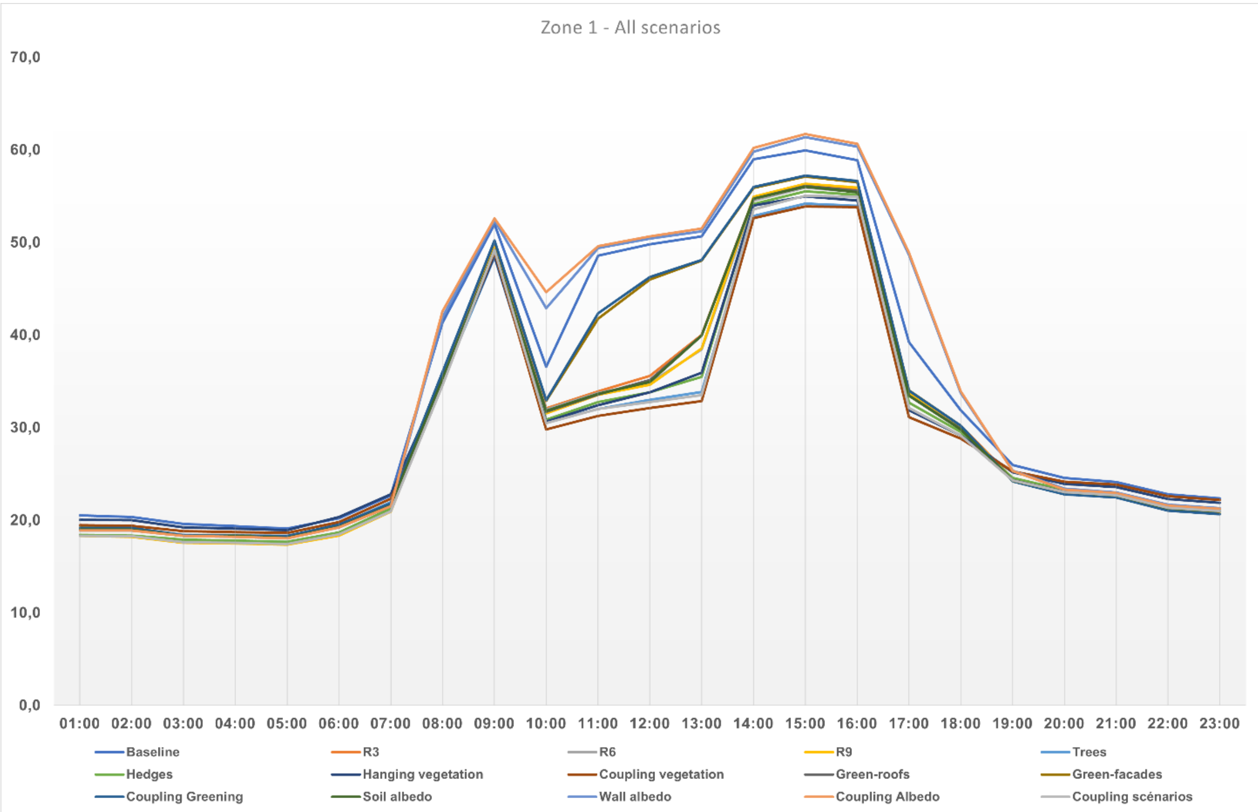


Figure A3: PET Values for the zone 1 for 10.08.2021

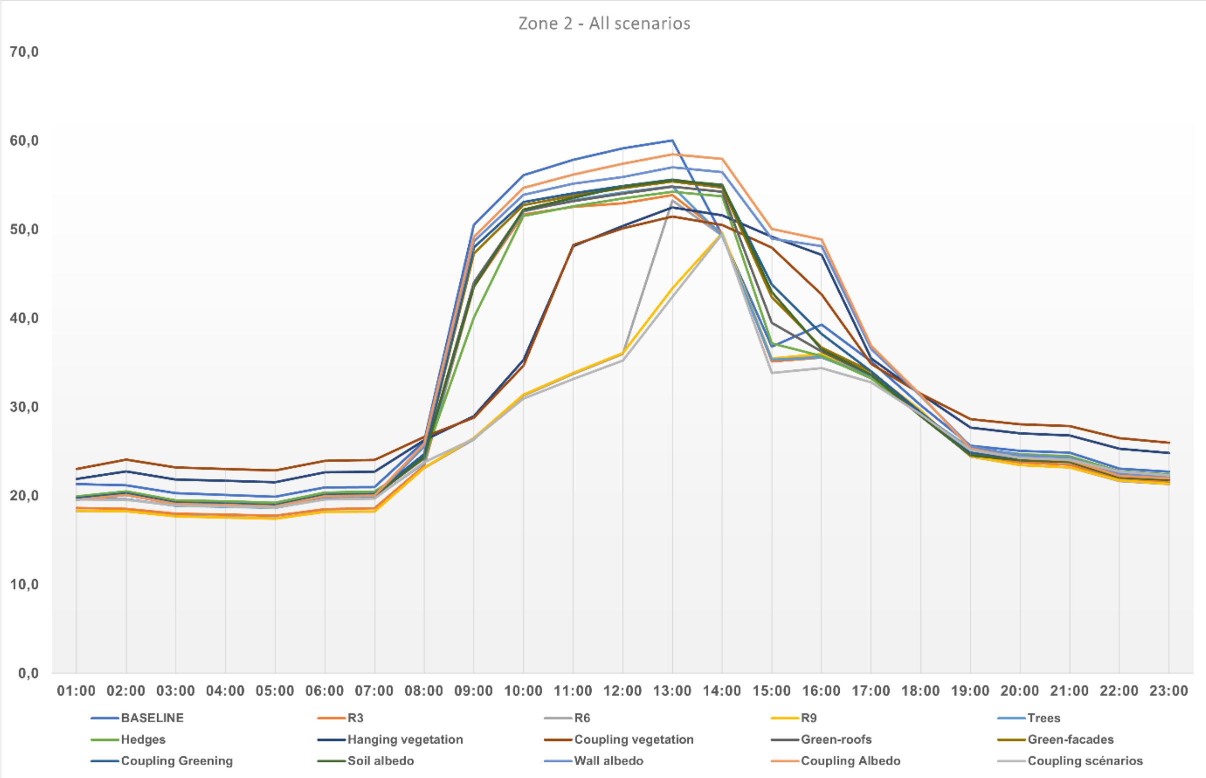


Figure A4: PET Values for the zone 2 for 10.08.2021

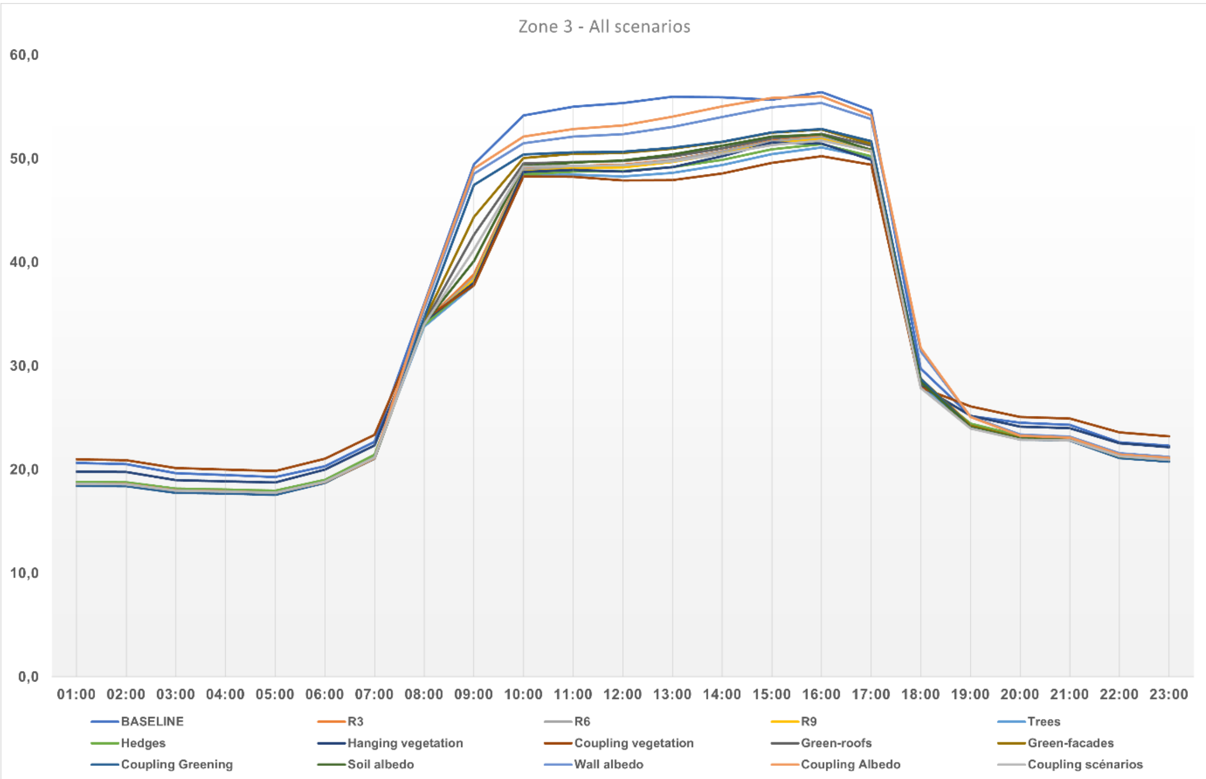


Figure A5: PET Values for the zone 3 for 10.08.2021

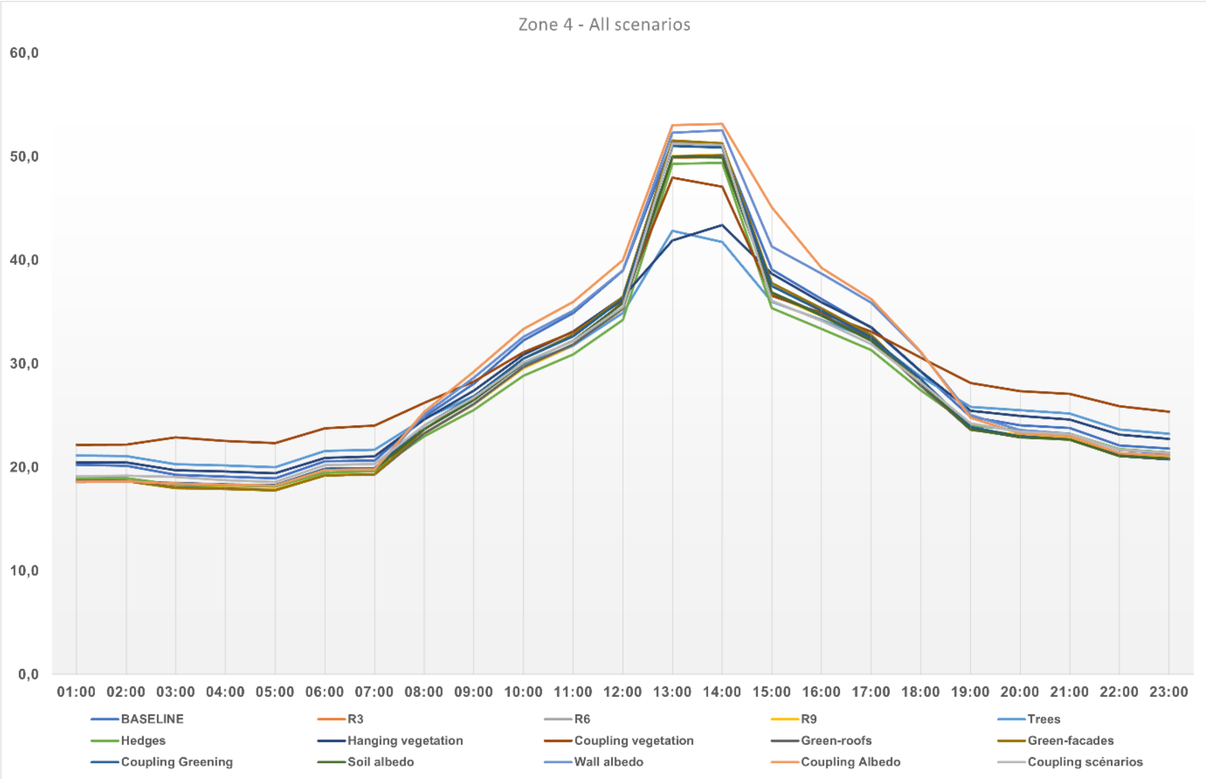
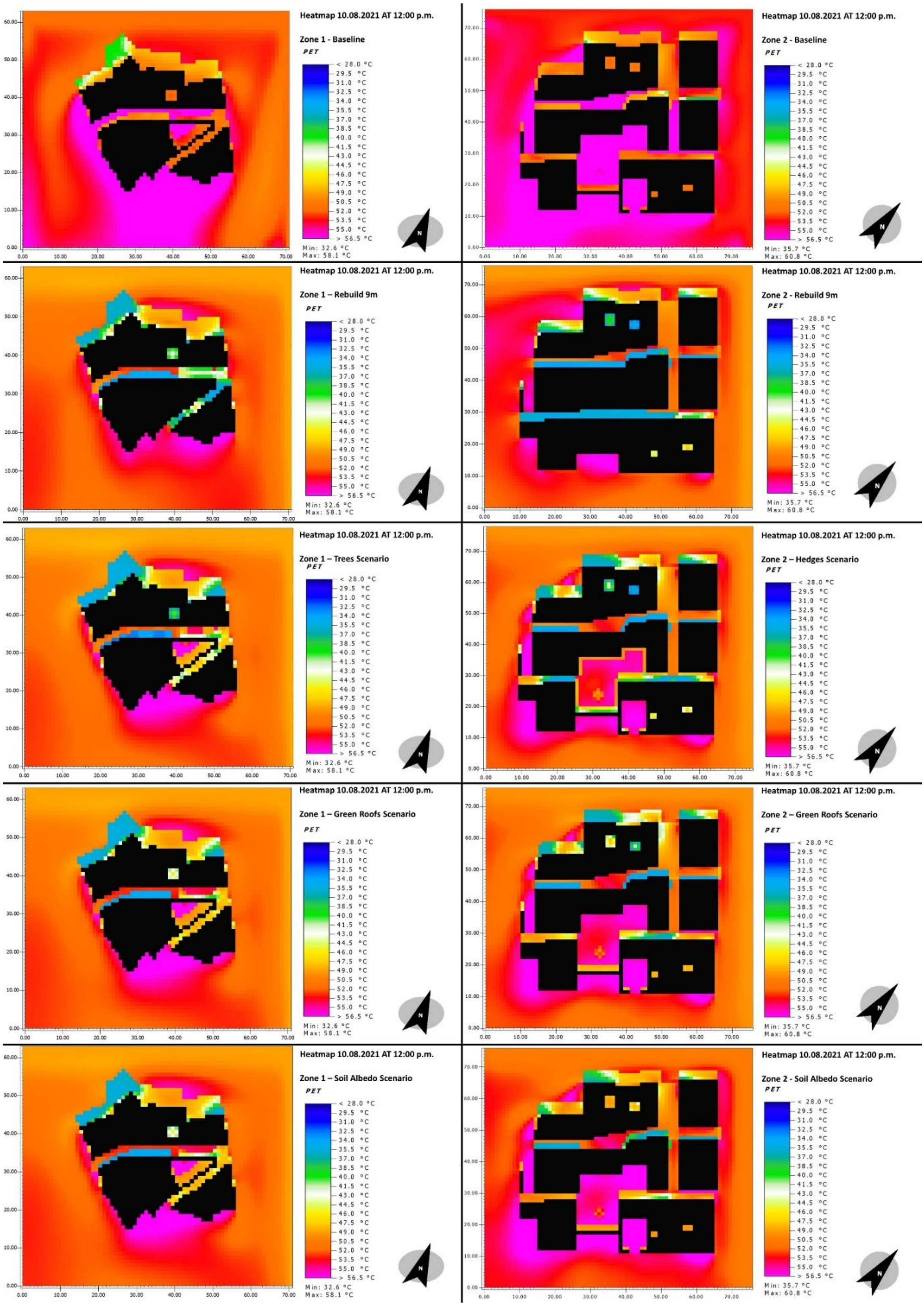


Figure A6: PET Values for the zone 4 for 10.08.2021


Heatmap 10.08.2021 AT 12:00 p.m.
Zone 1 - Baseline
PET
< 28.0 °C
29.5 °C
31.0 °C
32.5 °C
34.0 °C
35.5 °C
37.0 °C
38.5 °C
40.0 °C
41.5 °C
43.0 °C
44.5 °C
46.0 °C
47.5 °C
49.0 °C
50.5 °C
52.0 °C
53.5 °C
55.0 °C
> 56.5 °C
Min: 32.6 °C
Max: 58.1 °C
N
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 2 - Baseline
PET
Min: 35.7 °C
Max: 60.8 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 1 – Rebuild 9m
PET
Min: 32.6 °C
Max: 58.1 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 2 - Rebuild 9m
PET
Min: 35.7 °C
Max: 60.8 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 1 – Trees Scenario
PET
Min: 32.6 °C
Max: 58.1 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 2 – Hedges Scenario
PET
Min: 35.7 °C
Max: 60.8 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 1 – Green Roofs Scenario
PET
Min: 32.6 °C
Max: 58.1 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 2 – Green Roofs Scenario
PET
Min: 35.7 °C
Max: 60.8 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 1 – Soil Albedo Scenario
PET
Min: 32.6 °C
Max: 58.1 °C
Heatmap 10.08.2021 AT 12:00 p.m.
Zone 2 - Soil Albedo Scenario
PET
Min: 35.7 °C
Max: 60.8 °C

