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Coupling of different nature base solutions for pedestrian thermal comfort in a Mediterranean climate

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ABSTRACT

The comfort sensation of pedestrians outdoors greatly impacts residents' happiness and standard of living. With the Earth's temperature expected to rise due to global warming, people's outdoor activities will be limited. Therefore, it's essential to intensify the evaluation of the effects of heat reduction strategies on outdoor thermal comfort in cities to enhance human well-being. At the same time, safeguarding historical and cultural heritage as required by Sustainable Development Goal 11. Across the literature, a limited number of studies have investigated the implementation of nature-based solutions as heat mitigation strategies in historical cities. This research investigates the influence of combining different nature-based solutions and scenarios. Combining NBS involves modifying the urban morphology, street and facade surfaces, and vegetation intensity to examine the cooling impact and enhancement of thermal comfort. The research methodology involves conducting in situ measurements in a traditional urban fabric in Algiers's old city fabric, which is classified as a world heritage site. The research assesses the climatic conditions during a typical summer heat wave using the Physiological Equivalent Temperature (PET). Then, numerical simulations are performed using CFD software Envi-met for different scenarios. The results highlight that combining mitigation strategies shows limited improvement, with the outcome primarily influenced by one or two parameters. Also, In some instances, the use of nature-based solutions to reduce the heat has a slightly better cooling effect ($\Delta PET = 16.8\ ^{\circ}C$) compared to morphological reconstruction ($\Delta PET = 15.2\ ^{\circ}C$), yielding a difference of 1.6 °C in PET values. The reported results offer practical guidance for stakeholders who renovate traditional cities in Mediterranean climates to make informed decisions about urban heat mitigation methods. This research presents innovative perspectives by analyzing nature-based solutions at two different levels. First, individually, to gauge their impact and by combining strategies of the same category. Then by combining the most favorable scenarios for an in-depth examination. The research also balances the reduction of urban heat with the preservation of cultural heritage.

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 [1]. Indeed, an increase of 1.2 million km^2 is estimated, tripling the urban land cover in 2030 [2]. 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

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severity of storms, and heat-related mortality as the central issue [3].

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 [4].

Thermal comfort gauges human well-being, reflecting contentment with the temperature surroundings. It involves factors influencing heat exchange between the body and the environment [5]. 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 [6]. 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 [7–9]. A comfortable outdoor environment encourages extended outdoor stays, potentially saving energy compared to building cooling loads [10,11]. 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 [12].

Research has suggested changes in urban morphology [13–16] taking into consideration the effect of H/W ratio and Sky view factor ([17]; Fazia Ali-Toudert et [18,19], Orientation and geometry form of urban canyons [20–22]. Others recommend the use of green, blue, and white surfaces [23–25], vegetation, and the shading effect ([26,27]; Yu et [28,29], or modern and innovative materials [30–33]. 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 [34].

Pedestrians have generally experienced viable outdoor thermal comfort in historic cities with a significant shading effect in the streets [35], which allowed them to perform different activities in urban spaces [36]. Indeed, the high and heavy walls provide more shading and heat storage, leading to lower surface temperatures (F [37]). However, Historic cities are not immune to global warming and overheating [38] 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 [39].

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 [12,30,40,41] 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.

3. Methodology

A conceptual framework of the study is developed that summarizes and visualizes the research methodology of this paper. As shown in Fig. 1, the conceptual study framework is based on three methods: combining the literature review (See Table 1), 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.

3.1. Model presentation

3.1.1. Case study characterization

a. Geometric data & building proprieties.

The historic Casbah in Algiers, Algeria, spans over 105 ha and accommodates a densely populated community of over 40,000 residents. Renowned for its unique traditional architecture (See Fig. 2), the Casbah is a prime example of Mediterranean habitation, recognized as a UNESCO World Heritage Site since 1992 [47]. The city's layout follows a tree-like and hierarchical street network, reflecting functional distinctions from public to semi-public, semi-private, and private spaces, including dead ends [48]. The Casbah features a millennia-old urban design centered around housing units organized around a central patio, a prevalent Mediterranean architectural style. Local materials like terracotta and lime are commonly used in construction [49].

The study focused on specific areas chosen based on criteria, including vulnerability to high temperatures during summer, identified through a thermal comfort quantification study [50]. Additionally, areas along the busiest main street with high activity levels were selected, and priority was given to locations with collapsed houses, presenting potential opportunities for rehabilitation [50].

b. 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 [51,52], Algiers experiences notable summer warming and altered precipitation [53]. 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.

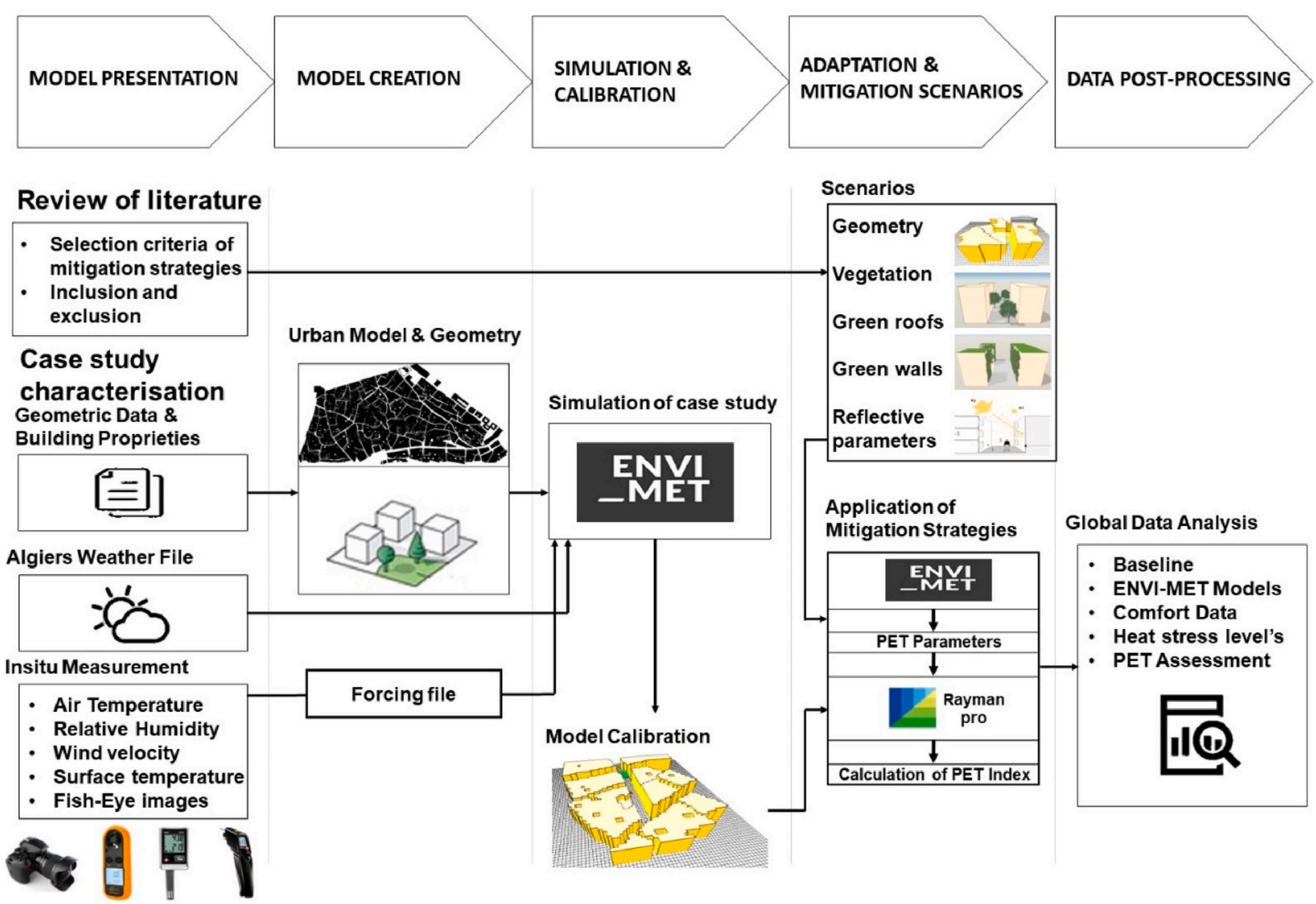


Fig. 1. Study conceptual framework.

Table 1
Literature review.

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.	[14]
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)	[42]
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, …)	[43]
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.	[17]
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.	[23]
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.	[7]
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,	[44]

(continued on next page)

Table 1 (*continued*)

Global Outdoor thermal comfort studies			
City (Country)	Köppen classification	Key findings	Reference
		PCM-doped infrared reflective coatings, and thermochromic materials. Findings show that White cool coatings have superior thermal performance. 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.	[4]
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.	[12]
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. - The proposed mitigation strategies are increasing the reflectivity of surfaces, increasing the number of green spaces, and building retrofits.	(Laureti et al., 2018)
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).	[30]
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.	[45,46]

(*continued on next page*)

Table 1 (*continued*)

Global Outdoor thermal comfort studies			
City (Country)	Köppen classification	Key findings	Reference
		- 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.	

3.2. *In situ measurement*

The temperature of a certain precinct is always affected by various factors, such as solar radiation, the thermal mass of materials, urban ventilation, and anthropogenic activities [54]. So, to investigate the outdoor thermal comfort and compare the impact of microclimatic conditions. It was necessary to take several measurement points with different sky view factors, types of streets, and orientations. Also, it is essential to critically define the temporal protocol for field measurement to exclude other possible interferences (B.-J. [55]).

The urban morphological details are explained in Table 2. Four points were selected for the measurements according to their morphologic variations. The methodology followed for the in-situ measurements was designed to measure microclimate variables such as Air temperature (Ta), Relative humidity (RH), Wind speed (WS), and Surface temperature(TS). Fish-eye images were also gathered to study the openness to the sky. All the instruments used were newly acquired, mainly for the study. Fig. 3 (B) summarizes the name, range, and accuracy of the instruments used in the measurement campaign.

Furthermore, Meteorological measurements were conducted for 7 Days from the 5th to the August 11, 2021. Measurements take place every 2 h from 6 a.m. to 8 p.m. Following the recommendations of Ali-Toudert [56], the sensors were kept at a 1.40 m height from the ground to avoid surface emissivity effects. The measured data has been published in the following dataset [57,58].

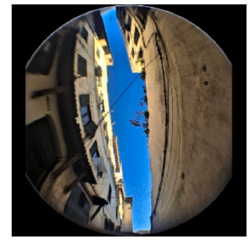
3.3. *Model creation & simulation*

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 0.5–10 m and a time-step of 1–5 s, it offers high spatial resolution, making it a prominent choice for urban microclimate assessment [14]. 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 [59].

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 [56]. Widely validated and

Fig. 2. Position of the city of Algiers in north Algeria and the historical city of Casbah.

Table 2
Morphological parameters of the selected sites in the Casbah of Algiers.

