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Optimizing a courtyard microclimate with adaptable shading and evaporative cooling in a hot mediterranean climate

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ABSTRACT

While in recent years significant improvements have been made in the thermal adaptation of indoor building environments, less progress has been made in improving thermal comfort in transitional spaces next to buildings. This makes it imperative to investigate the thermodynamics of such outdoor urban spaces, particularly in warm locations such as southern Spain. The application of suitable passive systems for the regulation of thermal exchanges and the creation of temperate conditions is explored. In order to determine the thermal comfort of users this study focuses on the assessment of two key parameters, mean radiant temperature and relative humidity, and how these are impacted by shading and misting systems in a courtyard. Field measurements analysed the extent to which shading and misting systems enhance user comfort levels in a Seville courtyard. The results indicate a considerable decrease in temperature, with thermal mitigation of up to 11.7 °C below reference points outside the courtyard. The percentage of hours within comfort ranges during heat waves increased by 100% by optimizing the results of an additional experimental campaign and considering results from previous ones. The main novelty of this research lies in the comparative study of standalone and integrated passive cooling strategies aiming to provide optimal results in high temperature and heat wave scenarios. The study findings help understand and estimate the effectiveness of low-cost and easily applicable strategies for maintaining comfort conditions during diurnal and nocturnal cycles in both hot seasons and heat waves.

Nomenclature

AR	Aspect Ratio
CT	Courtyard Temperature
MRT	Mean Radiant Temperature
PET	Physiologically Equivalent Temperature
TR	Thermal Range

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CS	Case Study
DTR	Diurnal Thermal Range
OT	Outdoor Temperature
TG	Thermal Gap
UHI	Urban Heat Island

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has voiced serious concerns about climate change as the major issue affecting all at present [1]. In the case of southern Spain, the IPCC [2] temperature increase forecast is particularly worrying. By the end of the century experts predict an average annual temperature increase of up to 3 °C in some coastal areas, while in inland areas such as Seville, severely affected by global warming [3], this figure could rise by up to 5 °C. The design of buildings and the layout of cities can play a key role in the mitigation of climate change [4]. In southern European cities, strongly affected by this fast-changing climate, courtyards are becoming increasingly important as effective passive cooling systems [5]. Inspired by traditional architecture, in hot areas these courtyards offer shade and can mitigate radiation intake, using certain geometric set-ups or aspect ratios [6]. Furthermore, the influence of different aspect ratios and the presence of windows facing the courtyard can also lead to additional ventilation patterns [7,8]. As well as significantly regulating their own inner temperature, courtyards can potentially alter the Urban Heat Island effect (UHI) [9,10].

The potential of courtyards to mitigate climate change, particularly in moderate climate zones, has been shown in experiments [11, 12]. A key parameter to be considered is the Thermal Gap (TG), also known as Delta T (ΔT), which is the difference between the courtyard air and the outdoor air temperatures. Previous research have used TG to determine the cooling potential of the courtyard [13,14]. TG is calculated as the difference between the outdoor temperature (OT) on the roof of the building and the courtyard temperature (CT) measured using a sensor placed at a fixed height above ground over a specific period (Equation (1)).

$$TG\,(^{\circ}C) = OT - CT \tag{1}$$

TG is impacted by external, form-related, and interior-related factors.

1) Boundary conditions, primarily the urban climatic environment and local microclimate, significantly determine the cooling performance of courtyards [5]. Diurnal and nocturnal temperature shifts also play a crucial role.
2) Geometry – particularly Aspect Ratio (AR) - is also a primary element which impacts microclimates. In these environments, the fixed form of the buildings generates shade, creating different microclimates [15].
3) Courtyard elements and interchangeable factors relating to courtyards include orientation [16], presence of vegetation or water, degree of exposure to wind and cross-ventilation potential [17], construction finishes (albedo) [18], and shade elements [19].

This research mainly focuses on the interior factors of the courtyard, which are the most manageable in adapting to climate change. The courtyard microclimate contributes to a building's energy savings by thermodynamically altering the semi-outdoor space next to interior rooms [20]. Furthermore, Energy Rating is a key consideration in contemporary building design [21]. According to the literature, climatic mitigation in courtyard spaces can be more effective in providing thermal comfort during most of the day in the warm season [22]. Furthermore, the indoor microclimate within a courtyard can be improved using passive strategies [23]. These strategies include vegetation [24], albedo variations [25–27], water-based systems such as water-sheets [28,29], misting [30,31], and the use of shading elements [32]. Some of the studies mentioned above touch upon improvements in outdoor comfort. Table 1 shows a systematic review of research on the application of easy-to-install low-cost passive strategies in specific microclimates, including previous data. All research located involving passive cooling strategies in specific microclimates such as courtyards and studies analysing these cooling strategies were considered. Distinctions are made between field campaigns and simulations, period studied and analysis of thermal comfort.

According to the literature reviewed the effect of evapotranspiration cooling strategies such as misting systems on the microclimate of courtyards has not been extensively studied. While only 9% of the reviewed research tested this strategy, none applied to courtyards, and passive strategies such as vegetation (28%), albedo (34%) and shading (23%) have been researched in further depth. Shading elements and misting systems appear to be the most effective strategies in a microclimate, with improvements exceeding 9 °C for courtyard shading [87], and up to 15 °C cooling in a microclimate prototype using a misting system [78]. In terms of comfort, these systems have enhanced the thermal sensation of the users of the spaces used for field campaigns [74,79].

1.1. Shade providers

The use of shading elements in courtyards or outdoor environments such as urban canyons has already been explored [98]. Trees as shading elements, covering 75% of the courtyard, provide the most significant air temperature decrease rates, from 3.3 to 2.5 °C [55]. Other studies analysing the effect of eaves and archways also showed how these improved comfort conditions [57]. Research on different geometric configurations has analysed the resulting shading effect. According to Akbari et al., the geometric parameters of the courtyards considering their depth have contrasting effects in summer and winter on the solar lighting performance due to the incidence of solar radiation [83]. A parametric study conducted by Muhaisen and Gadi showed the considerable influence of courtyard proportions and geometry on the shading performance of courtyard shapes [35]. In microclimates such as courtyards, which closely

Table 1
Mapping of passive cooling strategies on microclimates.

		Passive Strategies					Method				
Authors/Year	Case studies	Shading	Vegetation	Misting	Albedo	Other	Field Campaign	Simulation	Comfort	24-h cycle	Ref.
Muhaisen et al. (2006)	Simulated courtyards	✔	–	–	–	✔	–	✔	–	–	[33]
Muhaisen et al. (2006)	Simulated buildings in Rome (Italy)	–	–	–	–	✔	–	✔	–	–	[34]
Muhaisen et al. (2006)	Simulated courtyards	–	–	–	–	✔	–	✔	–	–	[35]
Muhaisen (2006)	Simulated courtyards	–	–	–	–	✔	–	✔	–	–	[36]
Aldawoud (2008)	Simulated courtyard	–	–	–	–	✔	–	✔	–	–	[37]
Shashua-Bar et al. (2009)	Courtyard in Negev Highland (Israel)	✔	✔	–	✔	–	✔	✔	–	✔	[38]
Moonen et al. (2011)	Simulated courtyards	–	–	–	–	✔	–	✔	–	–	[39]
Rojas et al. (2012)	Mediterranean courtyards (Spain)	–	–	–	–	✔	✔	✔	–	–	[40]
Berkovic et al. (2012)	Single courtyards in Beer-Sheba (Israel)	✔	✔	–	–	–	–	✔	✔	–	[41]
Al-Masri et al. (2012)	Simulated buildings in Dubai (EAU). Review	–	–	–	✔	–	–	✔	–	–	[42]
Yang et al. (2012)	Simulated courtyard	–	–	–	✔	–	–	✔	–	–	[43]
Shahidan et al. (2012)	Malay places (Malaysia)	–	✔	–	✔	–	✔	✔	–	✔	[44]
Almhafdy et al. (2013)	Hospitals (Malaysia)	–	✔	–	–	–	–	–	–	–	[45]
Almhafdy et al. (2013)	General Hospital (Malaysia)	–	–	–	–	✔	✔	✔	–	–	[46]
Cantón et al. (2014)	School Building in Mendoza (Argentina)	–	✔	–	–	–	✔	✔	–	–	[47]
Taleghani et al. (2014)	Block dwellings (Netherlands)	–	–	–	✔	–	–	✔	✔	–	[48]
Du et al. (2014)	Yang's House (China)	–	–	–	✔	–	✔	✔	✔	–	[49]
Qaid et al. (2014)	Single courtyard. Putrajaya Boulevard (Malaysia)	–	–	–	–	✔	–	✔	–	✔	[50]
Yaşa et al. (2014)	Courtyard with different shapes (model)	–	–	–	–	✔	–	✔	–	✔	[51]
Taleghani et al. (2014)	Dwellings in Amsterdam (Netherlands)	–	–	–	–	✔	–	✔	✔	–	[52]
Taleghani et al. (2014)	Campus in Portland (USA) and Delf (Netherlands)	–	✔	–	✔	–	✔	–	–	–	[53]
Taleghani et al. (2014)	Blocks buildings (Netherlands)	–	✔	–	✔	–	✔	✔	✔	–	[12]
Salata et al. (2015)	Cloister in Rome (Italy)	–	–	–	✔	–	✔	✔	✔	✔	[54]
Ghaffarianhoseini et al. (2015)	Different building types (Malaysia)	–	✔	–	✔	–	–	✔	✔	–	[55]
Taleghani et al. (2015)	Different courtyards (Netherlands)	–	–	–	–	✔	✔	✔	✔	–	[56]
Toe et al. (2015)	Traditional Malay Houses (Malaysia)	–	✔	–	✔	–	✔	✔	✔	✔	[57]
Almhafdy (2015)	Different courtyards building (model)	–	–	–	–	✔	–	✔	✔	–	[58]
Maniolu et al. (2015)	Simulated courtyard	–	–	–	✔	–	–	✔	–	–	[59]
Farnahm et al. (2015)	Case study in Japan	–	–	✔	–	✔	✔	✔	✔	–	[60]
Abdulkareem (2016)	Traditional house in Baghdad (Irak)	–	✔	–	–	–	–	–	✔	✔	[61]
Huang et al. (2016)	Traditional dwelling buildings in Lhasa (China)	✔	–	–	✔	–	✔	✔	✔	✔	[62]
Soflaei et al. (2016)	Traditional courtyard houses (Iran)	–	–	–	–	✔	–	✔	–	✔	[63]
Jihad et al. (2016)	Simulated courtyard (Morocco)	–	–	–	–	✔	–	✔	✔	–	[64]
Martinelli et al. (2017)	Different courtyards (Italy)	–	–	–	✔	–	–	✔	–	–	[65]
Soflaei et al. (2017)	Traditional houses (Iran)	✔	–	–	–	–	✔	✔	–	✔	[23]
Nasrollahi et al. (2017)	45 traditional houses in Shiraz (Iran)	–	–	–	–	✔	–	✔	✔	✔	[66]
Rojas-Fernández et al. (2017).	Residential and tertiary buildings in Andalucia (Spain)	–	–	–	–	✔	–	✔	–	✔	[67]
Guedouh et al. (2017)	Different Buildings in Biskra (Algeria)	–	–	–	–	✔	–	✔	–	–	[68]
Taleghani (2018)	Courtyard building in Portland (USA). Review	–	✔	–	✔	–	✔	✔	✔	–	[69]
Zamani et al. (2018)	Literature review	✔	✔	–	✔	–	✔	✔	✔	✔	[70]
Rodríguez-Algeciras et al. (2018)	Houses in historical centre (Camagüey, Cuba)	–	–	–	–	✔	–	✔	✔	–	[71]
Xu et al. (2018)	Museum in Yixin (China)	–	–	–	–	✔	–	✔	✔	–	[72]
Cindel et al. (2018)	Open places and models	✔	✔	–	✔	–	–	✔	✔	–	[19]
Ma et al. (2019)	Dao He Old Block in Taizhou (China)	✔	✔	–	✔	–	✔	✔	✔	–	[15]
Del Rio et al. (2019)	Dwelling in Kumagaya (Japan)	–	✔	–	✔	–	✔	✔	–	–	[73]
Rivera-Gómez et al. (2019)	20 Spanish courtyards (Spain)	–	–	–	–	✔	✔	–	✔	✔	[5]
Ulpiani et al. (2019)	Case study in Ancona (Italy)	–	–	✔	–	✔	✔	✔	✔	–	[74]