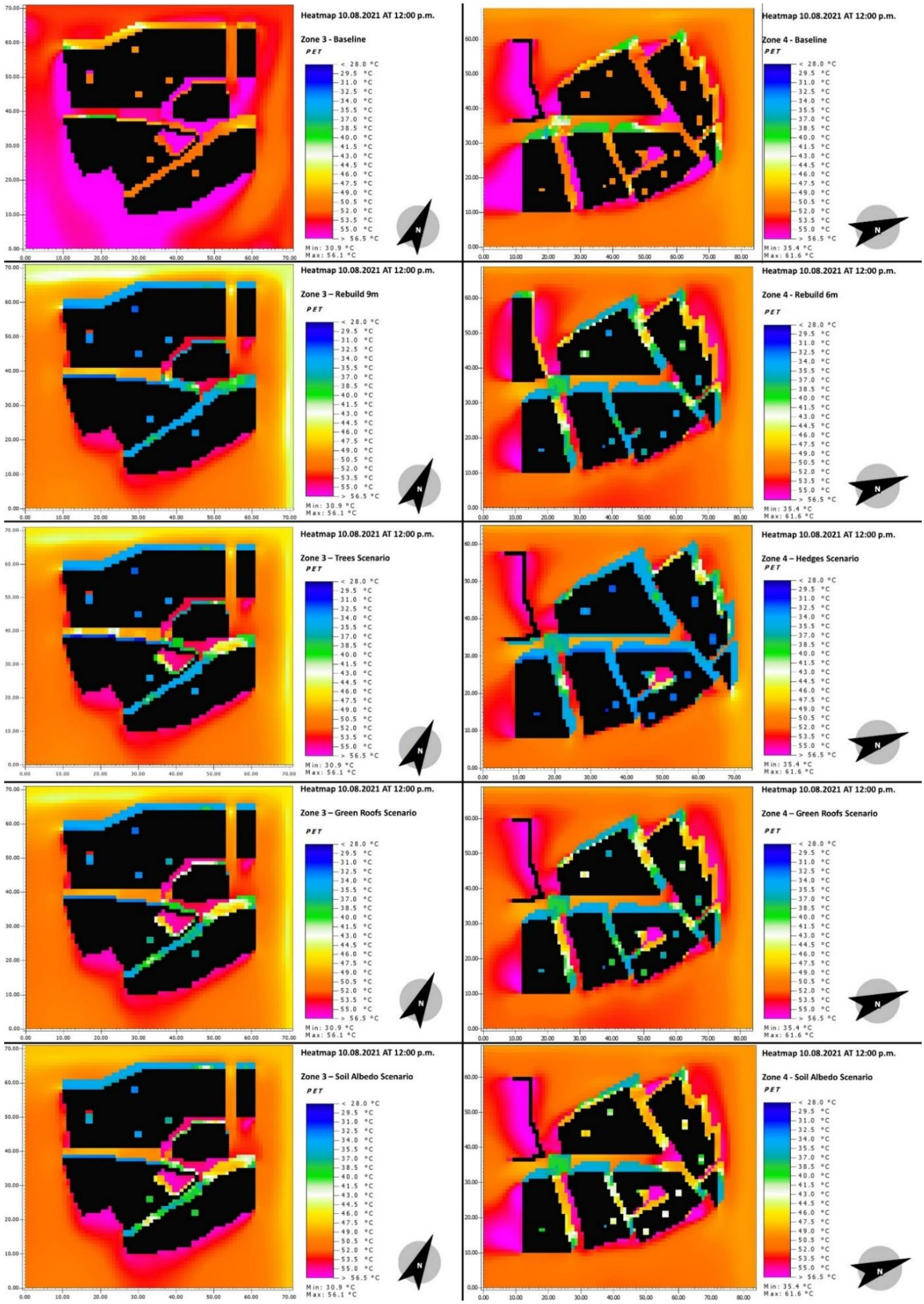


Figure A7: Heat maps of different mitigation strategies on the four zone at 12:00 p.m

Main findings & conclusion

VIII. Analyses and Conclusion

This research aimed to evaluate and understand outdoor thermal comfort conditions in the historical urban fabric of the Casbah of Algiers, integrating experimental approaches, climate modeling, and mitigation strategy assessments. The analysis of microclimatic conditions, based on in situ measurements and advanced simulations, identified the determinants of thermal stress and explored adaptive solutions in a Mediterranean context affected by climate change.

The experimental investigation highlighted significant thermal variability within the Casbah, influenced by urban morphology, the sky view factor (SVF), and the state of building degradation. Physiological comfort indices, notably the Physiologically Equivalent Temperature (PET) and mean radiant temperature (Tmrt), revealed high thermal stress levels in summer, with strong to extreme heat stress occurring during more than 52% of the daytime in August. In winter, conditions vary from moderate to cold thermal stress in the early morning and late afternoon, while mild stress is observed at midday. The sea breeze effect was found to be insignificant for outdoor thermal comfort during the study period.

The projection of climate change effects demonstrated a notable increase in thermal stress in the coming decades. According to simulations for the years 2050 and 2090, average daytime temperatures could rise by 24%, reaching up to 42.3°C, while nighttime temperatures would increase by 8.4%. These projections emphasize the urgency of adopting mitigation strategies to preserve outdoor thermal comfort and minimize health risks.

Mitigation strategies based on nature-based solutions were evaluated through simulation scenarios combining multiple interventions. The results indicate that the impact of these strategies varies depending on the urban context: cool pavements provide a significant cooling effect of up to 14.9°C, while increasing wall albedo can exacerbate solar radiation exposure in dense areas. Urban morphology remains one of the most effective strategies, with a notable cooling effect through the reconstruction of degraded plots. These findings provide a solid scientific basis for guiding policymakers and urban planners in implementing adaptive strategies for historical cities in Mediterranean climates.

Finally, the environmental impact assessment highlighted the need for an integrated approach to the rehabilitation of the Casbah, taking into account carbon emissions generated by various redevelopment alternatives. A detailed Life Cycle Assessment (LCA) is recommended to refine these estimates and guide decisions toward sustainable and heritage-friendly solutions.

In summary, this thesis highlights the importance of a holistic approach combining field studies, numerical simulations, and environmental analyses to improve outdoor thermal comfort in historic cities. The conclusions drawn provide relevant insights for urban resilience to climate change while preserving the architectural and cultural identity of traditional urban spaces.