Measurement location	Morphological characteristics	Sky view factor	
		Image	Value
Zone 1 	Street direction: E-W Width: 2.80 m Height: 11.30 m Canyon Hard surface texture (Granite)		**0.18**
Zone 2 	Street direction: N–S Width: 18.6 m Height: 8.10 m Exposed to direct solar radiation Hard surface texture (Granite/Concrete) Small Palm		**0.56**
Zone 3 	Street direction: E-W Width: 3.95 m Height: 8.20 m Canyon Hard surface texture (Granite) Small vegetation		**0.24**
Zone 4 	Street direction: N–S Width: 4.90 m Height: 8.95 m Exposed to direct solar radiation Hard surface texture (Granite)		**0.29**

reputable, ENVI-met stands as a dynamic simulation tool for microclimate simulations and outdoor thermal comfort assessment [60]. In our study, we specifically focus on the four main parameters for PET calculation [45,46].

- **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 3) 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 [61]. In our case, we added 10 cells on each side.

We employed a 60-min 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:

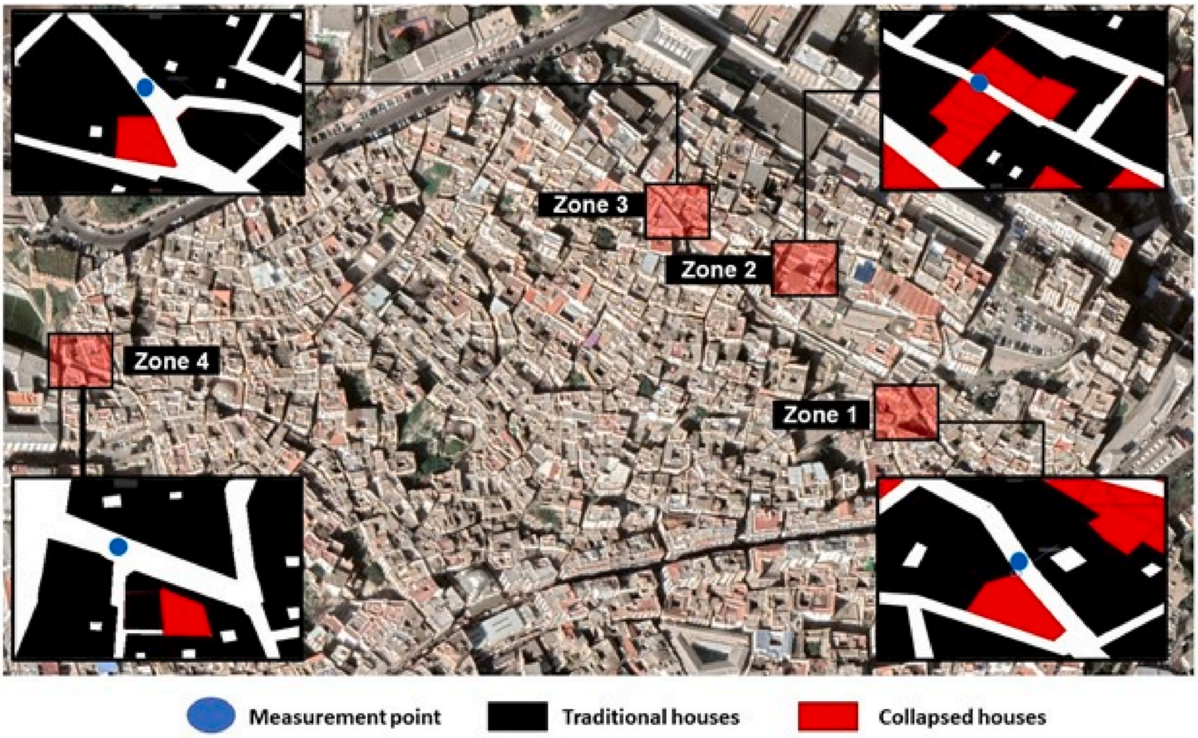
Plant processes: 600s; Surface Data: 30s; Radiation and Shadows: 600s; Flow field: 900s.

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

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

- **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



(A)

	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 Velocity (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

(B)

Fig. 3. A. Case study locations B. Instruments used for the meteorological measurements.

collection "From 5th to August 11, 2021".

3.3.1. Urban model and geometry

3.3.2. Simulation of case study

The start of simulation time was set up before sunrise, ensuring stable conditions [61] based on the microclimatic measurement files. The total simulated time was 72h, set from 00:00 a.m. (08.08.21) to 11:59 p.m. (10.08.21). The first hours of the model run were discarded to avoid any model spin-up effects [62].

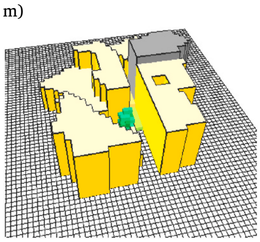
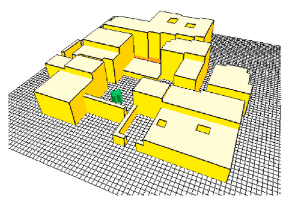
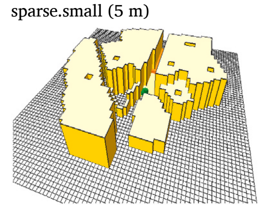
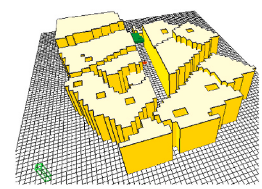
In the outputs, the four main parameters "Ta. HR. Va and Tmrt" were used to calculate the outdoor thermal comfort index. The (PET) is one of the most common indices [42] and is certificated by the German VDI-Guidelines 3787 to assess the urban scale's thermal comfort. The shared dataset [63] summarizes 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 (oC), humidity (RH %), mean radiant temperature (Tmrt, °C), and wind speed (WS, m/s) [62].

3.4. 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

Table 3
Input data for the four sites' models in ENVI-met software.

	Zone 1	Zone 2	Zone 3	Zone 4
Position				
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
Model geometry				
Grid size	71 m × 63 m	76 m × 76 m	71 m × 71 m	84 m × 69 m
dx = size of X grid	dx = 1.00	dx = 1.00	dx = 1.00	dx = 1.00
dy = size of Y grid	dy = 1.00	dy = 1.00	dy = 1.00	dy = 1.00
dz = size of Z grid	dz = 1.00	dz = 1.00	dz = 1.00	dz = 1.00
DEM Levels in model	0.00 m–3.00 m	0.00 m–2.00 m	0.00 m–2.00 m	0.00 m
Construction material				
Building material	Walls: - Created wall: W1: Terracotta; Lime mortar; Lime plaster W2:Concrete wall (hollow block) Roofs: Created roof: Terracotta, Lime mortar, Lime plaster	Walls: - Created wall: Terracotta, Lime mortar, Lime plaster Roofs: Created roof: Terracotta, Lime mortar, Lime plaster	Walls: - Created wall: Terracotta, Lime mortar, Lime plaster Roofs: Created roof: Terracotta, Lime mortar, Lime plaster	Walls: - Created wall: 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) (7.31 m)	Palm, small trunk, dense, small (5 m)	Created tree: spherical (small trunk. sparse.small (5 m)	Hanging vegetation (50 cm)
3D model				
Simulation				
Start Date	August 08, 2021	August 08, 2021	August 08, 2021	August 08, 2021
Start time	00h00	00h00	00h00	00h00
Total 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

included adherence to neighborhood models and metrics evaluation using Root Mean Square Error (RMSE) and Mean Bias Error (MBE) [64]. 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 [64]. Validation specifically targeted "air temperature" parameters, following a 72-h duration simulation, in line with Taleghani's recommendation [65,66]. Table 4 summarizes the validation outcomes for the four zones.

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

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

B. Validation of the model using RMSE/MBE

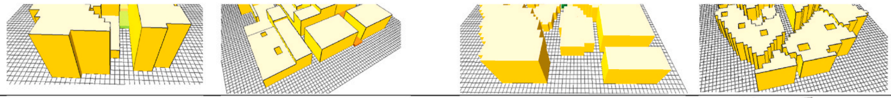
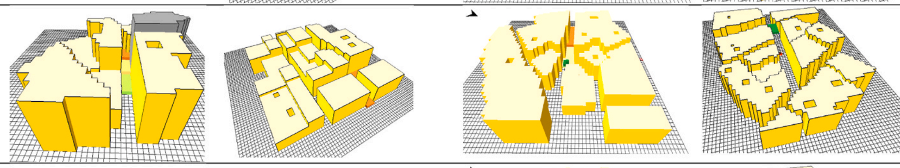
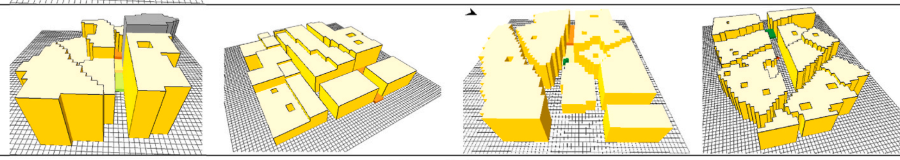
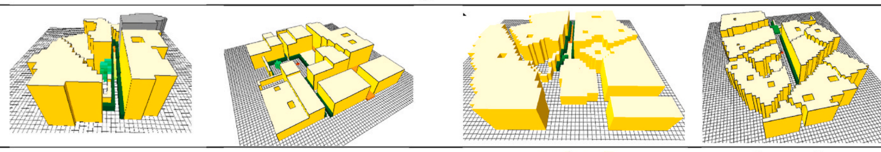
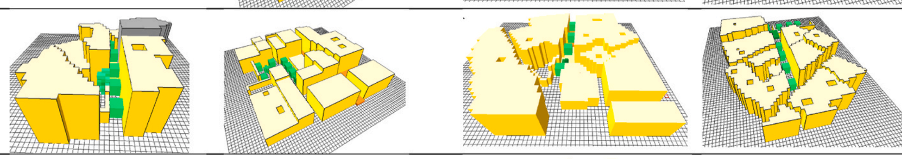
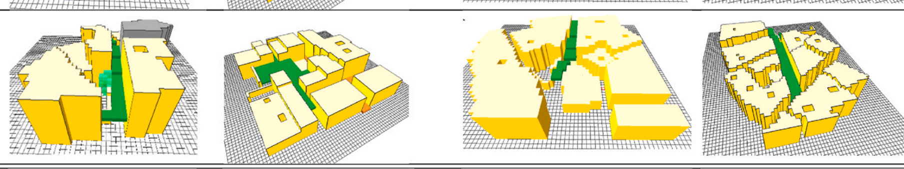
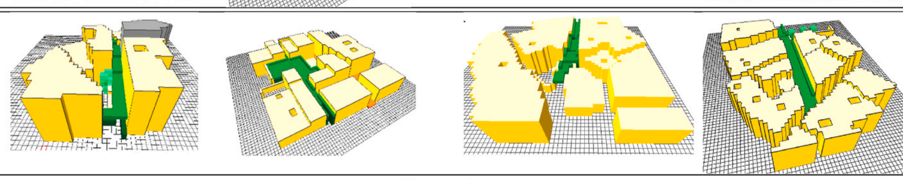
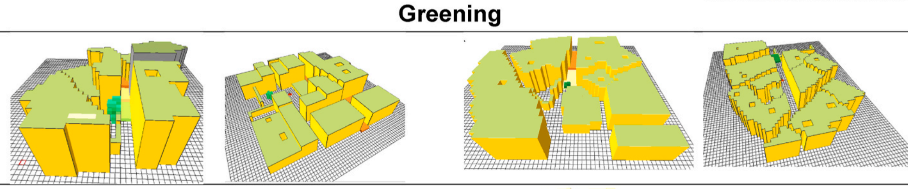
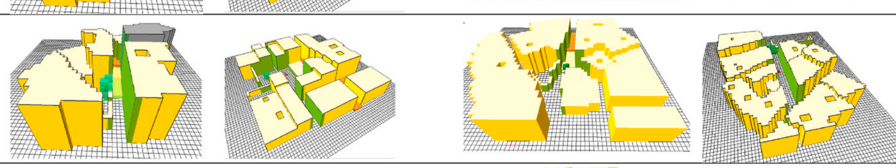
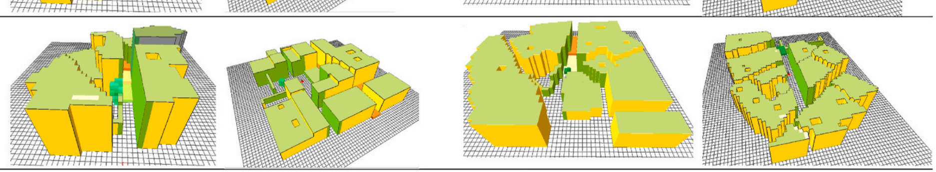
According to the ASHRAE Guideline 14, the simulation model is considered calibrated if it has an MBE that is not larger than 10%. (RMSE) is not larger than 30% when the Hourly data are used for the calibration (See Fig. 4). Although the literature review shows that the validation is carried out on a 48h simulation running using the air temperature parameter [67,68]. The model was validated for 72 h to improve its accuracy (See Fig. 5). These measures of model accuracy have also been used in other studies [69–71].