(*continued on next page*)

Table 1 (*continued*)

		Passive Strategies					Method				
Authors/Year	Case studies	Shading	Vegetation	Misting	Albedo	Other	Field Campaign	Simulation	Comfort	24-h cycle	Ref.
Oh et al. (2019)	Case study in Tokyo (Japan)	–	–	✔	–	✔	✔	✔	✔	–	[75]
Barrow et al. (2019)	Simulated model	–	–	✔	–	–	–	✔	✔	–	[76]
Zheng et al. (2019)	Case study in Singapore	–	–	✔	–	✔	✔	✔	✔	–	[77]
Ulpiani et al. (2019)	Urban spaces in Rome and Ancona (Italy)	–	–	✔	–	–	✔	✔	✔	–	[30]
Ulpiani et al. (2019)	Prototype in Marcas and Ancona (Italy)	–	–	✔	–	–	✔	✔	✔	–	[31]
Diz-Mellado et al. (2020)	School courtyard in Seville (Spain)	–	✔	–	✔	–	✔	–	–	✔	[24]
Desert et al. (2020)	Misting prototype (Chile)	–	–	✔	–	–	✔	✔	✔	–	[78]
Diz-Mellado et al. (2021)	Cases study in Cordoba (Spain)	✔	–	–	–	✔	✔	✔	✔	✔	[79]
Apolonio-Callejas et al. (2020)	Brazilian courtyards (Brazil)	–	–	–	–	✔	✔	✔	✔	–	[80]
Diz-Mellado et al. (2021)	Machine Learning in Courtyards (Spain)	–	–	–	–	✔	✔	✔	–	✔	[81]
De la Flor et al. (2021)	Case study in Seville (Spain)	–	–	–	–	✔	✔	✔	–	✔	[20]
López-Cabeza et al. (2021)	Cases study in Cordoba (Spain)	✔	–	–	–	✔	✔	✔	✔	✔	[82]
Hassan Akbari et al. (2021)	Iranian courtyards (Iran)	✔	–	–	–	✔	–	✔	✔	–	[83]
Lizana et al. (2022)	Case study in Seville (Spain)	–	–	–	–	✔	✔	✔	✔	✔	[84]
López-Cabeza et al. (2022)	Cases study in Seville (Spain)	–	–	–	–	✔	✔	✔	✔	✔	[85]
Galán-Marín et al. (2022)	Andalusian courtyards (Spain)	✔	✔	–	✔	✔	✔	✔	✔	✔	[86]
Diz-Mellado et al. (2022)	Urban analysis (Spain)	✔	–	–	–	✔	✔	–	✔	✔	[87]
López-Cabeza et al. (2022)	Spanish courtyards (Spain)	✔	✔	–	✔	✔	✔	✔	✔	✔	[88]
Hyunjung Lee et al. (2022)	Central European courtyard	✔	–	–	–	–	–	✔	✔	✔	[89]
Diz-Mellado et al. (2023)	Thermal comfort in 20 courtyards	–	–	–	–	✔	✔	✔	✔	✔	[6]
Diz-Mellado et al. (2023)	Social housing courtyards	✔	–	–	–	✔	✔	✔	✔	✔	[90]
Diz-Mellado et al. (2023)	Seasonal analysis courtyards	–	–	–	–	✔	✔	✔	✔	✔	[91]
Jiang et al. (2023)	Enclosed courtyard in China	–	–	–	–	✔	–	✔	✔	–	[92]
Habibi et al. (2024)	COVID strategies with courtyards	–	–	–	–	✔	–	✔	–	–	[93]
Zhao et al. (2024)	School courtyard in China	✔	–	✔	–	✔	✔	✔	✔	–	[94]
Yin Cheng et al. (2024)	Case study in Taiwan	–	✔	–	–	✔	✔	✔	✔	–	[95]
Zhao et al. (2024)	Semi outdoor spaces in China	–	✔	–	–	✔	✔	✔	✔	–	[96]
Abdeen et al. (2024)	Green walls design	–	✔	✔	–	✔	✔	✔	–	–	[97]

resemble the outdoor environment, shading is highly effective. The use of shading elements in courtyards during summer and heat waves increased comfort hours by 45%–66% [87]. In some experiments, detachable shading devices were placed to control the radiation flux during daytime hours, detecting 32–40% of shade projections and recording thermal differences of up to 2 °C in courtyards in the same location but with different geometries [47]. The effectiveness of the shade generated by other elements such as trees and/or other plant species was analysed, establishing the need for 50% more water for unshaded species [38]. Different modelling and simulation processes identified the influence of plants and trees on the microclimate generated, detecting a TG of up to 9.3 °C in the simulated model, as opposed to the 13.7 °C previously monitored [99].

In general, the literature has analysed three variations in shading: shading generated by the geometry of the building, shading produced by vegetation or trees, and that resulting from the use of specific shading devices. Based on the results of the passive strategies implemented, the addition of shading devices is considered the most effective, with a difference of up to 10 °C compared to the thermal reduction generated by shade from trees.

1.2. Misting systems

Evapotranspiration-based misting cooling systems operate by spraying water in fine droplets that rapidly evaporate upon contact with air, absorbing ambient heat during the phase change. These systems are considered more efficient than water ponds as they use small amounts of water to cool a large surface area [76,100]. Misting cooling systems are beneficial in warm and dry climates, where increased relative humidity has no negative impact on user comfort [74]. They effectively cool outdoor and semi-outdoor spaces with adequate airflow, preventing air humidity saturation and increasing evaporation rates [75]. Misting systems are especially effective in hot, dry climates because of the potential for increasing initially low relative humidity percentages. Moreover, by spraying water in small droplets, distribution and evaporation in the air mass are facilitated, further contributing to the courtyard thermal tempering [101]. It also enhances occupants' cooling sensation due to skin moisture and evaporation. Implementing water mist cooling strategies improves user comfort and provides health benefits [60]. Existing research has examined the conditions created by the fog effect, with some studies testing misting comfort in hot and humid climates [77]. Ulpiani et al. highlight the importance of design in improving potential comfort conditions [74], establishing that the strategy is effective in environments with temperatures above 30 °C, relative humidity below 70% and wind speed of less than 3 m/s [31].

1.3. Research aim

The literature review in Table 1 suggests the need to compare integrated passive strategies incorporating both shading and water, and directly influencing two key factors in courtyard microclimates: radiation and relative humidity (RH). Shading devices and misting systems show the most potential for hot and dry climates, compared with other strategies such as vegetation and albedo which affect thermal inertia. There is a clear lacuna in research on the thermal implications of widely used simple systems such as shading elements (e.g. awning devices) and misting in hot dry climates over 24-h cycles. This study aims to address this shortcoming by testing the cooling potential of passive shading strategies such as shading and misting systems, analysing their combined use in courtyards over time.

Considering the above, the following research aims are established.

1) To test different shading and misting system strategies and their combination
2) To identify the thermal performance of different strategies in different outdoor conditions
3) To test changes in configuration in order to adapt to 24-h cycles.