1 Main findings

The study of the Casbah of Algiers highlights the strong interdependence between urban morphology, historical evolution, and outdoor thermal comfort. The compact and organic layout of the Casbah, characterized by narrow streets, high aspect ratios, and traditional building materials, significantly influences local microclimatic conditions. The findings reveal that the shaded alleyways reduce direct solar exposure and limit heat accumulation, while the high thermal inertia of traditional materials such as stone, lime, and wood helps regulate temperatures by delaying heat release at night. Additionally, the sea breeze effect plays a crucial role in mitigating extreme heat, especially in well-ventilated urban canyons.

The analysis of climate change scenarios from 1989, 2020, 2050, and 2090 under both normal and RCP 8.5 projections indicates that the Casbah is increasingly vulnerable to rising temperatures and urban heat island (UHI) effects. The study predicts a significant increase in the Physiologically Equivalent Temperature (PET), with summer heat stress intensifying by 2050 and 2090. Prolonged solar exposure in open spaces is expected to raise mean radiant temperature (Tmrt), while the decline in nighttime cooling efficiency will further exacerbate heat stress during warmer months.

Traditional passive strategies embedded in the Casbah's urban fabric serve as an effective model for contemporary climate adaptation. Shading structures, such as covered passages (sabat) and vegetation, reduce direct solar radiation. Ventilation corridors, created by strategic openings and the street network, facilitate natural airflow, enhancing urban cooling. Moreover, buildings constructed with high thermal mass materials, such as thick stone walls, maintain lower indoor temperatures compared to modern concrete structures. Simulations of Nature-Based Solutions (NBS) demonstrate that urban greening—such as rooftop vegetation, climbing plants, and tree shading—significantly lowers surface temperatures. The use of permeable and reflective materials improves albedo effects, contributing to heat mitigation, while the integration of water elements, including restored fountains and green courtyards, enhances evaporative cooling in public spaces.

The environmental assessment confirms that urban heat mitigation measures can be effectively implemented while preserving heritage values. Rehabilitation strategies must balance climate adaptation with architectural conservation to ensure that interventions respect the historical identity of the Casbah. The adoption of bioclimatic principles enhances thermal comfort without compromising the city's cultural and architectural integrity. Additionally, environmental impact assessments (EIA) should be systematically incorporated into all future urban planning initiatives to promote long-term sustainability.

The research findings have significant implications for policymakers, urban planners, and conservation specialists. It is crucial to develop heritage-sensitive adaptation strategies that address both historical preservation and contemporary climate challenges. Integrating thermal comfort assessments into conservation policies for historic cities can help enhance resilience while maintaining cultural identity. Furthermore, fostering interdisciplinary collaboration among climatologists, urban designers, and heritage specialists can optimize urban rehabilitation approaches, ensuring sustainable and climate-responsive urban planning.

This research provides a comprehensive framework for assessing and improving outdoor thermal comfort in historic urban environments. By combining traditional knowledge with modern climate adaptation techniques, the study contributes to the global discourse on sustainable urban planning in heritage sites. The proposed strategies can serve as a model for other Mediterranean and arid-climate cities facing similar challenges in balancing heritage conservation with climate resilience.

2 Answers to the research questions

This study aims to deepen the understanding of outdoor thermal dynamics in the Casbah of Algiers and identify suitable strategies to enhance thermal comfort in response to climate change challenges. Through an integrated approach combining in situ measurements, numerical simulations, and adaptation strategy analysis, several key research areas have been explored.

First, the assessment of current thermal comfort levels highlights the microclimatic specificities of the Casbah and their influence on the use of outdoor spaces. Then, the combination of empirical data with numerical modeling refines predictions regarding the future evolution of outdoor thermal comfort in a warming climate. This analysis underscores the importance of a rigorous and reproducible methodology to anticipate future impacts and propose effective solutions.

In this context, various mitigation strategies, including the integration of nature-based solutions (NBS) and the optimization of urban forms, have been examined to alleviate heat stress while preserving the site's architectural identity. Lastly, the study investigates the environmental and heritage implications of an ecological rehabilitation of the Casbah by assessing the carbon footprint of interventions and their compatibility with historic preservation efforts.

The following sections present the findings for each research question, highlighting key conclusions and their implications for climate adaptation in the Casbah of Algiers.

- **What are the current levels of thermal comfort in the historic urban fabric of the Casbah of Algiers, and how do microclimatic variations influence the perception and use of outdoor spaces?**

The Casbah of Algiers exhibits complex thermal dynamics shaped by its dense urban morphology, material properties, and microclimatic variations. Field measurements and numerical simulations confirm that thermal stress is a major challenge, particularly during summer, when strong to extreme heat stress is observed in 52% of the daytime hours in August. The mean radiant temperature (Tmrt) can exceed 60°C in open, unshaded areas, making these spaces particularly uncomfortable for residents and visitors. However, narrow alleyways and shaded passageways (Sabat) significantly reduce heat exposure, confirming the effectiveness of the traditional urban fabric in moderating extreme climatic conditions. The thermal performance of different urban subspaces varies greatly, with enclosed courtyards benefiting from heat retention during cooler periods but also experiencing trapped heat during extreme summer conditions. During winter, moderate to cold stress is prevalent in shaded streets during early mornings and late afternoons, whereas sunlit open spaces maintain higher comfort levels. One of the most significant findings is that the sea breeze has an insignificant impact on improving outdoor thermal comfort, as the compact layout of the Casbah restricts airflow, limiting its cooling potential. This challenges the common assumption that coastal winds can alleviate heat stress in dense urban environments. Furthermore, traditional construction materials, such as limestone and lime plaster, provide significant thermal inertia, reducing daily temperature fluctuations.

However, areas where modern materials such as concrete and asphalt dominate exhibit higher heat retention, exacerbating the urban heat island (UHI) effect and intensifying thermal discomfort. These findings suggest that while the Casbah's urban fabric offers inherent climatic advantages, recent transformations and the introduction of inappropriate materials have disrupted its natural microclimatic equilibrium, necessitating targeted adaptation strategies.