3.5. Adaptation and mitigation scenarios

3.5.1. 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 Fig. 6, and different scenarios for each group. The specifics of how these strategies are applied in each study area are

Table 4
Application of the mitigation scenarios in the four site locations.

Reconstructi	
Reconstruction 6m	
Reconstruction 9m	
Vegetation	
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)

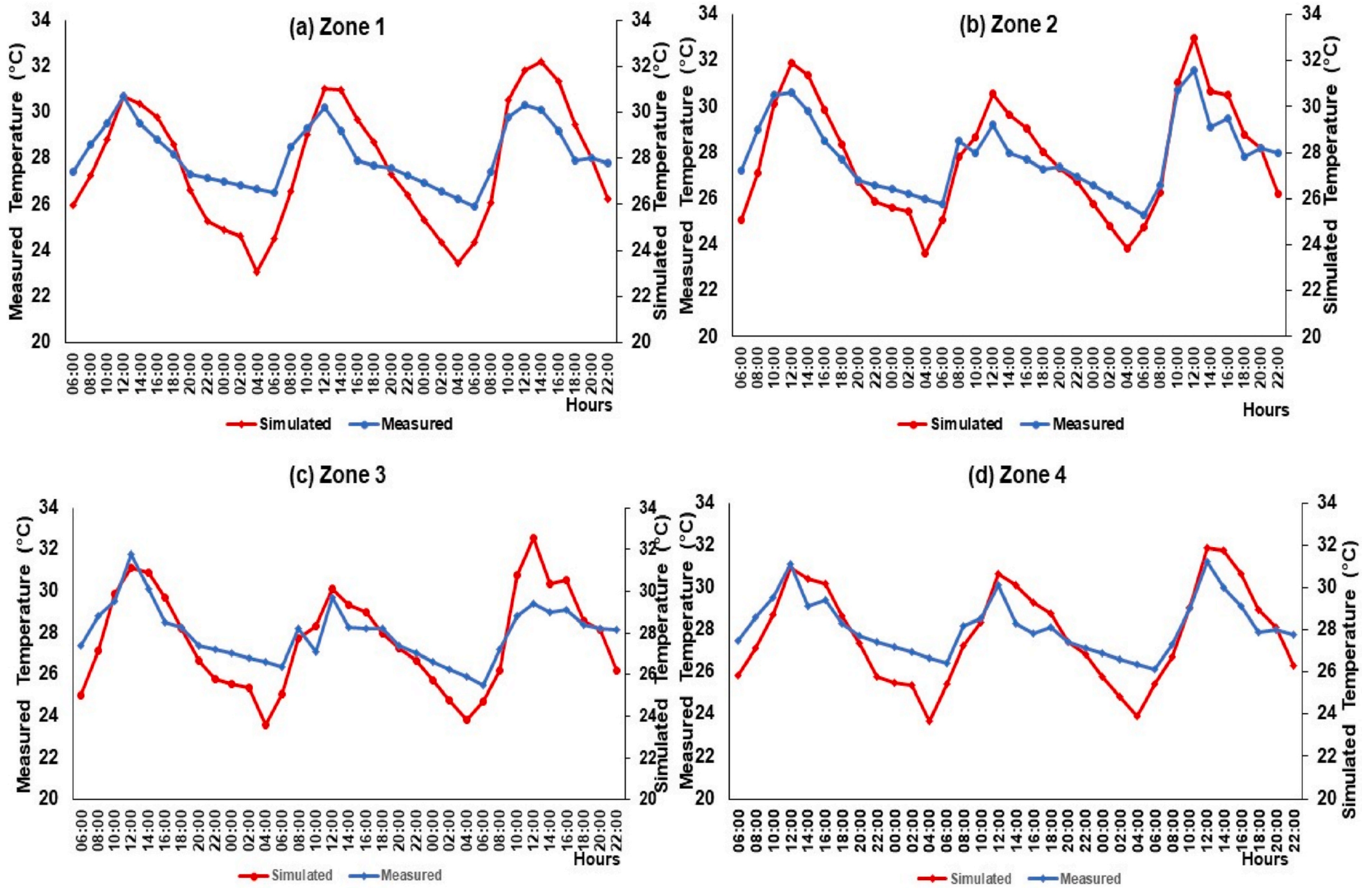


Fig. 4. Validation measured/ simulated for 08–10.08.2021(a. Zone 1 b. Zone 2 c. Zone 3 d. Zone 4).

outlined in Table 4.

3.5.1.1. Geometry. Urban geometry, particularly the arrangement of streets and buildings, significantly influences the thermal comfort of pedestrians. Research by Ref. [72,73]. Emphasizes the impact of urban canyons and their role in wind cooling potential, which can alleviate heat stress. The Andreou study [74] 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 Ref. [4]., 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 m. This strategy seeks to maintain the site's integrity, contributing to both urban sustainability and thermal comfort for residents.

3.5.1.2. Vegetation. Vegetation, highlighted by Ref. [75], is vital for mitigating urban heat. Studies[7,34,67,76] explore its impact on microclimates, emphasizing temperature reduction and wind influence [77]. Emphasize how urban vegetation alters air temperature, humidity, and wind patterns.

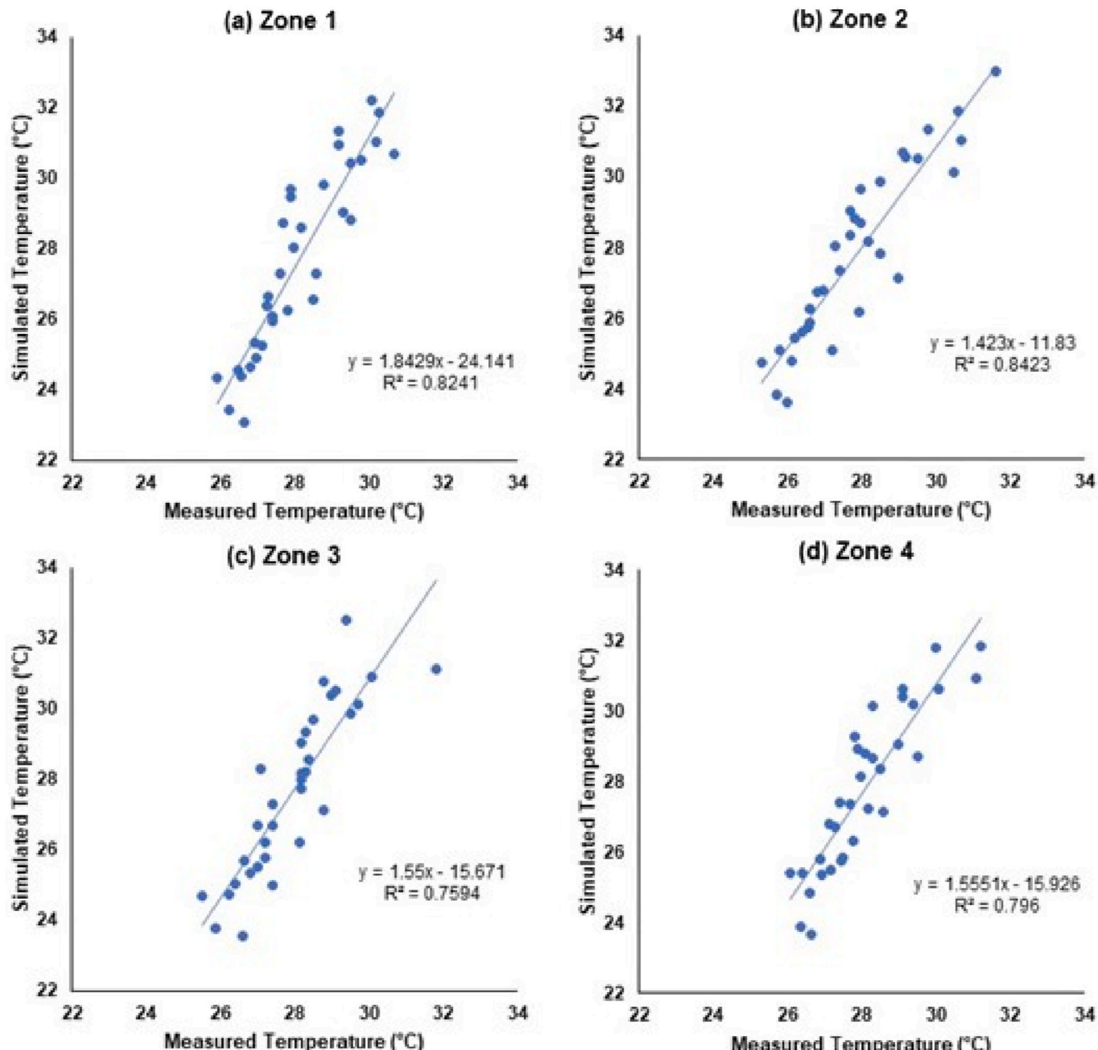
Street greenery not only offers physical and psychological comfort but is aesthetically valued [78–80] found that tree shade in urban canyons reduces surface and radiant energy during the day, enhancing nighttime comfort. Green canopies, as per [81]., improve microclimates and cut energy consumption.

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, 2 m high hedges, suspended vegetation at 5 m, and a combination. Table 4 summarizes their arrangements, aiming to provide insights into sustainable urban planning in the Casbah.