This study examines a courtyard in a city in southern Spain, a region that has traditionally relied on shade and water evaporation to

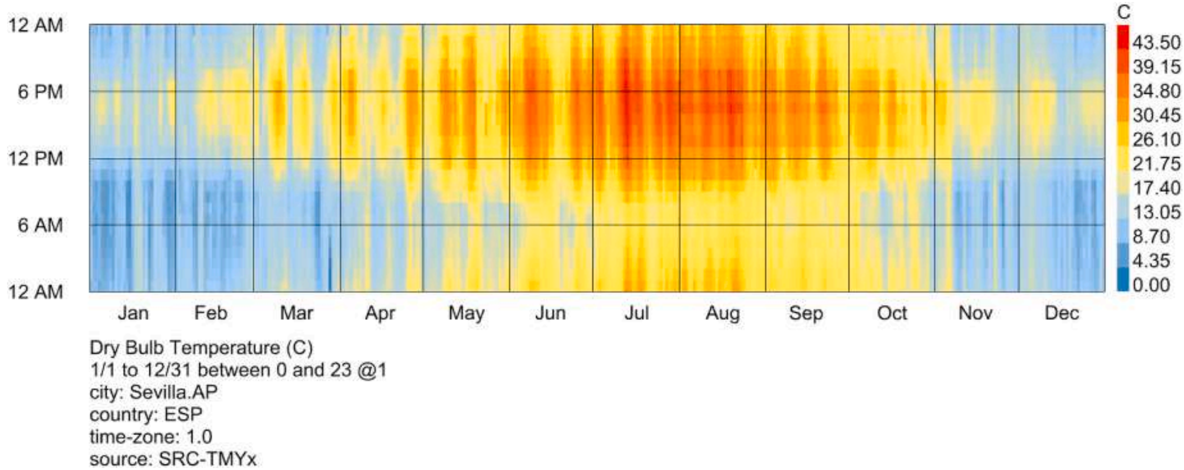

Fig. 1. Dry bulb temperature of the city of Seville during one year. Data extracted from the TMYx weather file derived from hourly weather data through 2021 in Seville [110].

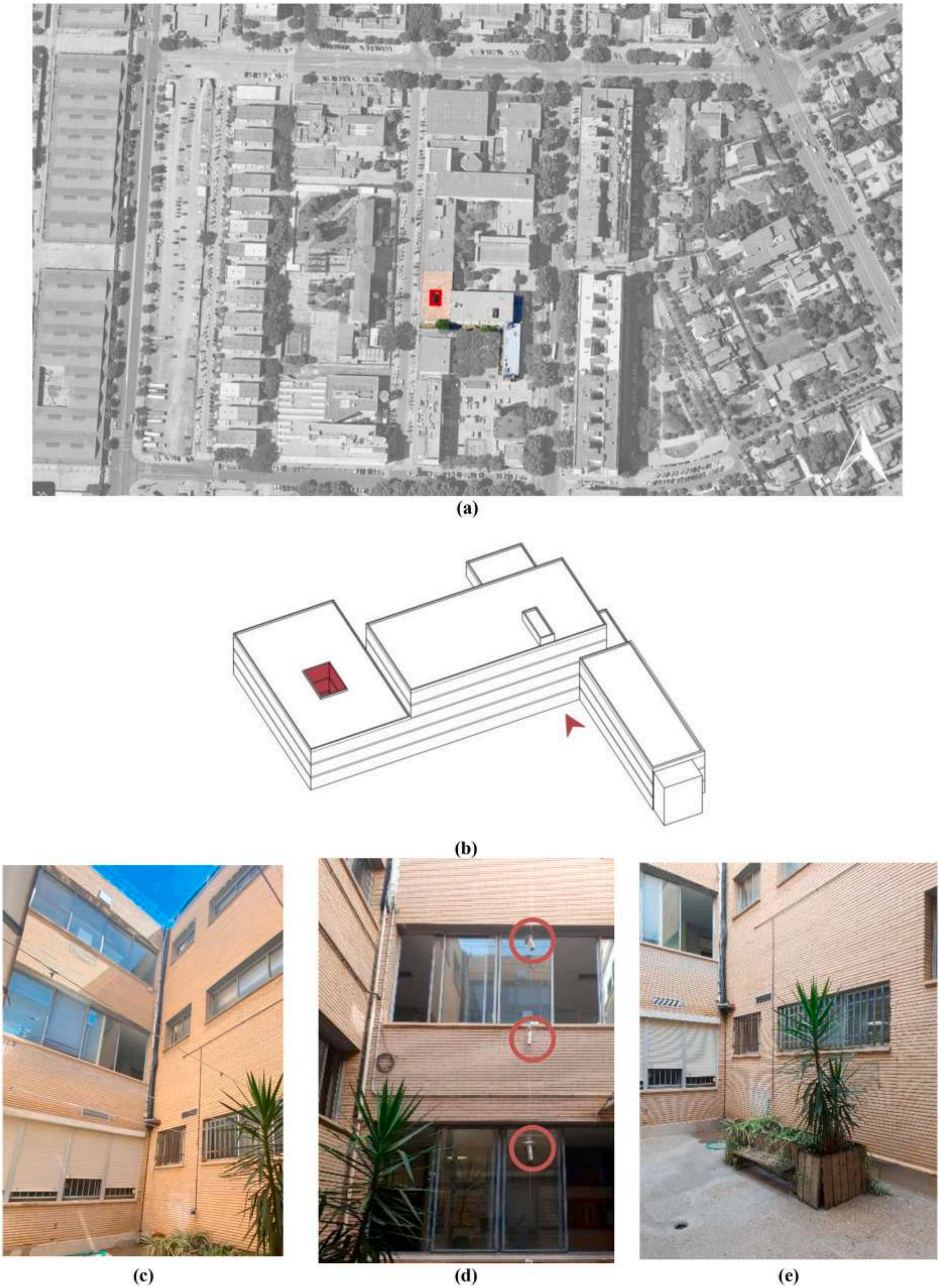

Fig. 2. Case study courtyard. (a) Orthophotography of the urban environment; (b) Simplified model of case study building; (*c*-*d*-e) Interior of the courtyard.

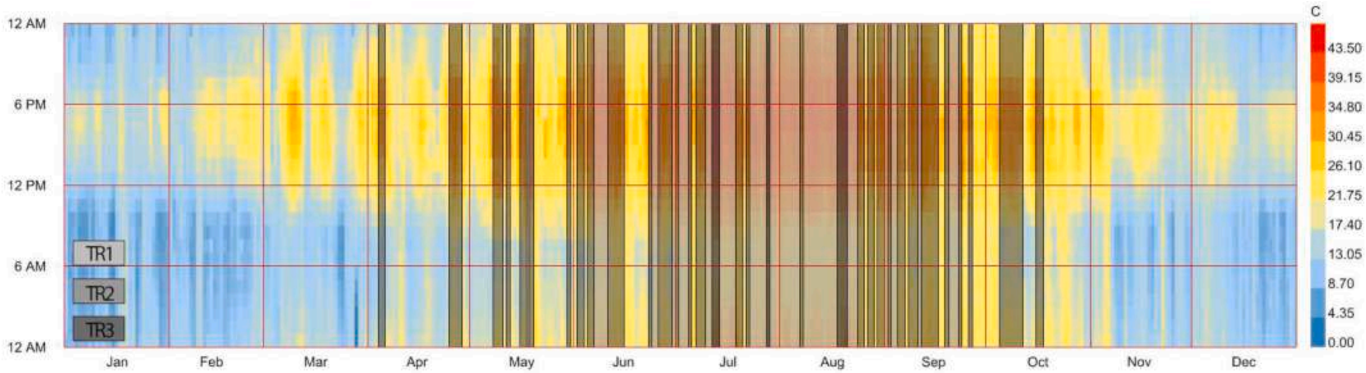

Fig. 3. Thermal ranges selected according to the dry bulb temperature of the city of Seville during one year. Data extracted from the TMYx weather file derived from hourly weather data through 2021 in Seville [110].

Table 2
Planning of the monitoring campaigns.

Monitoring Campaign	Passive Strategy	Time frame
A	–	24 h
B	Shading device	24 h
C	Misting system	6 s/min 24 h
D	Shading device and Misting system	24 h and 6 s/min 24 h
E	Shading device and Misting system	Shade (9am-9pm); Misting 6 s/min 24 h

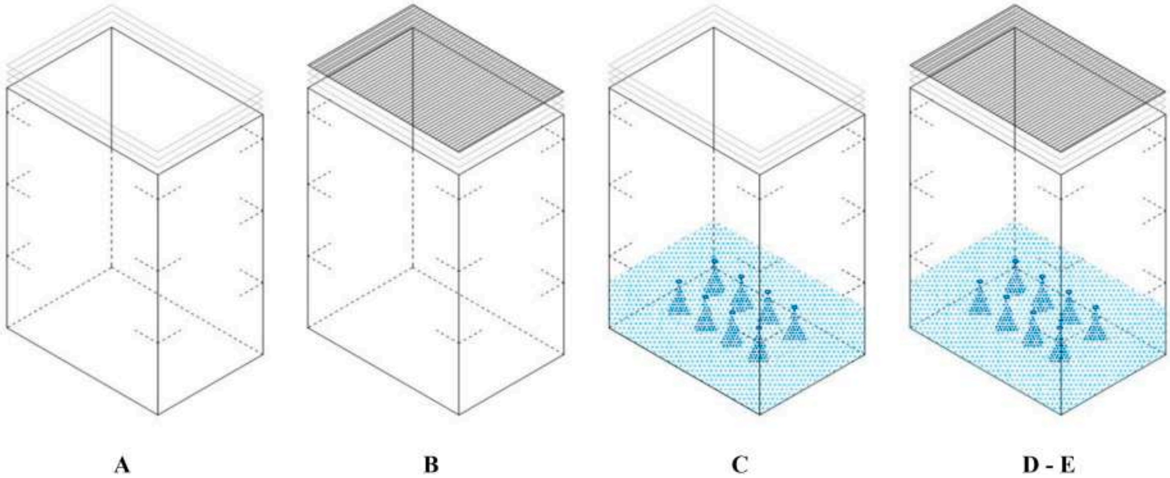

Fig. 4. Different scenarios of the field monitoring campaigns. A: No passive strategies; B: shade element; C: misting system; D–E: shade element and misting system.