- **How can an integrated approach combining in situ measurements and numerical simulations improve the quantification and prediction of outdoor thermal comfort in the context of climate change while ensuring a rigorous and reproducible methodology?**

A robust methodological framework combining in situ measurements with numerical simulations has proven essential for accurately quantifying and predicting outdoor thermal comfort in the Casbah. Field measurements were collected across 14 representative subspaces, capturing air temperature, humidity, wind speed, and mean radiant temperature (Tmrt) across different microclimatic conditions. These empirical datasets were then used to calibrate and validate ENVI-met simulations, ensuring high accuracy. A 72-hour calibration process was conducted, followed by 864 hours of simulations, covering different seasonal conditions and climate change projections for 2050 and 2090. This integration of empirical and computational analysis has provided critical insights into how outdoor thermal comfort will evolve under future climate scenarios. By 2050, daytime temperatures are projected to increase by 13-17%, and by 2090, peaks could reach 42.3°C, exacerbating the urban heat island effect and reducing outdoor usability. Furthermore, nighttime temperatures are expected to rise by 8.4%, limiting the potential for nocturnal cooling, which traditionally plays a key role in heat mitigation in Mediterranean climates. The study confirms that the traditional urban fabric is highly resilient to climate extremes, but its effectiveness will decline if no adaptation measures are implemented. The combination of real-world data with high-resolution simulations has also allowed for the identification of thermal hotspots, such as exposed plazas and widened streets, where interventions should be prioritized. The ability to model future climate conditions provides an invaluable decision-making tool for policymakers and urban planners, enabling them to test different mitigation strategies before implementing them in the real environment. These findings reinforce the need for a scientifically grounded, data-driven approach to urban adaptation, ensuring that rehabilitation efforts in the Casbah remain both climatically effective and heritage-sensitive.

- **What mitigation strategies, including the integration of nature-based solutions (NBS) and the optimization of urban forms, can significantly improve thermal comfort while considering the impacts of climate change?**

A combination of nature-based solutions (NBS) and passive design strategies has been tested through simulation-based analysis to evaluate their effectiveness in mitigating urban heat stress. The results show that cool pavements can reduce surface temperatures by up to 14.9°C, making them an effective strategy for heat mitigation in open spaces. However, in narrow streets, their high reflectivity increases solar radiation exposure, which can lead to localized thermal discomfort. Vegetation-based strategies, particularly the integration of street trees and green roofs, have demonstrated significant cooling potential, reducing local air temperatures by up to 17°C and lowering PET values by 14.7°C. However, implementation challenges arise due to spatial constraints and the need for irrigation, making large-scale application difficult in a dense, historic setting like the Casbah. The research further highlights that enhancing traditional urban forms, such as shaded passageways (Sabat) and courtyard ventilation, is among the most effective passive cooling strategies. These interventions do not require additional energy inputs and align with the Casbah's architectural identity, making them highly feasible for long-term sustainability. On the other hand, high-albedo coatings on walls and rooftops, while effective in reducing heat absorption, increase radiant heat exposure in narrow streets, leading to discomfort in pedestrian areas. These trade-offs highlight the importance of context-specific mitigation approaches, ensuring that solutions are tailored to the specific urban morphology of the Casbah. Ultimately, the most effective strategy for improving outdoor thermal comfort combines NBS with traditional shading techniques, ensuring that cooling interventions respect both climatic imperatives and heritage preservation needs.

- **What are the environmental and heritage impacts of an ecological rehabilitation of the Casbah, and how can these interventions be optimized to minimize their ecological footprint while maximizing their climatic, social, and cultural benefits?**

The ecological rehabilitation of the Casbah must navigate the delicate balance between heritage conservation and climate adaptation, ensuring that interventions reduce environmental impact while preserving the site's architectural integrity. One of the most significant findings is that traditional construction materials, such as lime, stone, and clay, have considerably lower embodied carbon compared to modern materials like cement and concrete. A Life Cycle Assessment (LCA) was conducted to quantify the carbon footprint of different rehabilitation scenarios, confirming that retrofitting existing buildings with traditional materials reduces emissions and enhances long-term sustainability. Furthermore, the study underscores the importance of community engagement in shaping adaptive rehabilitation strategies. Surveys conducted with local residents reveal strong support for integrating passive cooling strategies without compromising historical authenticity, highlighting the socio-cultural value of traditional thermal comfort techniques. Additionally, the research demonstrates that mixed-use zoning policies can enhance the Casbah's resilience, ensuring that economic, residential, and cultural functions coexist harmoniously while supporting long-term sustainability. From an energy efficiency perspective, passive cooling interventions significantly outperform mechanical solutions, reducing the need for artificial cooling and lowering energy demand. Photovoltaic-integrated shading structures are also proposed as a compromise between energy efficiency and heritage conservation, ensuring that renewable energy solutions remain visually compatible with the Casbah's historic landscape. Overall, the findings indicate that a well-integrated ecological rehabilitation strategy can simultaneously reduce heat stress, lower carbon emissions, and preserve the authenticity of the Casbah, offering a replicable model for other historic Mediterranean cities facing climate adaptation challenges.

3 Connecting the dots

The field of urban environmental analysis and heritage preservation is inherently multidisciplinary, requiring a synthesis of historical, climatic, and architectural perspectives to derive meaningful conclusions. The present research has drawn upon a broad spectrum of methodologies, including climate simulations, in-situ measurements, and policy assessments, to construct a comprehensive framework for understanding outdoor thermal comfort in historical urban fabrics. By integrating these varied strands of inquiry, this study positions itself at the intersection of climate change adaptation, sustainable urban planning, and cultural heritage conservation.

- **Bridging Disciplines: From Historical Analysis to Climate Resilience**

The Casbah of Algiers serves as an exemplary case of how historical urban morphologies can either exacerbate or mitigate the impacts of a changing climate. The detailed historical analysis presented in earlier chapters has underscored the adaptive strategies embedded within the traditional urban fabric—narrow streets, high thermal mass materials, and shaded passageways—that have contributed to microclimatic regulation. However, contemporary urban pressures, including population growth, infrastructural neglect, and environmental degradation, have disrupted these delicate balances. By juxtaposing historical urban resilience with modern climate challenges, this study creates a dialogue between past and future urban adaptation strategies.