3.5.1.3. Greening. Among nature-based solutions strategies, greenery systems are considered one of the most appropriate sustainable solutions to resolve urban heat island-related issues [82]. 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 [31,83]. Several studies have been conducted on the performance of greening built surfaces [65,66,78,79,84], also knowing that Roofs account for nearly 20–25% of overall urban surface areas [85].

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.

3.5.1.4. 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 [86–89]. Highly reflective surfaces in urban canyons can efficiently reflect solar radiation, aiding in heat dissipation and alleviating urban heat islands [90]. Three scenarios are proposed to assess the impact on the Casbah: modifying soil albedo from 0.40 (Current) to 0.80, analyzing the effect



(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)

Fig. 5. A. Correlation Air temperature measured/simulated for 08–10.08.2021 (a. Zone 1 b. Zone 2 c. Zone 3 d. Zone 4).

of wall reflectance from 0.50 (Current) to 0.80, and exploring a combined scenario incorporating both strategies.

3.5.2. 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. Fig. 7 provides a concise overview of the scenario composition for each zone.

The coupled scenarios are, therefore, as follows.

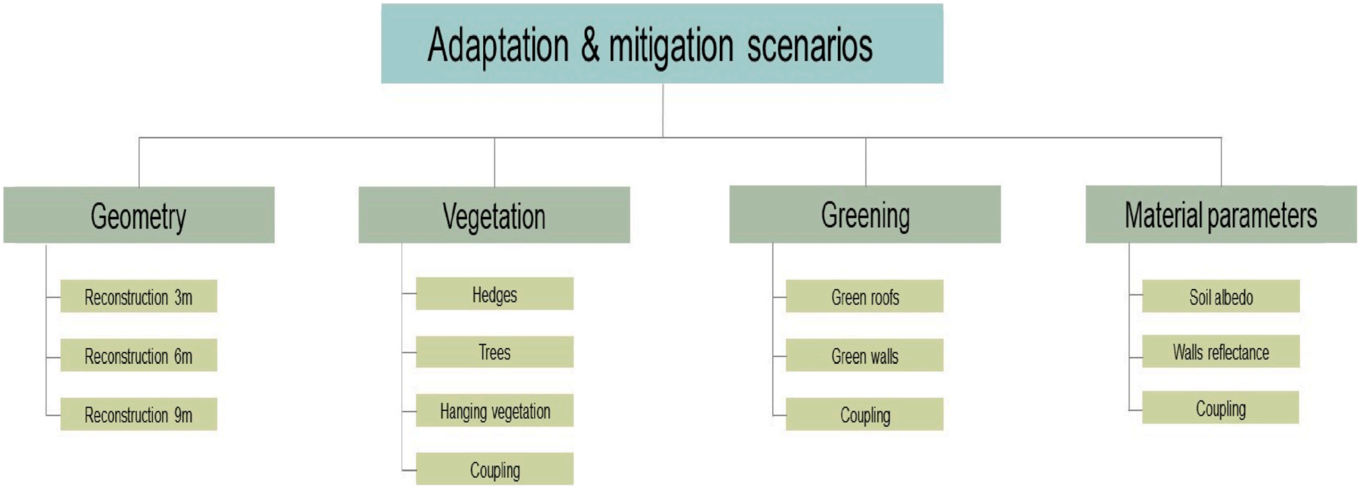


Fig. 6. Adaptation and mitigation strategies selected in the study.

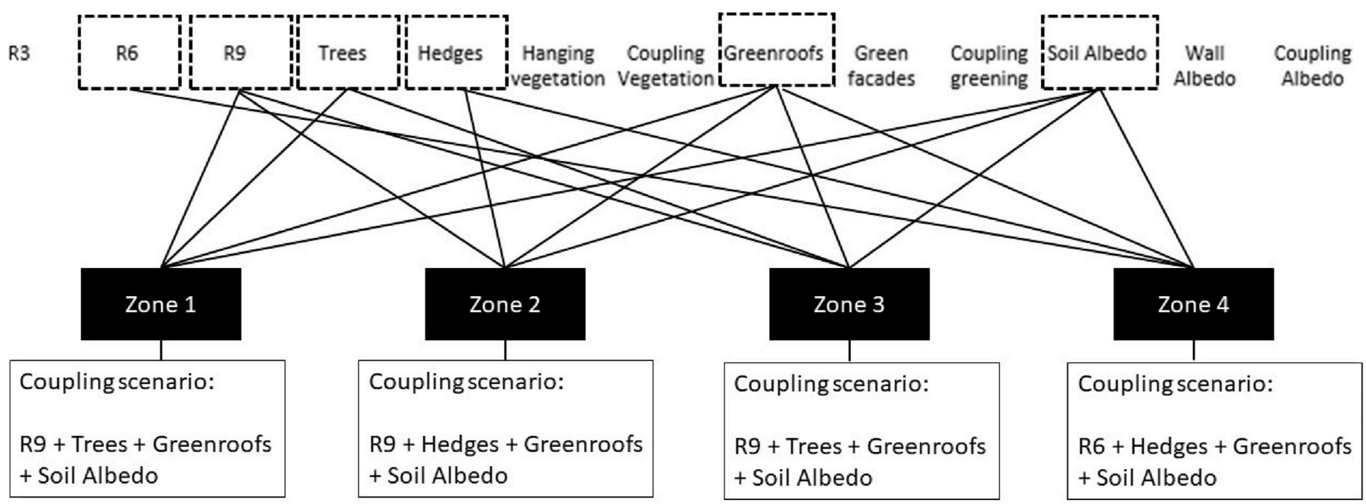


Fig. 7. Composition of the best-case scenarios for the four zones.

3.5.3. Calculation process of PET index and heatmaps

The most critical factors of PET are the mean radiant temperature Tmrt (∘C) [91], wind speed (m/s), and air temperature (∘C) [92]. Relative humidity RH (%) only shows a very weak impact on PET [93]. 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) [94].

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

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

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 1.40 m height for all scenarios in four zones at 12:00 p.m. were generated.

4. Results

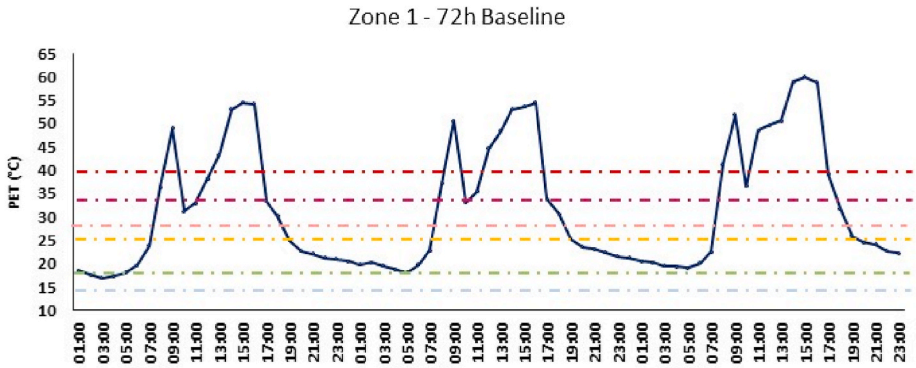
4.1. What are the summer thermal comfort levels in the historical urban fabric?

a. Zone 1:

Fig. 8(a) shows the Physiological Equivalent Temperature (PET) in measurement zone 1 from August 08, 2021 to August 10, 2021. The baseline exhibits a repeating 4-phase pattern over the 3 days. PET values rise from 4:00 a.m. to 9:00 a.m. and 11:00 a.m. to 4:00 p.m. From 9:00 a.m. to 10:30 p.m., a decrease occurs due to solar radiation masking. Temperature drops from 5:00 p.m. to 3:00 a.m., with a decrease from 2:00 p.m. to 6:00 p.m. as solar radiation lessens. The highest values, reaching 59.9 °C on 10.08, are at midday (3:00 p.m.). PET assessment reveals three comfort levels (Neutral, hot, extremely hot) in zone 1 during the period, aligning with Mediterranean climate standards [42].

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

b. 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 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)

Fig. 8. (a) 72h PET Values for the zone 1 from August 08, 2021 to August 10, 2021
(b) PET Values for the best-case scenarios in zone 1 on October 10, 2021.

Fig. 9 (a) depicts the Physiological Equivalent Temperature (PET) in measurement zone 2 from August 08, 2021 to August 10, 2021. Baseline graphs exhibit two phases daily: PET rises from 4:00 a.m. to 1:00 p.m., then decreases from 2:00 p.m. to 10:00 p.m. Peak PET is 59.1 °C at noon. Fig. 9 (b) displays four comfort levels: Neutral, Slightly warm, Hot, and Extremely hot. Extreme discomfort (>50 °C) is observed from 10:00 a. m. to 12:00 p.m. Strong heat stress (>34 °C) occurs from 3:00 p.m. to 5:00 p.m. 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.

c. Zone 3:

The graph for zone 3 (Fig. 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. Fig. 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 (See Fig. 11).

d. Zone 4:

The baseline graph of Zone 4 shows a temperature increase from 4:00 a.m. to 1:00 p.m., followed by a decrease from 2:00 p.m. to 11:00 p.m. 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 p.m. to 3:00 p.m. and moderate heat stress at 10:00 a. m. and 5:00 p.m. Hedges have the best cooling effect, reducing the temperature by almost 5 °C and bringing the comfort level to a lower state.

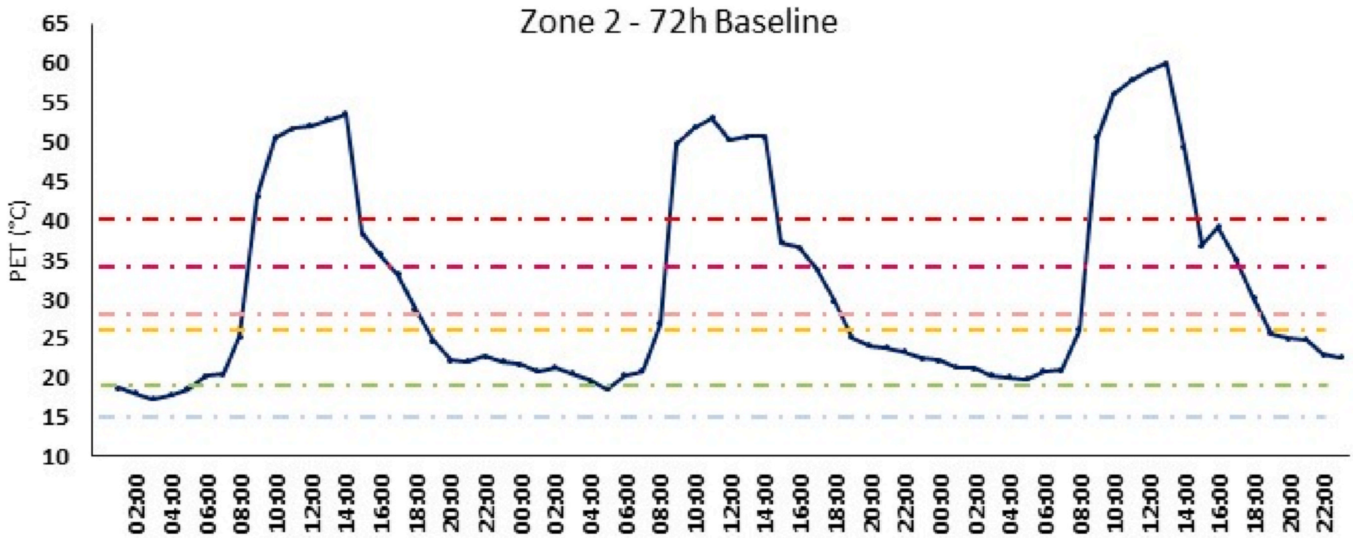
4.2. Which mitigation parameters to considered in reducing thermal stress levels in the mediterranean climatic zone?