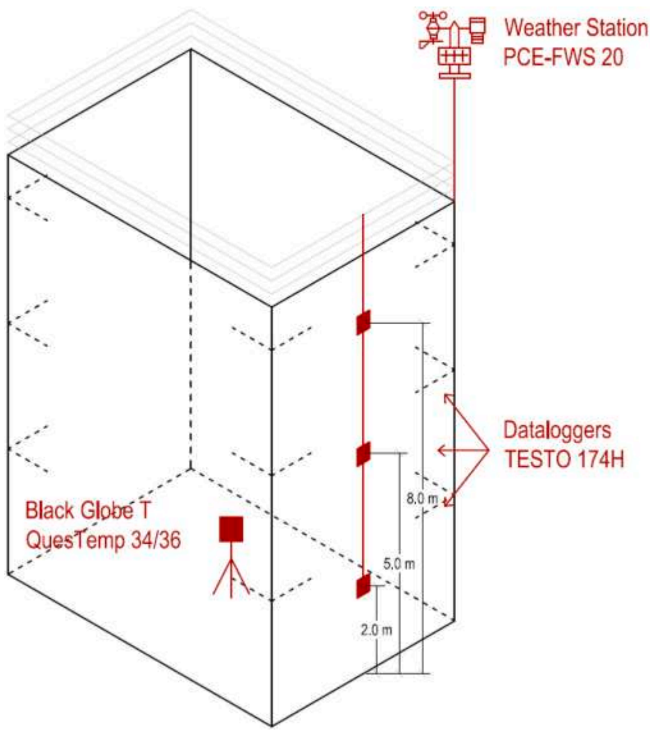

Fig. 5. Location of all sensors used during monitoring campaigns.

reduce heat [102]. The city's temperature, relative humidity, and wind speed conditions are in keeping with those analysed in previous research [74]. The case study selected is a courtyard of average size and geometry for this climate zone. Previous research results were considered to extrapolate the study results to other courtyards [87]. The study analyses comfort in semi-outdoor spaces across different thermal ranges and with various passive strategies, using the PET outdoor comfort index validated for use in semi-outdoor spaces such as courtyards [6]. Field monitoring campaigns were designed to meet the research objectives. After selecting shading and misting strategies, experimental works aimed to determine their individual and joint influence. Campaigns were then carried out in different thermal scenarios. Finally, the optimal combination and reconfiguration of system operations were proposed to improve the courtyard microclimate in each 24-h cycle.

The overall assessment, based on the objectives defined, demonstrated the tempering potential of passive cooling strategies such as shading and misting systems, their combination over time in a typical Mediterranean courtyard, and the increase in comfort hours for users [67]. The novelty of the study is therefore based on the experimental assessment of combinations of adaptive passive cooling strategies in a whole 24-h cycle and the implementation of evapotranspiration-based latent cooling systems in the specific semi-outdoor courtyard environment. Despite the experimental nature of the results and their inherent limitations, the characteristic aspect ratio and the perfect North-South orientation of the courtyard allow the study's findings to be extrapolated to similar case studies in inland cities in warm climates.

2. Methods

In the initial stage, four different configurations of courtyard microclimate were evaluated. In a second stage, a fifth one was added to quantify the improvement from targeted management of the evaluated strategies throughout a whole 24-h cycle. These configurations were all assessed under the same climatic conditions in different field monitoring campaigns. The first one (A), the reference scenario, had no strategy; the second (B) added a 24-h shading device; the third (C) used a 24-h misting system; and the fourth (D) combined a shading device and a misting system. After analysing the results, a fifth scenario (E) was considered under worst climate conditions (heat wave), pursuing the optimal combination by using a removable shading device at night in combination with the 24-h misting system. Quick and easy implementation and cost-effectiveness were considered for all scenarios.

2.1. Local climate and selected case study

Seville is one of the warmest cities in Europe. The Spanish Building Code, *Código Técnico de la Edificación* (CTE) [103], classifies Seville's climate as B4, with mild winters and high summer temperatures. According to the Köppen classification, it falls into the Csa category, with characteristically hot, dry summers with low rainfall. The Diurnal Thermal Range (DTR) (Equation (2)) [104,105] captures the difference between the minimum (T_{min}) and maximum (T_{max}) temperature values over a 24-h cycle [106,107].

$$DTR = T_{max} - T_{min} \quad (2)$$

In summer, DTR in Seville reaches 16–17 °C and temperatures can exceed 40 °C in the hottest months (Fig. 1). Due to climate change, the summers in this city are becoming longer, as the heat starts earlier on in the year and ends later [108]. According to IPCC projections for coming decades the city of Seville will be affected by more frequent heat waves [109].

The research case study is located in an educational building built in 1959 within a consolidated urban environment (Fig. 2a). The building consists of a basement, ground floor (gf), and three other floors: gf+1, gf+2, and upper floor. It includes 3 vol of different heights which combine uses as offices and classrooms (Fig. 2b). The west-facing volume has an inner courtyard 11.7 *m* deep with a floor surface area of 5.9 b y 8.5 *m*. Fig. 2c–e shows different views of the case study during the field monitoring campaign.

The influence of geometry on the thermodynamic behaviour of the courtyards, which is of great importance [5], is defined by the ratio between the height (H) and the width (W), known as the aspect ratio (AR) (Equation (3)). The case study analyses two ARs (ARI = 2.00 and ARII = 1.4), simplified parallelepipeds found on either side of the courtyard. The average AR, 1.7, is the mean of the two previous values.

$$AR = H/W \quad (3)$$

2.2. Field monitoring campaigns

Field monitoring campaigns were conducted in June and July 2021, taking a whole week for each configuration. Days with similar weather conditions were then selected to effectively compare the different strategies implemented in the courtyard. During this

Table 3
Technical data of the measurement instruments.

Environment	Sensor	Variable	Resolution	Range	Accuracy
Courtyard	TESTO 174H	RH	2%	0–100%	±0.1%
		Dry bulb Temp.	0.1 °C	−20 to +70 °C	±0.5 °C
	QUESTemp 34/36	RH	±0.5 °C	20–95%	–
		Dry bulb Temp.	±0.5 °C	0 to +120 °C	–
Outdoor	PCE-FWS 20	Wind	–	0–180 km/h	±1 m/s
		RH	1%	12–99%	±5%
		Dry bulb Temp.	0.1 °C	−40 to +65 °C	±1 °C

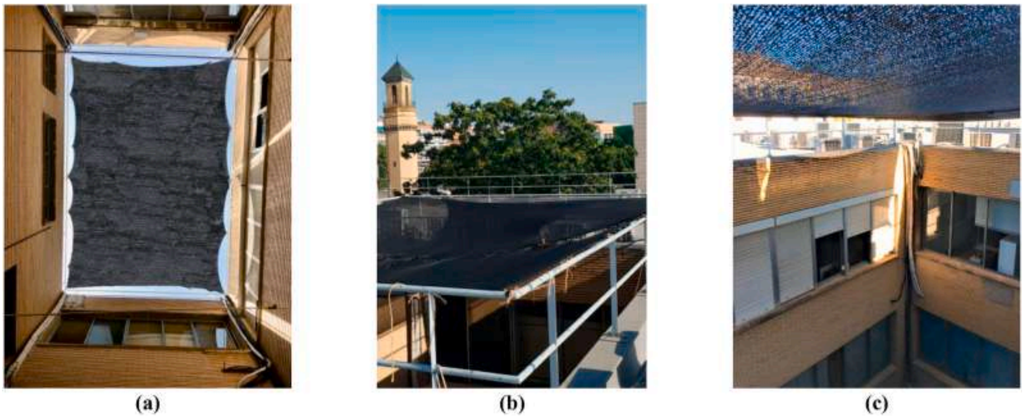

Fig. 6. Location and positioning of shading element.

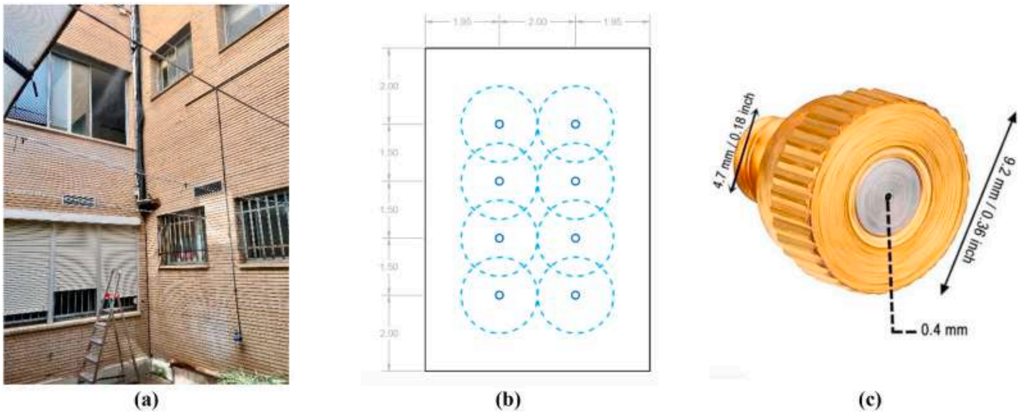

Fig. 7. Location and positioning of misting system (a, b) and characterisation of nozzles (c).

experimental phase, temperature and humidity sensors were placed at various heights inside the courtyard to measure thermal stratification more accurately [5]. This parameter is key to microclimate performance in courtyards due to the influence of thermodynamic flows [40]. Following the method of previous research [5] and the data from Spanish Meteorological Agency (AEMET) [111], the monitoring campaigns covered three different thermal ranges (TR) based on the maximum daily temperature: TR_1 ranged from 30 to 35 °C; TR_2 from 35 to 40 °C; and TR_3 exceeded 40 °C. These ranges represent typical maximum air temperatures in spring and autumn (TR_1), in summer (TR_2), and in a heat wave (TR_3) (Fig. 3).