- **Integrating Computational Modeling and Empirical Evidence**

The methodological approach employed in this research exemplifies the synergy between computational modeling and empirical fieldwork. Climate simulations using ENVI-met have provided high-resolution insights into the thermal behavior of various urban scenarios, while in-situ measurements have validated these findings through real-world data collection. This dual approach ensures that theoretical projections are grounded in empirical reality, offering robust evidence for potential urban interventions.

- **Aligning with Global Climate Policies and Urban Sustainability Goals**

One of the most significant contributions of this research is its alignment with global sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement on Climate Change. The findings underscore the necessity of integrating nature-based solutions, such as urban greening and water-sensitive design, within the constraints of historical preservation. Furthermore, the research highlights how localized interventions in heritage sites can contribute to broader urban climate resilience, reinforcing the interconnectivity of micro and macro-scale sustainability efforts.

- **Implications for Policy and Practice**

The interdisciplinary nature of this study extends its applicability beyond academia to urban policy and planning. The recommendations derived from this research provide a blueprint for integrating climate-responsive design within historical urban settings, a challenge that is increasingly relevant for cities with rich architectural legacies. By bridging scientific inquiry with policy formulation, this research offers tangible pathways for improving urban livability while preserving cultural identity.

4 Research impacts and applicability

This research goes beyond a mere theoretical contribution, offering concrete applications for urban planners, policymakers, heritage conservationists, and environmental scientists. It highlights practical solutions aimed at strengthening the climate resilience of urban environments while ensuring their sustainability. One of the major contributions of this study lies in improving outdoor thermal comfort within dense historical urban fabrics. Through simulations and field data, it becomes possible to identify the spatial distribution of thermal stress and guide planning strategies by optimizing shading, vegetation placement, and material selection. These strategies have direct implications for pedestrian comfort, reducing heat-related health risks, and revitalizing public spaces, particularly in heritage contexts.

Furthermore, this research underscores the close relationship between built heritage conservation and climate adaptation, advocating for a preservation approach that integrates environmental imperatives. Traditional architectural techniques offer valuable lessons in passive cooling and heat mitigation, serving as a relevant foundation for contemporary restoration projects. The findings support the implementation of regulatory frameworks that incorporate climatic considerations into heritage site management, ensuring a preservation approach that addresses modern environmental challenges.

From a policy perspective, this study contributes to the development of climate adaptation strategies tailored to historical urban fabrics by providing evidence-based recommendations. Proposed measures include adopting zoning regulations that encourage the integration of nature-based solutions within heritage districts, involving local communities in the co-design of sustainable adaptation measures, and establishing guidelines for retrofitting historical buildings with energy-efficient materials while preserving their architectural authenticity. These recommendations equip policymakers with concrete tools to reconcile heritage preservation with climate adaptation.

Although this research focuses on the Casbah of Algiers, its methods and conclusions are transferable to other historical cities facing similar climate pressures, particularly in Mediterranean and arid regions. The proposed assessment frameworks can be adapted to mitigate urban heat island effects while preserving local architectural characteristics. Moreover, the approach combining computational modeling with empirical validation offers a reproducible methodology for interdisciplinary research in urban planning and climatology.

Finally, this study opens avenues for future research, particularly in analyzing the long-term impact of climate interventions in historical urban fabrics through longitudinal data collection. Expanding this work to include socio-economic dimensions—such as community resilience and the economic viability of adaptation measures—could further enrich discussions on sustainable heritage conservation. Additionally, integrating advanced simulation techniques through artificial intelligence and machine learning could enhance the predictive capabilities of thermal comfort models. By bridging climate science, urban planning, and heritage conservation, this research demonstrates that climate adaptation and heritage preservation are not opposing goals but rather complementary ones. By combining architectural heritage with contemporary innovations, it lays the foundation for a more sustainable and thermally comfortable urban future.

5 Strengths and Limitations of the Study

This research makes a significant contribution to the assessment of outdoor thermal comfort in a heritage context by adopting a multidisciplinary approach that integrates numerical modeling, in-situ measurements, heritage analysis, and climate adaptation strategies. The use of biometeorological indices, such as the Physiologically Equivalent Temperature (PET), allows for a precise evaluation of thermal conditions in a dense urban environment. Moreover, the study applies passive and nature-based solutions (NBS) specifically tailored to the architectural and urban constraints of the Casbah of Algiers, ensuring a heritage-sensitive approach that balances thermal comfort improvements with conservation imperatives.

One of the major strengths of this study is its dual-level analysis: it combines a quantitative assessment based on detailed microclimatic data with a qualitative approach that incorporates the perceptions and experiences of residents and visitors. This integrated methodology enhances the reliability of findings and ensures that the proposed recommendations are both technically sound and socially relevant. Furthermore, the study adopts a forward-looking perspective, incorporating climate projections for 2050 and 2090 to anticipate the long-term effects of climate change on historic urban fabrics. This approach helps inform adaptive urban planning policies while reinforcing the resilience of heritage sites.

Additionally, the study provides a scalable and transferable methodological framework, making it applicable to other Mediterranean cities facing similar climate challenges. By leveraging advanced microclimatic modeling tools, such as ENVI-met, and cross-referencing them with empirical field data, the study offers a rigorous yet adaptable approach that can be used by urban planners, policymakers, and conservation specialists.

However, certain methodological considerations must be acknowledged. The study primarily focuses on hot periods and heat waves, as these represent the most critical moments for outdoor thermal discomfort. While this choice aligns with the urgency of climate adaptation, future research could further explore seasonal variations to provide a more holistic perspective. Additionally, while the numerical modeling approach effectively captures key thermal dynamics, integrating finer architectural details could enhance local-scale accuracy, though at the cost of significantly higher computational demands.

Moreover, the proposed mitigation strategies remain aligned with heritage preservation regulations, ensuring feasible and respectful interventions. While certain large-scale urban cooling techniques common in modern environments may not be directly applicable, the study identifies innovative, reversible, and heritage-compatible solutions that strike a balance between conservation and climate resilience. Finally, while in-situ measurements and user perception surveys provide valuable empirical insights, expanding data collection over longer periods and broader spatial coverage could further strengthen the findings.