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 (Figs. 12–15). The best case is taken according to temperature improvements throughout the day.

Fig. 12 illustrates diurnal PET variation for 14 scenarios in zone 1 at 8 a.m., 12 p.m., and 5 p.m. PET values generally peak at 8 a.m., with 12 p.m. reaching 50.6 °C in "Coupling albedo." At 5 p.m., the lowest value is 31 °C in "Coupling vegetation" with trees, hedges, and hanging vegetation. Notably, PET is generally better at 5 p.m. 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 9 m, trees, green roofs, and soil albedo."

Fig. 13 shows PET variation at 8 a.m., 12 p.m., and 5 p.m. in zone 2. The lowest PET is at 8:00 a.m. in all scenarios. The highest average PET is at 12:00 p.m., with coupling albedo reaching 57.7 °C. The lowest temperature is in "rebuild 6″ at 8:00 p.m. at 23.1 °C. Cooling differences between scenarios are similar at 8:00 a.m. and 5:00 p.m. but more noticeable at 12:00 p.m. Albedo and greening coupling scenarios don't outperform individual scenarios due to a single parameter impact, e.g., global coupling affected by rebuild 9 m at 12:00 p.m.

Morphological scenarios have the greatest influence, improving PET by 23 °C at 12:00 p.m. Among vegetation scenarios, "hanging



(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)

Fig. 9. (a) 72h PET Values for the zone 2 from August 08, 2021 to August 10, 2021
(b) PET Values for the best-case scenarios in zone 2 on October 10, 2021.

vegetation" cools most at 12:00 p.m., but "hedges" perform better overall. The best configurations for daily cooling in zone 2 are "Rebuild 9 m," "hedges," "green roofs," and "soil albedo".

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

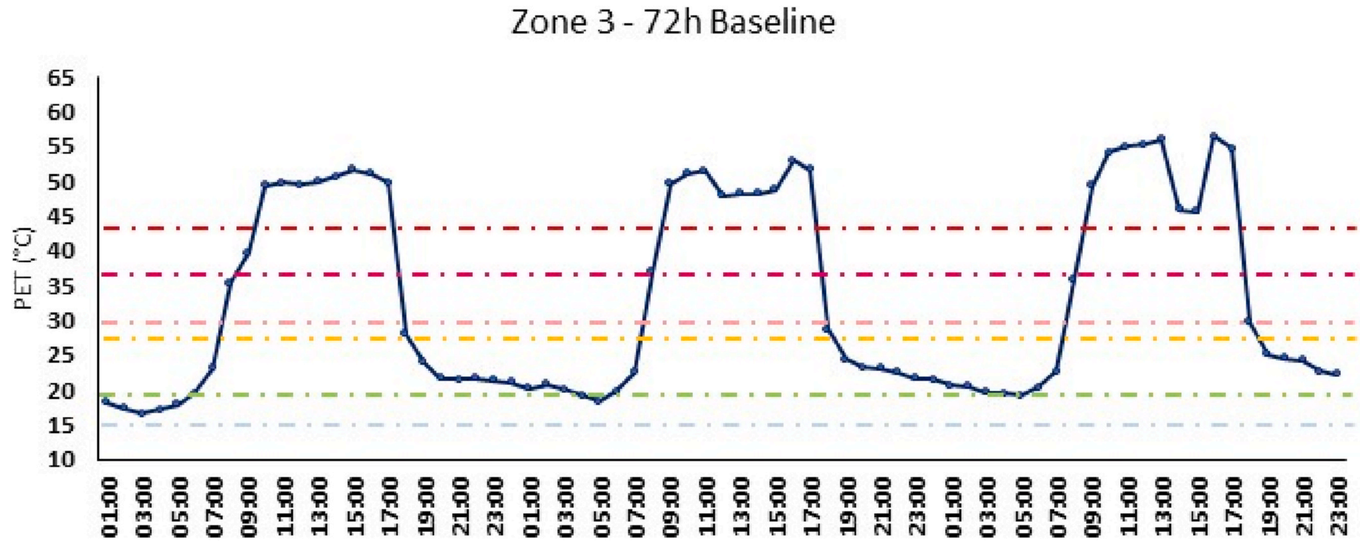
The Physiological equivalent temperature (PET) of 14 scenarios in zone 4 is shown in Fig. 15, with the diurnal variation at 8 a.m., 12 p.m., and 5 p.m. The maximum PET values are observed at 12:00 p.m. in most scenarios, reaching 40 °C in the "Coupling Albedo" configuration. The lowest temperature is recorded at 8 a.m. 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 p.m.). Among the scenarios, the "Rebuild 6 m," "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 5 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 9 m rebuild yields the best results, enhancing PET by 6.4 °C at 8:00 a.m. and 15.2 °C at 12:00 p.m., 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 p.m. (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 p.m., mitigating heat stress from extreme to strong.



(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)

Fig. 10. (a) 72h PET Values for the zone 3 from August 08, 2021 to August 10, 2021
(b) PET Values for the best-case scenarios in zone 3 on October 10, 2021.

Materials strategy affects PET negatively. Increased wall reflectance induces a greenhouse effect, elevating PET by 9.4 °C at 5:00 p.m., 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 p.m.

4.3.2. Zone 2

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

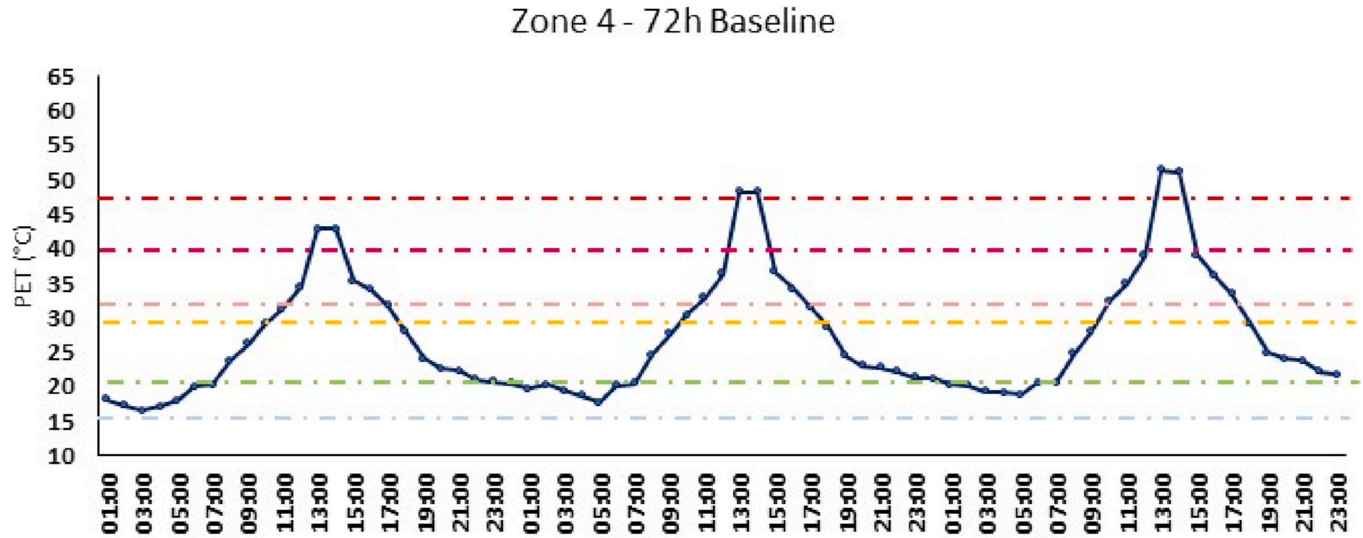
Efficient vegetation, specifically “Hedges and Coupled Vegetation,” plays a crucial role. Hanging vegetation positively impacts noon temperatures (ΔT PET = 8.7 °C) but has a slight negative effect in the morning/evening. Hedges (5.6 °C) consistently cool the area, maintaining neutral thermal comfort 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 a.m. and 5.1 °C at noon, moderating stress levels at 5 p.m. Ground albedo is effective in reflecting radiation, resulting in temperature reductions at 12 p.m. (ΔT PETSoil. Albedo = 4.3 °C) and 5 p.m. (ΔT PETSoil.Albedo = 1.5 °C).

4.3.3. Zone 3

Severe heat stress in Study Area 3 occurs from 10:00 a.m. to 5:00 p.m., 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 a.m., 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 p.m. to 10:00 p.m.), achieving neutral thermal comfort.

Green roof and soil albedo scenarios decrease PET values by 1.9 °C at 8:00 a.m. and 5.5 °C at 12:00 p.m., showing effectiveness. However,



(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)

Fig. 11. (a) 72h PET Values for the zone 4 from August 08, 2021 to August 10, 2021
(b) PET Values for the best-case scenarios in zone 4 on October 10, 2021.

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 p.m. 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 6 m and 9 m. 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 a.m. and 5:00 p.m.

Figure A7 maps show urban configuration and solar radiation impact on PET values at 12:00 p.m. for four sites. Baseline and best-case scenarios, using a 1.40 m 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.