The field monitoring campaigns were divided into four parts, as Table 2 and Fig. 4 show.

2.2.1. Monitoring

The full monitoring campaign exceeded the minimum two-week monitoring period suggested by previous protocols [5]. This extended timeframe was necessary to ensure a comprehensive analysis of the different outdoor temperature ranges associated with each strategy implemented. A PCE-FWS20 weather station model on the rooftop monitored outdoor weather data at 15-min intervals. In addition, three TESTO174H temperature and humidity data loggers were hung from a cord (at heights of 2.0 *m*, 5.0 *m*, and 8.0 *m* above the courtyard floor) to evaluate the thermal stratification, considering the official temperature at screen level established by the World Meteorological Organization (WMO) [112]. All data loggers were protected from direct solar radiation by a ventilated shield. The difference between the measurements obtained from outside and inside the courtyard was used to calculate the thermal gap (TG) [5].

A black globe thermometer was used to estimate the mean radiant temperature (MRT) following ISO 7726 [113]. QUESTemp 34/36 recorded the temperature of the black globe located in the centre of the courtyard. Due to equipment limitations, black globe temperature monitoring was not feasible in all case studies. Estimated Mean Radiant Temperature (MRT) data were therefore applied to calibrate a simulation model using LadyBug Tools [114] (Appendix, Table A1 and Table A2). Technical details and locations of instrumental devices are shown in Fig. 5 and Table 3.

2.2.2. Shading and misting systems

In the experiments, the same type of canvas was used for shading in the courtyards as in previous research [87]. The misting system

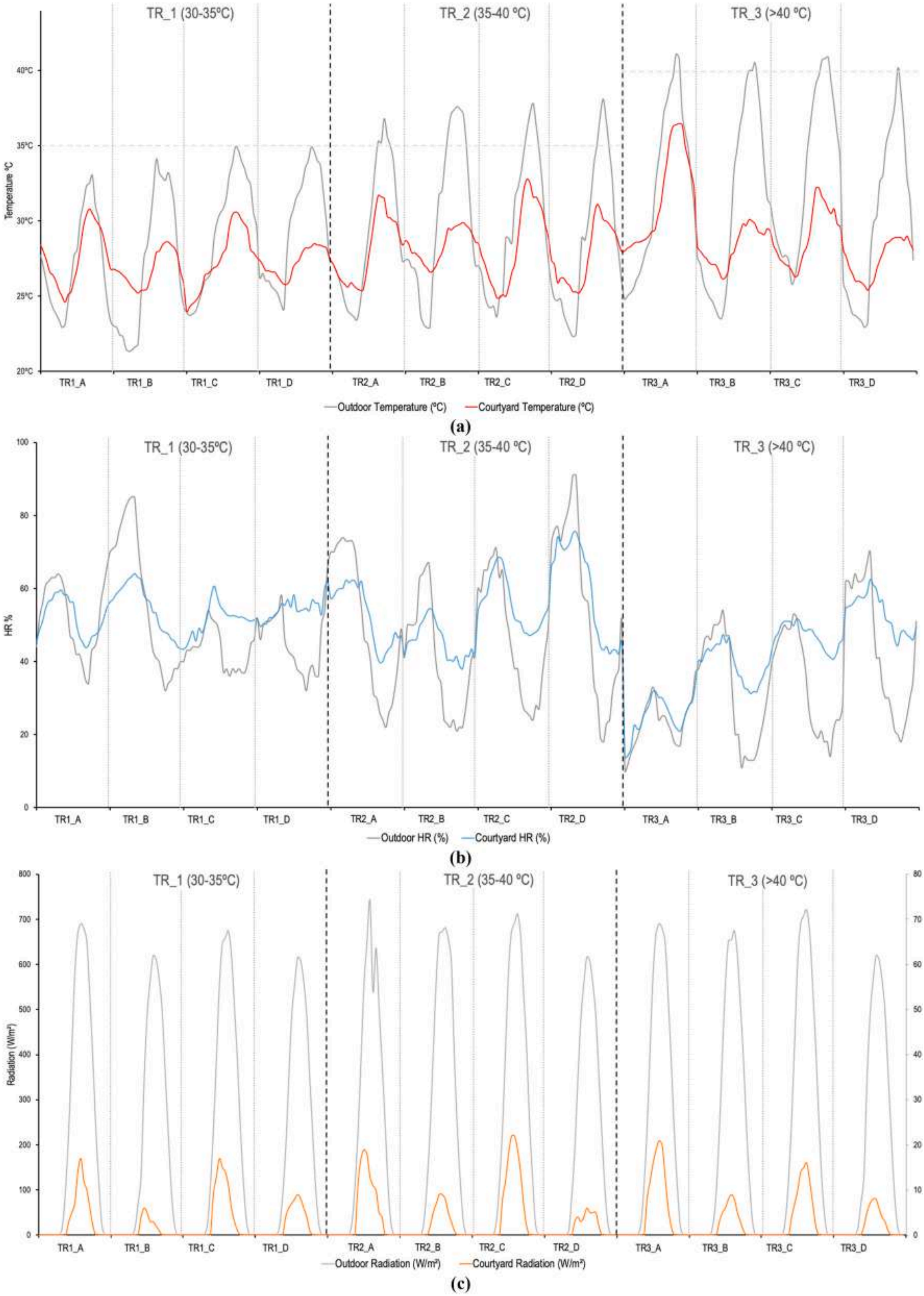

Fig. 8. Field monitoring campaigns results. a) Air temperature, b) Relative Humidity (RH), c) Global Radiation.

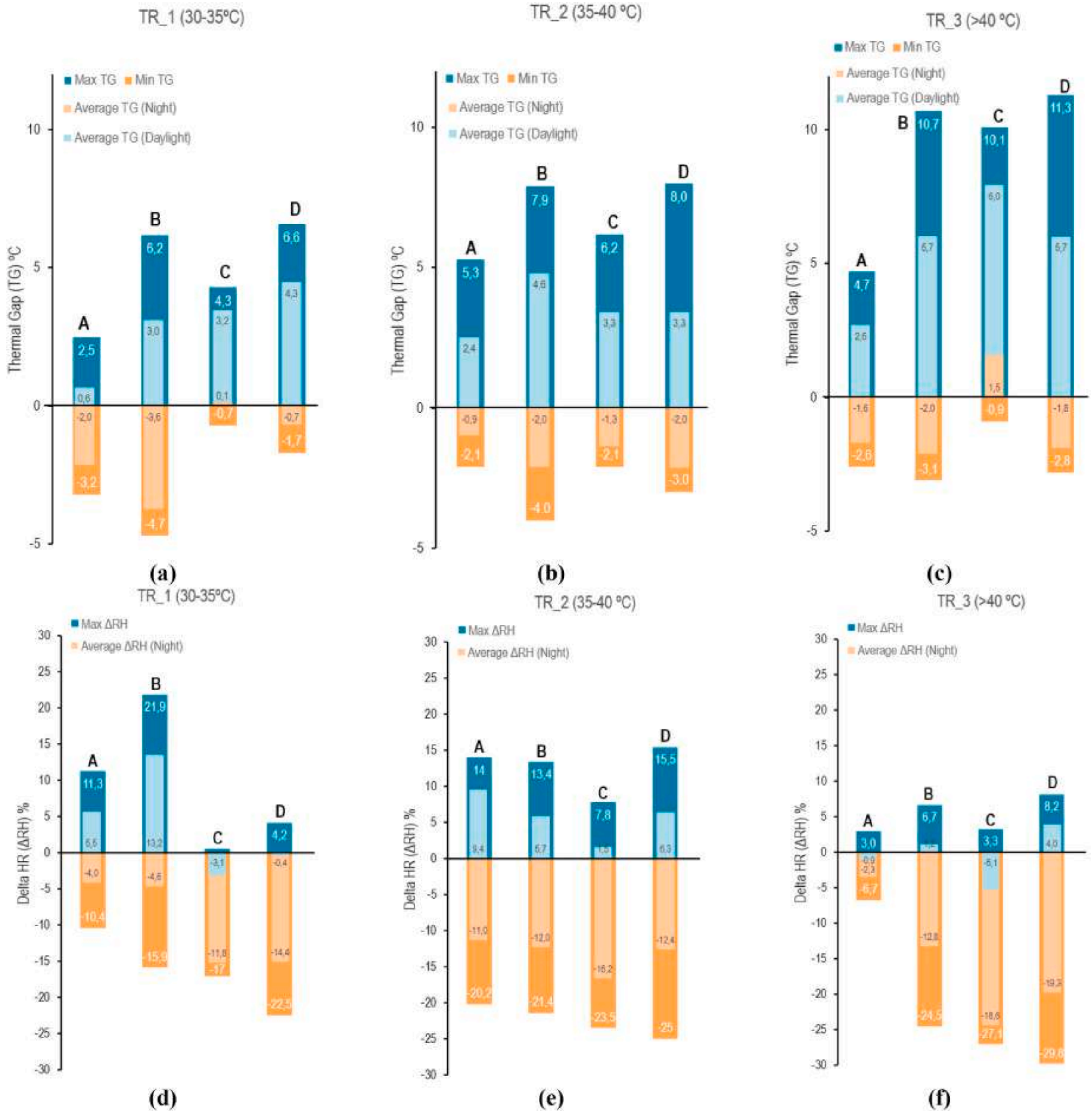

Fig. 9. Maximum, minimum, and average gap results for each monitoring campaign (A–D). a-c) Air temperature, *d*-f) Relative Humidity.

and number of nozzles were established following the recommendations of the manufacturer regarding spacing distances [115] and based on previous microclimate misting research [116]. The implementation of different strategies in the courtyards is depicted in Figs. 6 and 7. A breathable, black high-density polyethylene canvas awning (UV filter 75% with a density of approximately 70 g/m^2) was used to allow for ventilation. This awning, separate from the roof, covered the courtyard, and facilitated convective flows (Fig. 6).