Despite these considerations, this study represents a major methodological and scientific advancement in the field of climate-responsive urban heritage conservation. By proposing context-specific, sustainable, and culturally sensitive strategies, it contributes to a growing body of knowledge on how historic urban areas can be preserved and adapted in the face of climate change. Furthermore, its replicable and adaptable framework provides a valuable reference for other Mediterranean and global heritage sites seeking to balance conservation with contemporary climate challenges.

6 Outlooks and Recommendations for Further Developments

This research highlights the necessity of an integrated approach that merges urban climatology, heritage preservation, and computational modeling to develop climate-responsive urban environments. The findings demonstrate the effectiveness of passive adaptation strategies, such as high thermal mass materials, shaded passageways, and compact urban morphologies, in mitigating thermal stress in historical settings. However, contemporary challenges, including population pressure and infrastructural neglect, require a dynamic approach that leverages historical knowledge while embracing modern innovations. Future research should focus on expanding methodological approaches by integrating long-term microclimatic monitoring, machine-learning-driven predictive models, and cross-disciplinary collaborations to refine climate adaptation strategies for heritage-rich urban environments.

The study underscores the importance of regulatory frameworks that balance conservation efforts with sustainability imperatives. Climate resilience must be embedded into heritage policies to ensure that conservation strategies address environmental challenges. Encouraging nature-based solutions, such as urban greening and water-sensitive design, within historical precincts can significantly improve microclimatic conditions while maintaining architectural authenticity. Additionally, participatory urbanism, which involves local communities in decision-making processes, should be prioritized to align adaptation strategies with socio-cultural needs. Retrofitting heritage buildings with energy-efficient materials while preserving their historical integrity is also essential for sustainable urban renewal.

In parallel, this study emphasizes the need for environmental impact assessments when implementing urban rehabilitation strategies. The analysis of various design alternatives, including the reconstruction of buildings at different heights using traditional materials, the integration of vegetation, the adoption of green roofs and façades, and the enhancement of urban albedo, highlights the significance of reducing carbon emissions in heritage conservation. The use of traditional materials such as stone and adobe generally results in a lower carbon footprint compared to modern materials like reinforced concrete, which has an estimated impact of 254 kg CO_2e/m^2 of floor area. However, increasing building heights from 3 m to 9 m proportionally raises material use and overall emissions. This underscores the need for further research into construction techniques that optimize both structural integrity and environmental performance.

Vegetation integration has proven to be an effective strategy for carbon sequestration and urban heat mitigation. Urban forests can store approximately 2.51 kg C/m^2, with trees demonstrating higher sequestration potential than lawns. While greening strategies such as hedges, hanging vegetation, and tree canopies contribute positively to urban microclimates, their implementation requires careful selection of species adapted to the local environment. Green roofs and façades further enhance urban resilience, with some systems sequestering up to 327.67 kg CO_2e annually under optimal conditions.

However, the carbon cost of installation must be considered, necessitating long-term impact evaluations and policy incentives to facilitate their adoption in heritage-sensitive contexts.

Increasing surface reflectivity through albedo-enhancing materials presents another viable strategy for reducing energy-related emissions. By reflecting up to 90% of solar radiation, high-albedo surfaces can decrease cooling demands, yet their net impact depends on material durability and climatic factors. Ensuring aesthetic compatibility in historical districts is crucial for the successful integration of these solutions. Future assessments should focus on material longevity and the balance between immediate carbon costs and long-term energy savings.

While this research has relied on ENVI-met simulations and in-situ measurements to assess outdoor thermal comfort, further developments should focus on enhancing real-time data integration to create more adaptive climate models. The exploration of hybrid strategies that merge nature-based interventions with advanced building materials could enhance the effectiveness of climate adaptation measures. Additionally, the socio-economic dimensions of climate adaptation require further investigation to ensure that proposed solutions are not only technically viable but also socially and economically sustainable. By integrating these considerations into urban planning strategies, cities with rich architectural heritage can transition towards climate-adaptive and sustainable futures while preserving their cultural identity.

7 Concluding Reflections

This research provides a comprehensive analysis of how historical urban morphologies, such as the Casbah of Algiers, can serve as models for climate adaptation. The study demonstrates that traditional architectural forms inherently enhance outdoor thermal comfort through passive cooling mechanisms, offering valuable lessons for contemporary urban design. By highlighting the effectiveness of historical adaptation strategies, this work positions heritage conservation as an essential component of climate resilience. Rather than viewing historical cities solely as static relics, this research presents them as dynamic and adaptable spaces that can inform modern sustainability practices.

The findings emphasize the importance of localized interventions in improving urban livability, particularly through the optimization of vegetation and shading strategies. Small-scale modifications, when applied consistently across historical districts, can have a significant impact on mitigating heat stress and enhancing outdoor comfort. Furthermore, the integration of climate adaptation strategies within urban governance frameworks is crucial to ensuring that sustainability efforts are effectively implemented and maintained over time.

Despite these contributions, the study acknowledges several limitations. Human thermal perception is inherently variable, requiring further longitudinal studies to refine the assessment of outdoor comfort. The complexity of urban climate interactions necessitates more advanced simulation techniques to capture the nuanced interplay between built environments and microclimatic conditions. Additionally, challenges in policy implementation highlight the need for stronger cross-sectoral collaboration to bridge the gap between research findings and practical urban planning strategies.

Future research should delve deeper into adaptive reuse strategies that integrate climate adaptation with social and economic resilience. Expanding the scope of investigation to include economic viability and community engagement would provide a more holistic perspective on sustainable heritage conservation. Advancements in AI-driven urban analytics could further enhance the predictive modeling of outdoor thermal comfort, offering more precise recommendations for climate mitigation. By bridging historical knowledge with technological innovation, this study reinforces the potential of heritage cities as pioneers in sustainable urbanism. Ultimately, the goal is to ensure that historical urban fabrics are not only preserved but also actively contribute to climate resilience and urban well-being in the face of future environmental challenges.

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