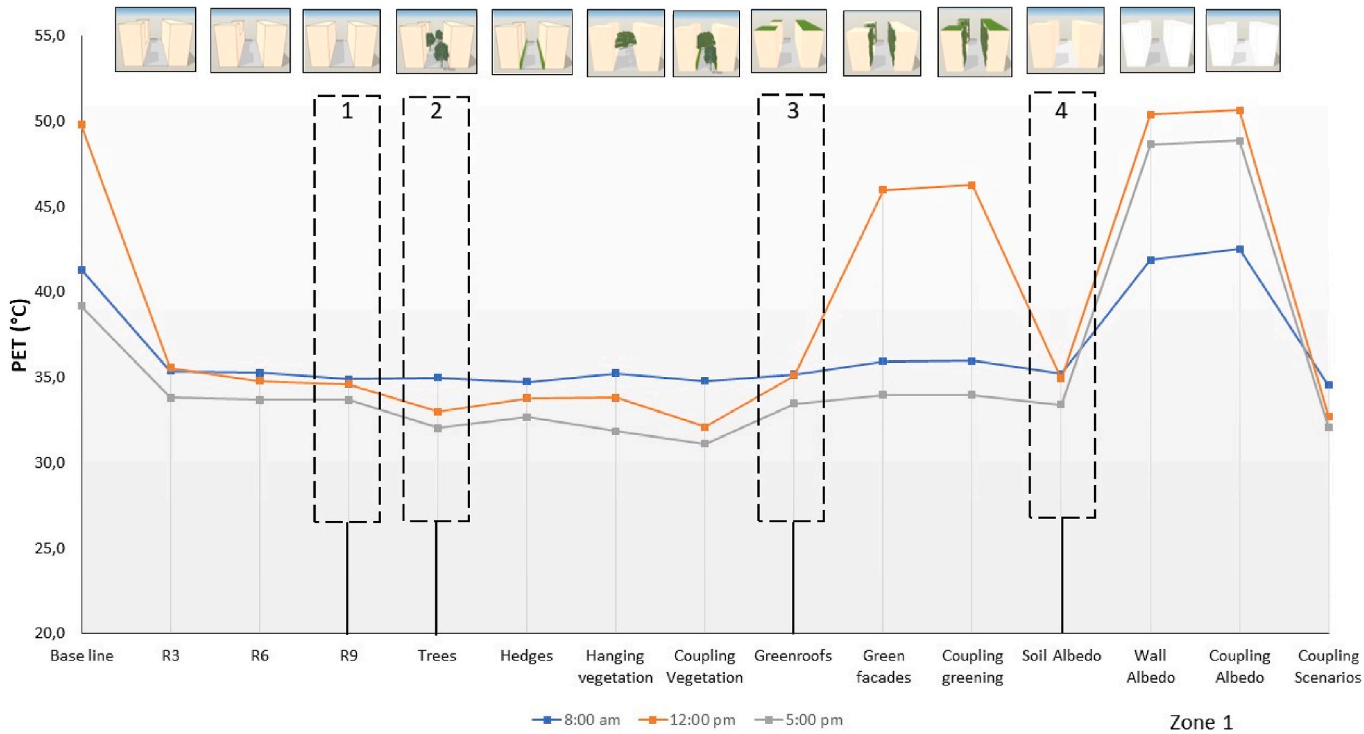


Fig. 12. Mean cooling effect in zone 1 by different scenarios on August 10, 2021 at 8 a.m., 12 p.m., and 5 p.m.

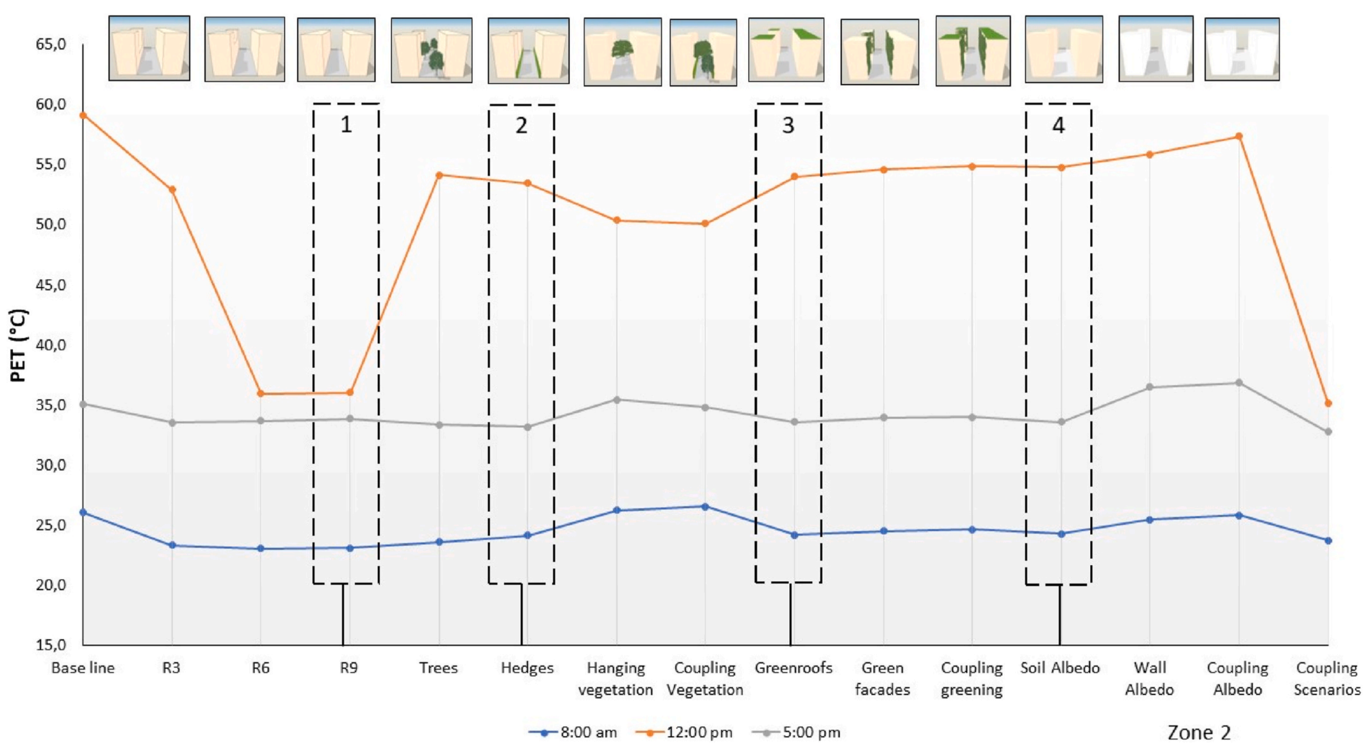


Fig. 13. Mean cooling effect in zone 2 by different scenarios on August 10, 2021 at 8 a.m., 12 p.m., and 5 p.m.

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.

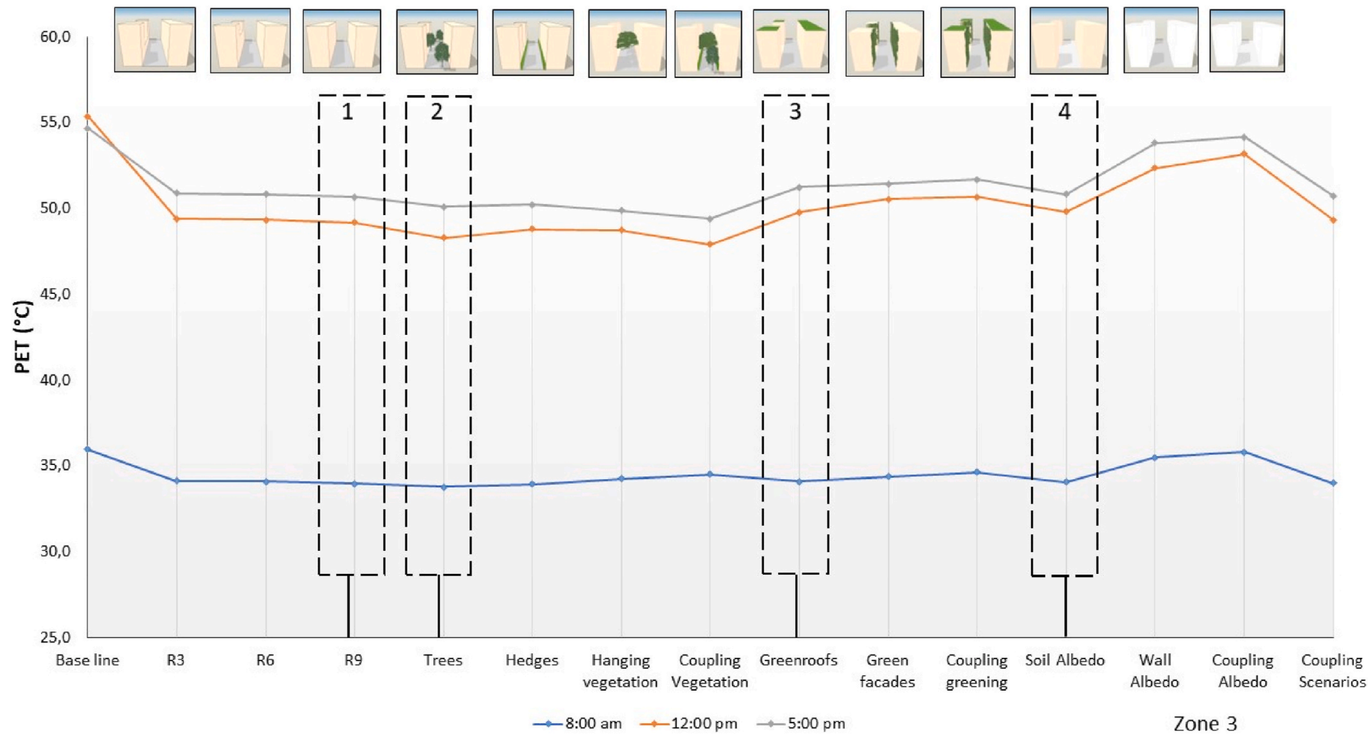


Fig. 14. Mean cooling effect in zone 3 by different scenarios on August 10, 2021 at 8 a.m., 12 p.m., and 5 p.m.

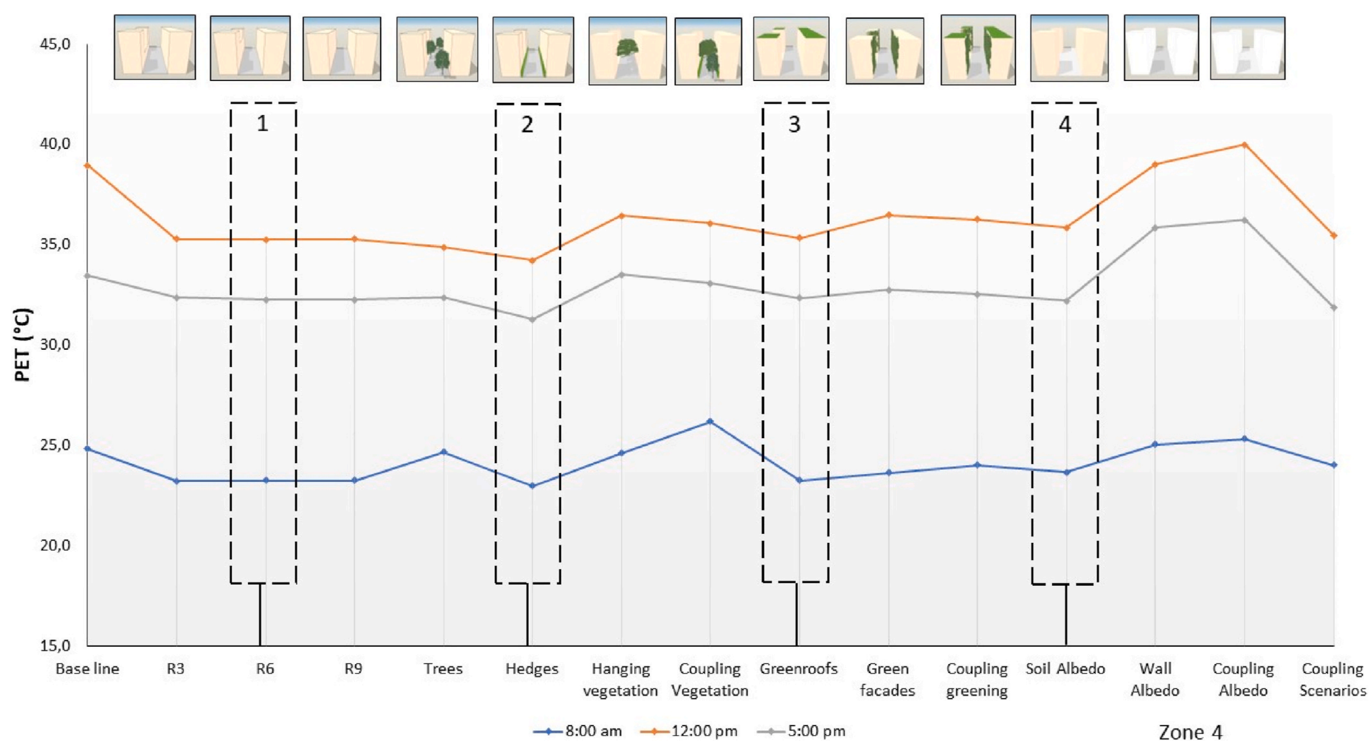


Fig. 15. Mean cooling effect in zone 4 by different scenarios on August 10, 2021 at 8 a.m., 12 p.m., and 5 p.m.