The misting system was designed to cover the study area. The nozzles were installed in the central area of the courtyard, typically occupied by potential users, following previous research [117]. Eight nozzles were positioned at a height of 3 m (Fig. 7a), spaced 1.5 and 2 *m* apart (Fig. 7b), and directed towards the ground to ensure optimal and complete coverage. A 0.4 mm nozzle diameter was selected (Fig. 7c) for a very fine droplet size, ensuring the correct distribution of the system [117].

2.3. Thermal comfort analysis

Outdoor thermal comfort is influenced by factors such as climate, location, physical conditions and solar radiation exposure [118]. Whereas previous studies almost always concentrated on outdoor environments, this research focuses on the analysis of semi-outdoor spaces [119–121]. Physiological Equivalent Temperature (PET) index, adaptable to different climates and thermal ranges [122,123], was chosen over other commonly used indices such as Predicted Mean Vote (PMV) [124,125], rational Standard Effect Temperature

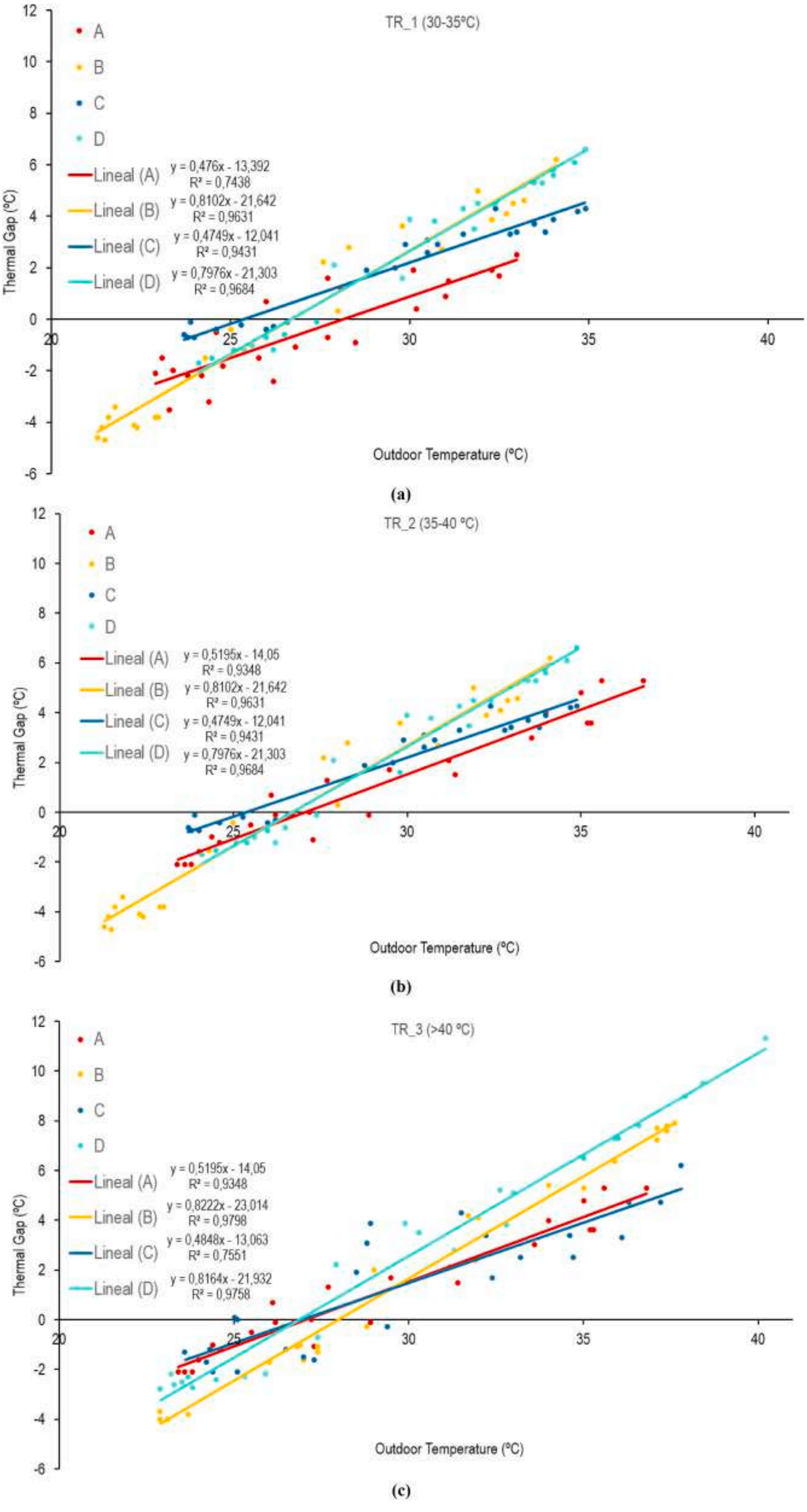

Fig. 10. General trend of each combination of strategies (A–D) as a function of TG and outdoor temperature. a) Thermal Range 1, b) Thermal Range 2, c) Thermal Range 3.

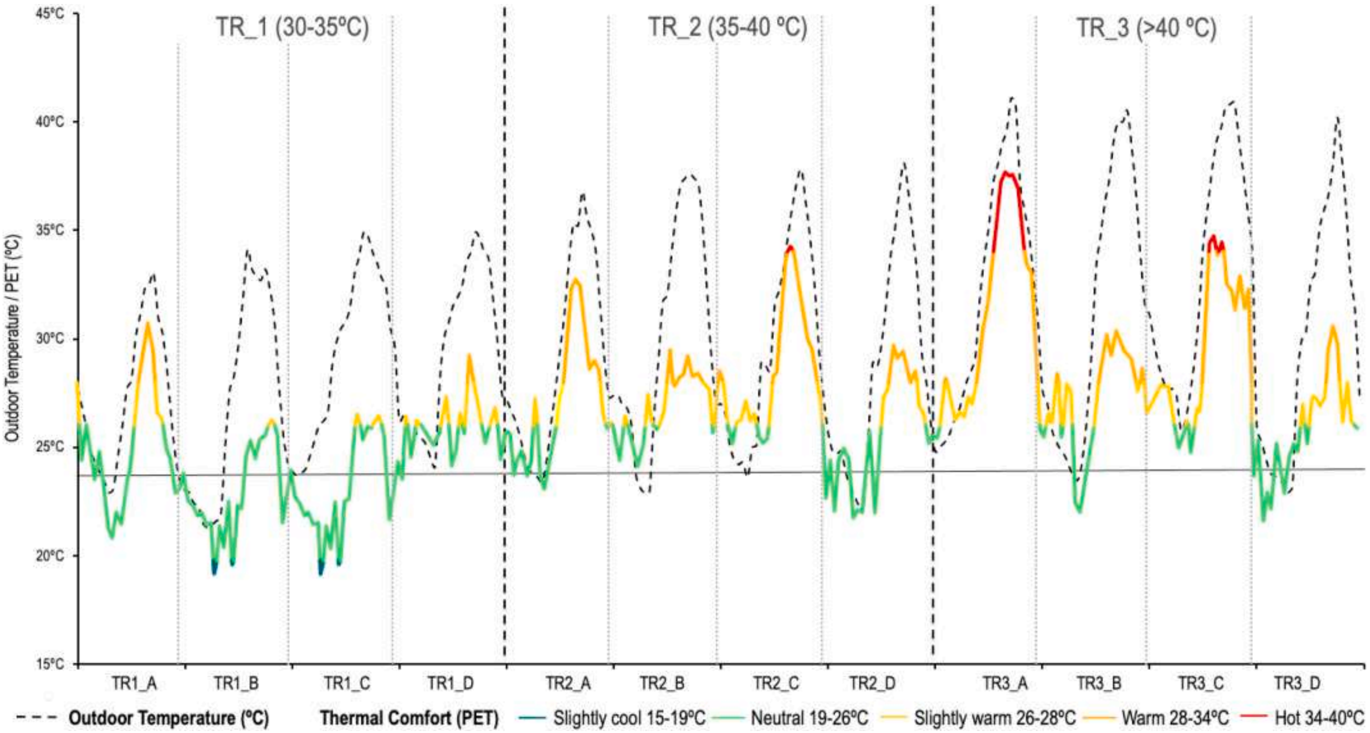

Fig. 11. Comfort results according to PET.

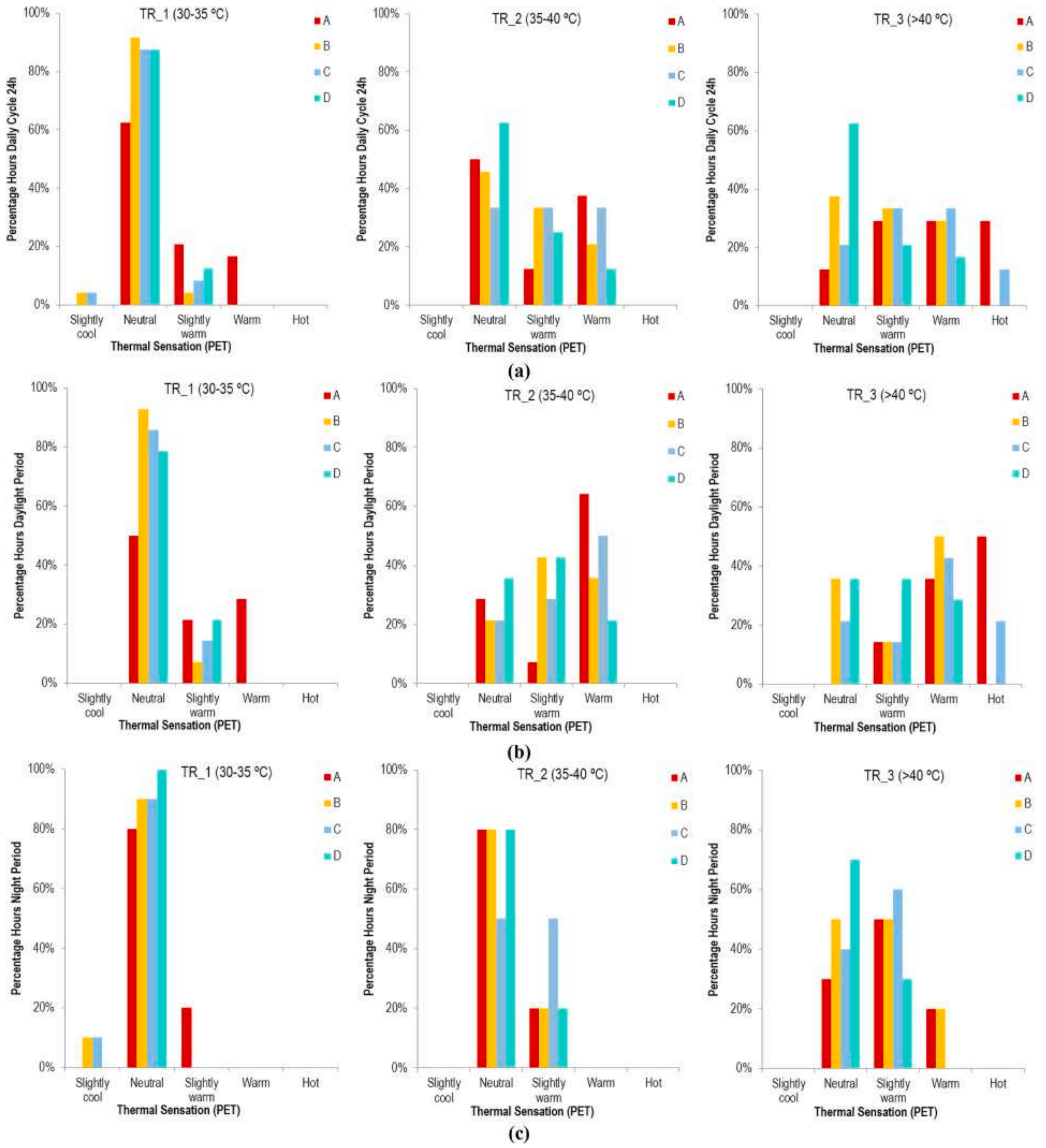

Fig. 12. Comfort results according to PET of each combination of strategies (A–D). a) Daily Cycle 24 h, b) Daylight period, c) Night period.

(SET*) [126–128], Universal Thermal Climate Index (UTCI) [129–132], and Perceived Temperature (PT) [133]. According to Part IV of the recent Metamatrix Thermal Comfort methodology [118], PET is deemed the optimal index for the case study analysed. Previous research established several PET scales for different climatic zones [134,135]. As this comfort index displays a greater range of adaptation to different climates it is better-suited to use in semi-outdoor spaces such as courtyards [79]. For these reasons, the use of PET in this research was considered more appropriate than the other indices mentioned above. In the Csa climate zone, where the selected case study is located, PET scales had been developed for Crete (Greece), Rome (Italy) and Tel Aviv (Israel) [134,135]. This study follows the scale adapted by Cohen et al. [136] for Tel Aviv, with a similar latitude and climatic conditions to Seville. It was also selected in previous studies which used PET to assess comfort in this microclimate [87].

2.3.1. Modelling of PET index

In this study, the PET index was obtained using the Rayman [137–141] software tool, which calculates radiation fluxes in different environments based on several parameters. During the monitoring campaigns, the necessary input data were recorded and entered into Rayman as input data files: wind speed (WS), dry-bulb temperature, also known as air temperature (Ta), relative humidity (RH) and mean radiant temperature (MRT). This tool adjusts readings to user profiles (weight, height, gender, age, clothing, and metabolic activity). Values proposed by Höppe [142] were used in this research, corresponding to male users aged 35 years, 1.75 *m* tall and weighing 75 kg, with a metabolic activity of 80 W and a clothing thermal resistance of 0.9 clo. The clothing thermal resistance selected for the present research was 0.5 clo, the average value for summer according to EN 16798 [143]. The wind speed used to calculate PET was measured on the roof of the building, considering the logarithmic reduction for a dense environment following a specific LadyBug protocol [144].

3. Results

3.1. Results of the field monitoring campaigns

This section presents the monitoring results from various campaigns (A-D). A representative day was chosen for each campaign and temperature range (TR_1, TR_2 and TR_3) selecting days with similar temperatures for each thermal range.

Fig. 8 shows the results for the three thermal ranges (TR_1, TR_2 and TR_3). During the campaigns one day was selected for each of these thermal ranges: A) no interventions, B) 24-h shading, C) 24-h misting system, D) combination of shading element and misting system.

The outdoor data monitored on the roof of the building are shown in grey, while light colours are used to represent the temperature recorded every 15 min by the sensor at +2.00 m (red) in Fig. 8a, relative humidity (blue) in Fig. 8b, and simulated global radiation (orange) in Fig. 8c, based on the sensors placed inside the courtyard.

Air temperature (Fig. 8a): courtyard temperature varies less than outdoor temperature. The courtyard temperature gradually increases as the outdoor temperature increases. With no interventions (A) higher temperatures were recorded, while the combination of shading and misting (D) resulted in lower temperatures inside the courtyard.

Relative humidity (Fig. 8b): RH increases when the misting systems are switched on for scenarios C and D, especially during the night. However, the maximum RH in the courtyard was more dependent on outdoor relative humidity than on the use of a misting system.

Simulated Global Radiation (Fig. 8c): in the courtyard was significantly lower than outside due to the shade generated by its own geometry and decreases during campaigns B and D due to the inclusion of the shading element.

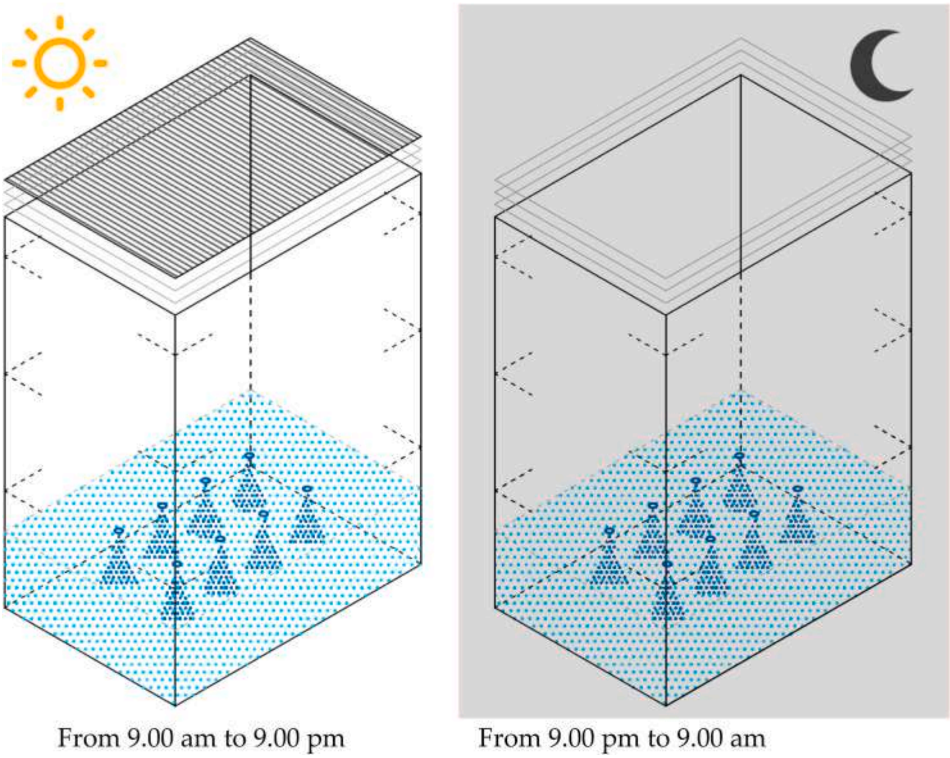

Fig. 13. Planning of the field monitoring campaign E. Shade and Misting system during daylight (9.00 a.m.–9.00 p.m.)., and misting system during night (9.00 p.m.–9.00 a.m.).