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 p.m. 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 Figs. 12–15.

These findings are in line with studies by Sodoudi and Kong [11,67], which showed the relationship between the fragmentation of green

Table 5
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
5 : 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
6 : 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
7 : 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

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 [84]. 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 Figs. 12 and 13. This supports Wang's conclusion [95] 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 (Fig. 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 9 m has the greatest effect, followed by suspended vegetation.

Thirdly, Figs. 12–15 depict diurnal variations in the cooling impact of 14 scenarios at 8:00 a.m., 12:00 p.m., and 5:00 p.m. Across all scenarios, mean cooling rises from 8:00 a.m. to peak at 12:00 p.m., then declines until 5:00 p.m. Rebuilding in Zone 2 yields the highest mean cooling at 12:00 p.m. (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 p.m. 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 Ref. [96], demonstrating that cool paving enhances outdoor thermal comfort in high-density urban areas [97]. 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 [98].

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 [99]. 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 [100,101] suggested that increased facade heterogeneity led to higher surface temperatures due to elevated radiation reflection. These findings align with [102], 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 [103] 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 [65,66].

The cooling impact of greening is consistent at 8:00 a.m. and 5:00 p.m., 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 [104] findings in Melbourne contradict, stating green roofs don't enhance the PET index for pedestrians.

Contrary to Ref. [105], this study reveals that, in traditional urban fabrics, green roofs have a superior cooling effect compared to green walls. In disagreement with [106], 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 Ref. [107,108] 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 [17,109,110] support the role of urban geometry in shading and outdoor thermal comfort.

Zone 3, experiencing the highest discomfort, is evident in Fig. 10, with peak PET values reaching 55.4 °C and 54.6 °C at 12:00 p.m. and 5:00 p.m., respectively. The latter's PET curve surpasses that of 12:00 p.m., 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 Ref. [18,111] emphasized the impact of factors like orientation, aspect ratio, and sky view factor on street canyon overheating [4]. 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 (F [21,37,112]). Meanwhile, studies on microclimates and strategic mitigations are mostly conducted on current case studies in modern cities [14,19,113]. 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 1 m × 1 m x 1 m, 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 1 m.

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 h 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 h 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 h [14,68,114] 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 h), 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 [115]. 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 (1 m × 1 m x 1 m 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.

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CRediT authorship contribution statement

Hicham Fawzi Arrar: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Dalel Kaoula:** Writing – review & editing, Resources, Methodology, Formal analysis, Conceptualization. **Mattheos Santamouris:** Methodology, Supervision, Writing – review & editing. **Amina Foufa-Abdessemed:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization. **Emmanuel Rohinton:** Writing – review & editing, Supervision, Methodology. **Mohamed Elhadi Matallah:** Writing – review & editing, Visualization, Validation, Software, Methodology, Data curation. **Atef Ahriz:** Validation, Data curation. **Shady Attia:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

ARRAR FAWZI HICHAM reports financial support was provided by Wallonie-Bruxelles International. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in the article has been shared in Dataset Link format in the paper

Acknowledgments

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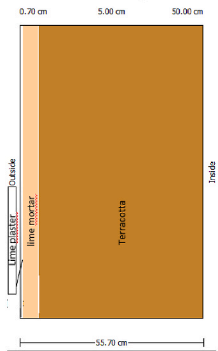
Appendix A

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

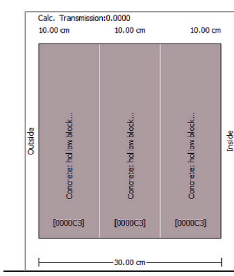
Construction material

Building material

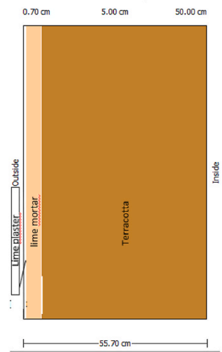
Walls:
- Created wall: Terracotta;Lime mortar;Lime plaster



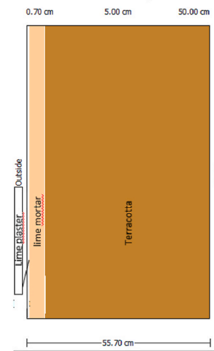
- Concrete wall (hollow block)



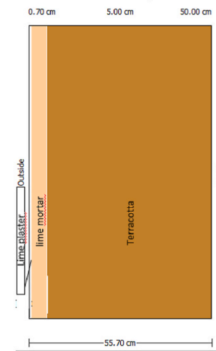
Walls:
- Created wall: Terracotta;Lime mortar;Lime plaster



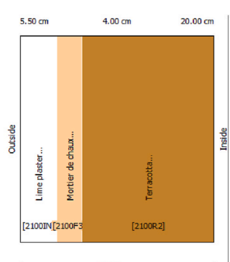
Walls:
- Created wall: Terracotta;Lime mortar;Lime plaster



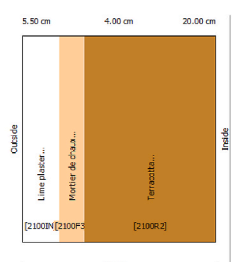
Walls:
- Created wall: Terracotta;Lime mortar;Lime plaster



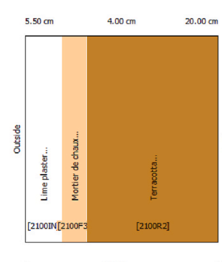
Roofs:
Created roof:
Terracotta;Lime mortar;Lime plaster



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



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



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

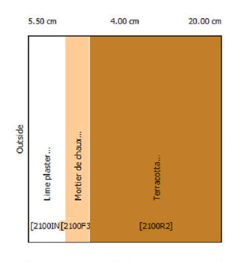


Table A2
Average daily temperature per scenario

Scénarios	Zone 1 – Average temperature	Zone 2 – Average temperature	Zone 3 – Average temperature	Zone 4 – Average temperature
Baseline	34,30	33,32	35,64	28,48
R3	30,58	30,60	32,53	26,92
R6	30,40	27,25	32,48	26,91
R9	30,16	26,89	32,37	26,93
Trees	29,68	31,25	32,15	27,53
Hedges	29,87	31,24	32,33	26,70
Hanging vegetation	30,35	32,29	32,84	27,72

(*continued on next page*)

Table A2 (*continued*)

Scénarios	Zone 1 – Average temperature	Zone 2 – Average temperature	Zone 3 – Average temperature	Zone 4 – Average temperature
Coupling vegetation	29,78	32,53	33,02	29,49
Green-roofs	30,44	31,67	32,74	26,91
Green-facades	31,92	32,20	33,06	27,27
Coupling Greening	31,97	32,40	33,19	27,35
Soil albedo	30,41	31,89	32,65	27,08
Wall albedo	34,76	33,59	34,24	28,64
Coupling Albedo	34,95	33,95	34,54	28,99
Coupling scénarios	29,47	27,16	32,50	27,40

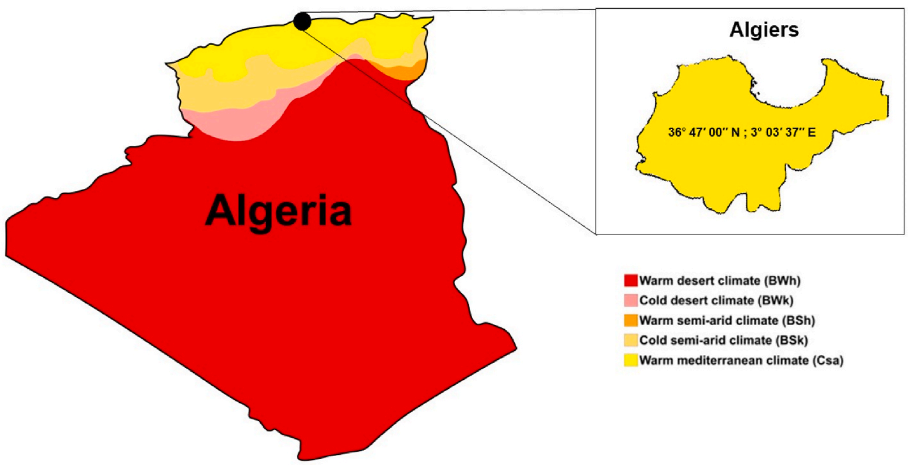


Fig. A1. Algiers climatic classification.

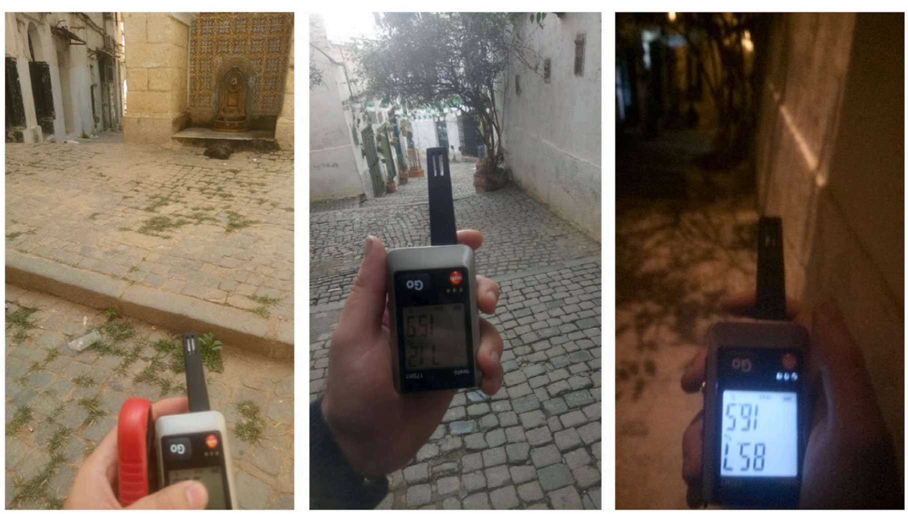


Fig. A2. Measurement campaign.

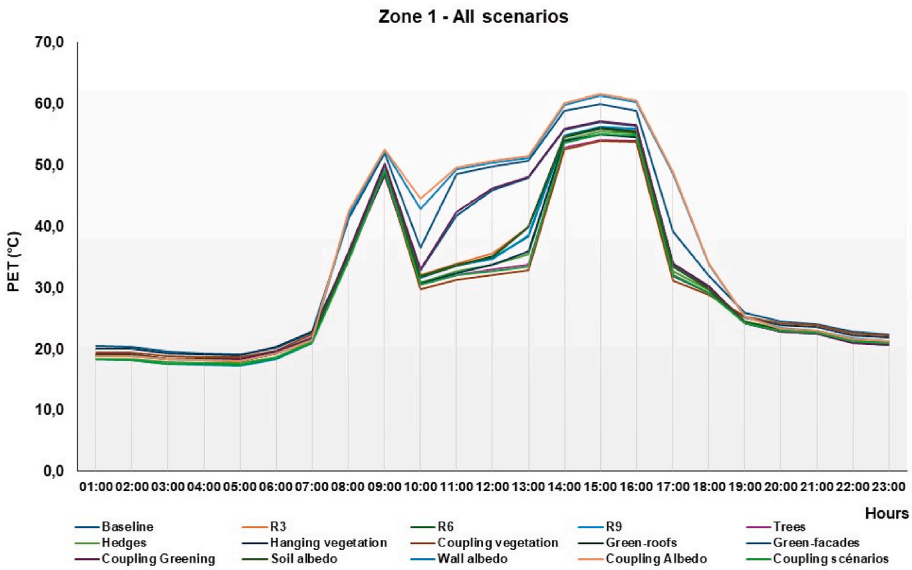


Fig. A3. PET Values for the zone 1 for August 10, 2021.

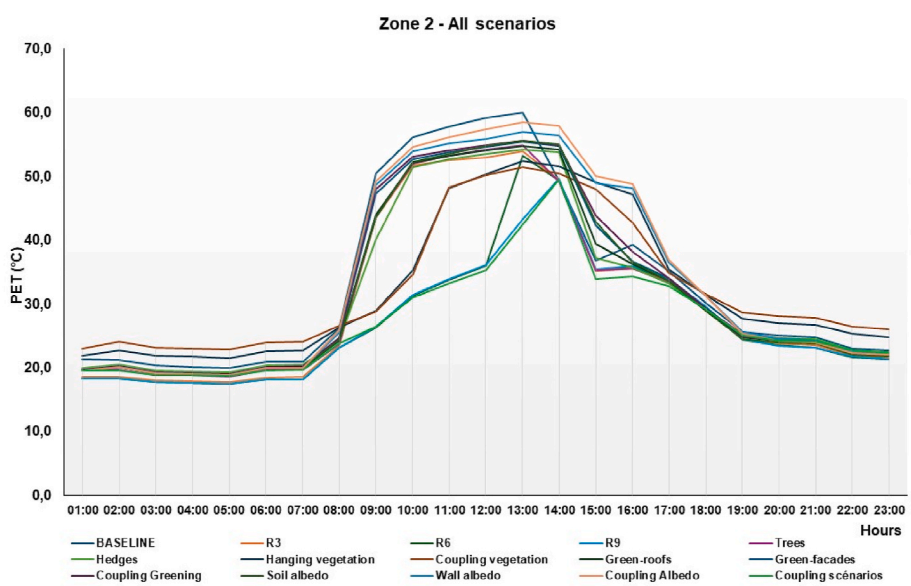


Fig. A4. PET Values for the zone 2 for August 10, 2021.

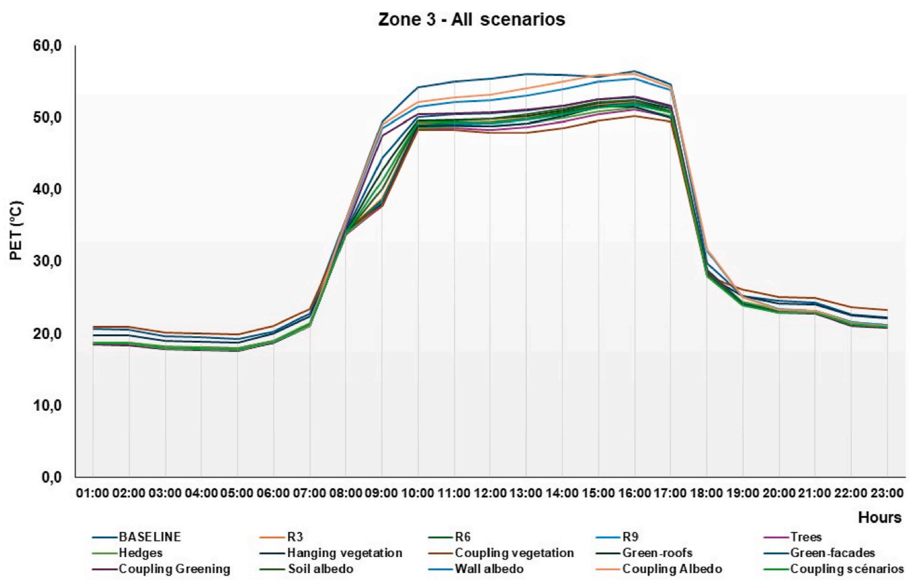


Fig. A5. PET Values for the zone 3 for August 10, 2021.

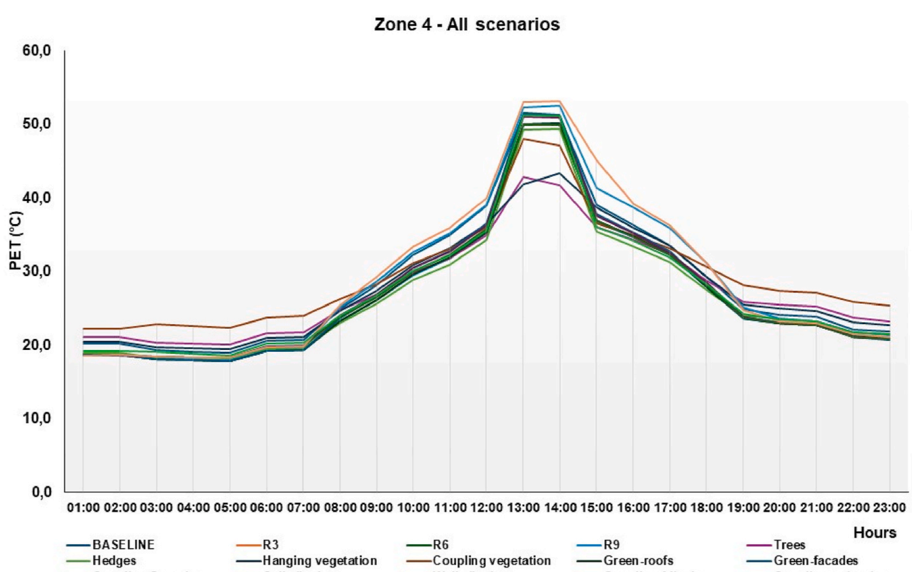


Fig. A6. PET Values for the zone 4 for August 10, 2021.

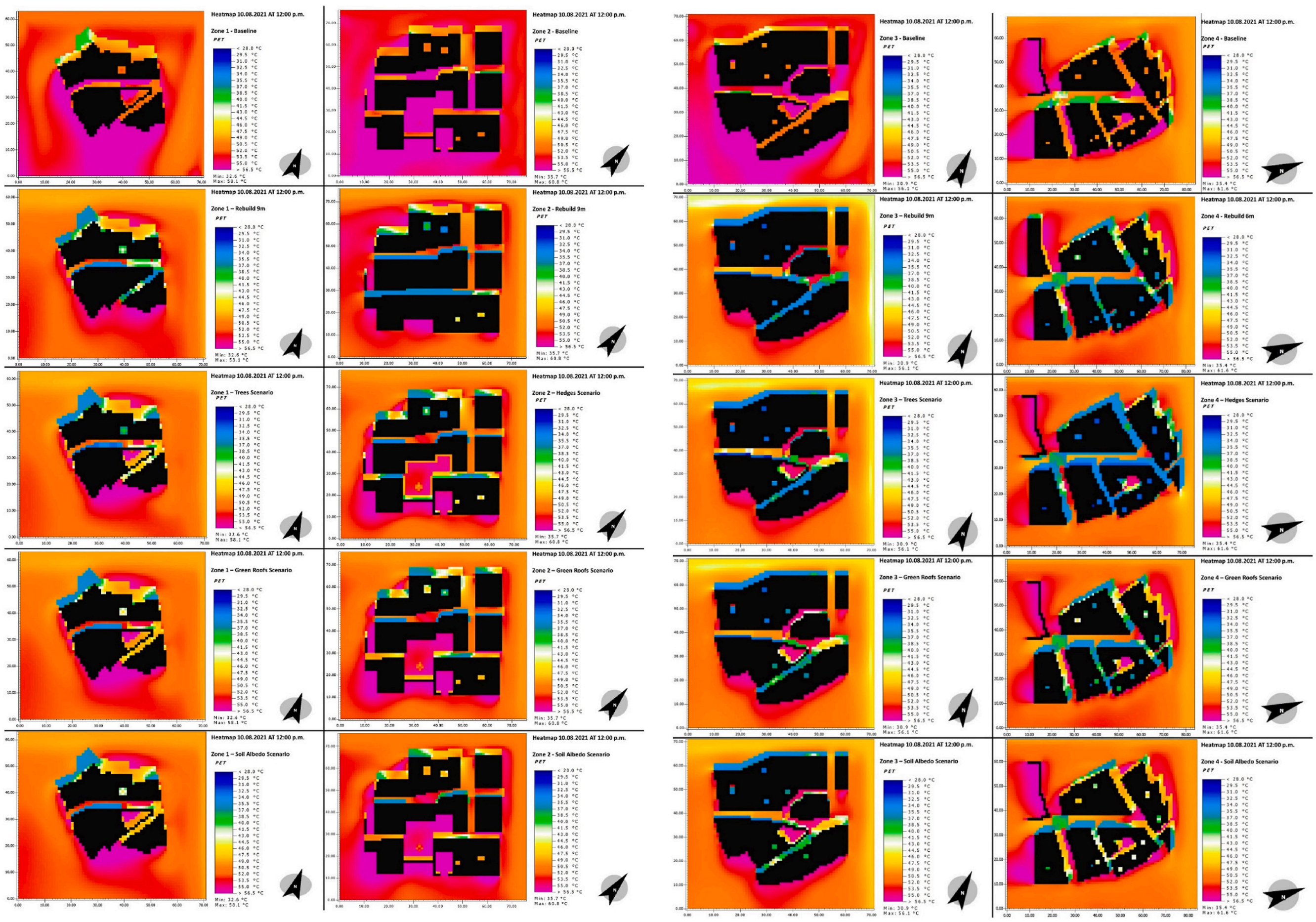


Fig. A7. Heat maps of different mitigation strategies on the four zone at 12:00 p.m.

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