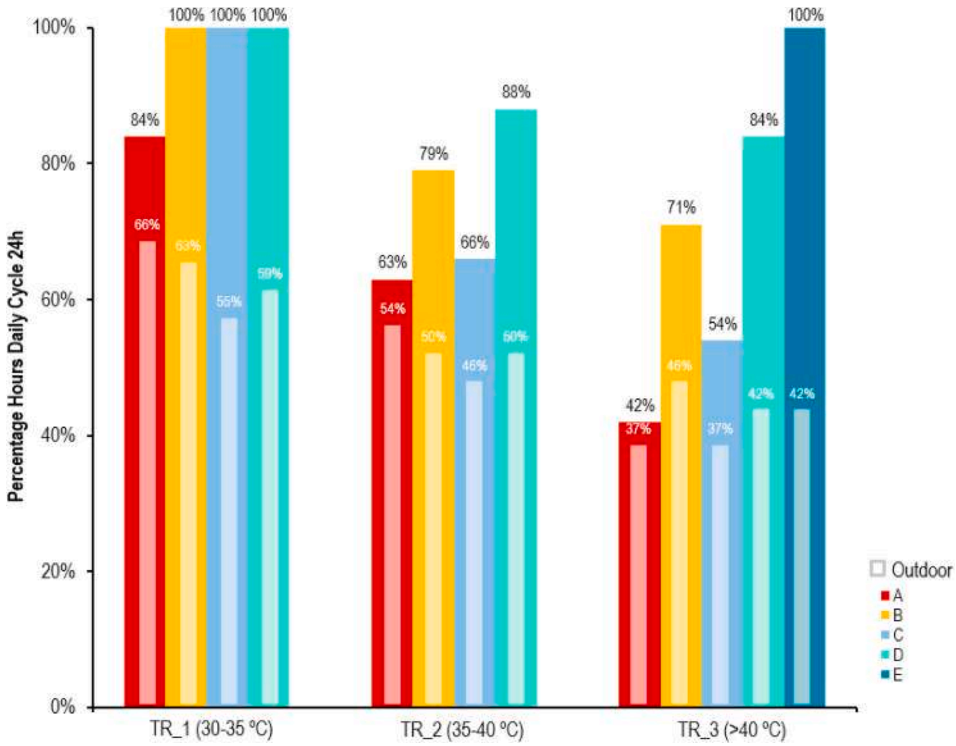

Fig. 14. Comfort results according to PET for each passive strategies combination and outdoor environment.

3.1.1. *Thermal gap*

The Thermal Gap (TG) between the courtyard and the outdoor temperatures was analysed in order to determine the tempering potential of the courtyard. In addition to considering the use of strategies that modify the relative humidity (RH), the Delta Relative Humidity (ΔRH), the difference between outdoor RH and the RH of the courtyard, was also calculated and correlated to the level of thermal comfort of the different scenarios.

Fig. 9 shows the maximum and minimum TG (Fig. 9 a-c) and ΔRH (Fig. 9 *d*-f), as well as the average ΔRH during daylight and night hours. In general, TG increases in the warmer temperature ranges. During the night, there is a slight overheating of the courtyard in all thermal ranges. In the case of RH, the implementation of strategies considerably increases humidity during the night, especially in campaigns C and D, which incorporate misting systems.

3.1.1.1. TR_1: 30–35 °C. The results show a maximum TG of between 2.5 °C with no strategy implemented (A) and 6.6 °C with shade and mist combined (D), while at night shading causes an overheating of 4.7 °C in campaign B but just 0.7 °C in campaign C (Fig. 9a). The results show better courtyard behaviour during the day with a combination of shading elements and misting systems. However, campaign C, with no shading element, shows the best performance at night-time.

3.1.1.2. TR_2: 35–40 °C. This shows a maximum TG of between 5.3 °C in A and 8 °C in D, while at night shading in campaign B results in overheating of the courtyard of up to 4.0 °C but of only 2.1 °C in A and C (Fig. 9b). The results show a similar combination of strategies to that of the previous thermal range, as well as a similar presence or absence of misting at night.

3.1.1.3. TR_3: >40 °C. Finally, in TR_3, with extreme heat temperatures, the results show a maximum TG of between 4.7 °C in A and 11.3 °C in D, while at night campaign B produces overheating of up to 3.1 °C in the courtyard and of barely 0.9 °C in campaign C (Fig. 9c). Again, the results show a better performance of the courtyard during the day when shading and misting systems are combined. The analysis of the average TG shows the importance of removing the shading element at night as the misting system can cool the courtyard by up to 1.5 °C more than the exterior.

3.1.2. *Optimal combination selection*

Fig. 10 relates the TG to the outdoor temperature for the individual strategies implemented in each thermal range. The trend lines, which predict the performance of each strategy with a high level of accuracy (R^2 ranged from 0.74 to 0.97), help to select the best strategy. A steeper slope means higher TG at a lower outdoor temperature, which is the performance desired in these circumstances. The use of shading produces this effect (B and D). According to the results of TR_3 (when extreme heat is measured outside), the use of misting systems in combination with shading clearly provides the best option (D). However, at night (when outdoor temperatures are lower), option C, which uses only misting systems, is consistently the best option, as it minimizes overheating in the courtyard. For this reason, a fifth combination of strategies is derived from the analysis of the graphs as the optimal solution: employing misting systems and shading during the day but removing the shading device at night.

3.2. Comfort results from PET index calculation

Fig. 11 displays thermal comfort results based on PET obtained from the data in the various monitoring campaigns together with the corresponding outdoor temperature data. The lines are colour-coded in accordance with the PET scale selected. The graph predominantly indicates hours in comfort conditions during the monitoring period, with the thermal comfort lines primarily occupied by neutral (light green) temperatures ranging from 19 to 26 °C, followed by slightly cool (dark green) temperatures from 15 to 19 °C, and slightly warm (yellow) temperatures ranging from 26 to 28 °C.

Fig. 12 shows the percentage of thermal comfort hours for each thermal range and passive strategy implemented, selecting days with consistent weather conditions. In Fig. 12a thermal comfort results according to PET for a daily cycle of 24 h are shown. Fig. 12b and c shows the results of the percentage of comfort hours for day and night periods respectively. Comfort notably increases during the night when misting systems are applied in campaign C, whereas the shading element in campaign B yields less favourable results during the same period.

The results of TR_1, with typical autumn and spring temperatures, indicate that the use of shading elements (B) ensures neutral thermal comfort conditions in 92% of the 24-h daily cycle. In contrast, campaign A, with no implemented strategies, displays the highest level of thermal discomfort, achieving warmth during 17% of the hours. Percentages of comfort hours according to PET for TR_1 are shown in Table A3.

The TR_2 results for typical summer temperatures indicate that the combination of shading elements and misting systems (D) ensures thermal comfort conditions for 63% of the hours. Considering campaigns B-D, misting systems (C) have the least impact on comfort conditions, producing slightly warm or cool sensations.

Percentages of comfort hours according to PET for TR_2 are shown in Table A4.

In TR_3, with extreme heat temperatures, the combination of shading elements and misting systems (D) is the most comfortable, providing either 63% of hours in thermal comfort or 84% with a slight sensation perceived. Campaign A, with no strategies implemented, is clearly the most unfavourable combination in terms of comfort during periods of extreme heat. Percentages of comfort hours according to PET for TR_3 are shown in Table A5.

3.2.1. Optimal combination selection

Given the results obtained, an additional monitoring campaign was planned and implemented during the heat wave period (field monitoring campaign E). In the new set-up, campaign D was modified, removing the shading element during the night, from 9:00 p.m. to 9:00 a.m., while keeping the misting system (Fig. 13).

Fig. 14 shows the previous results in percentage of comfort hours according to PET for each combination of passive strategies applied, while the outdoor thermal sensation (outside the courtyard) is now recorded in white bars, considering slightly cool, neutral and slightly warm sensations [136].

Combination D provides the highest thermal comfort, regardless of outdoor temperature. While the shading element (B) enhances comfort during the day, it leads to overheating at night. The additional campaign E, which applies shading only during the day and a misting system at night, resulted in 100% thermal comfort hours for the case study.

4. Discussion

This section provides a comparative summary of the main findings from all concluded campaigns, thereby determining the effectiveness of each passive cooling strategy across the different TRs. In the courtyard study, with no passive strategy (A), TG was 2.5 °C for TR_1 (outdoor temperature between 30 and 35 °C); 5.3 °C for TR_2 (outdoor temperature between 35 and 40 °C); and 4.7 °C for TR_3 (outdoor temperature above 40 °C). At night, the courtyard overheated by up to 3.2 °C compared to outdoor temperature. Thermal comfort hours ranged from 42% to 84% across all TRs analysed.

With a shading system (B) TG was 6.2 °C in TR_1; 5.3 °C in TR_2; and 10.7 °C in TR_3. At night the courtyard further overheated by 4.7 °C due to the thermal inertia of materials and lack of ventilation to release the stored heat. The shading device reduced the possibility of ventilation, trapping heated air inside. However, despite this nocturnal overheating, the percentage of hours in thermal comfort in the courtyard ranged from 71% to 100% across different TRs.

The introduction of a misting system (C) led to a TG of 4.3 °C in TR_1; 6.2 °C in TR_2; and 10.1 °C in TR_3. At night, the courtyard achieved some cooling, overheating by only 2.1 °C. Thermal comfort hours ranged from 54% to 100% across all TRs considered. However, the misting system worsened comfort during the day due to increased relative humidity.

When both the shading element and misting system were combined (D), TG increased by up to 6.6 °C in TR_1; 8 °C in TR_2; and 11.3 °C in TR_3. Overheating at night reached 3 °C. The misting system did not enhance night-time comfort due to increased relative humidity and air mass confinement by the shading device, limiting evaporation. Nonetheless, thermal comfort hours ranged from 84% to 100% across TRs.

In the final campaign (E), a combination of shading and misting systems was used, with the shading device removed at night. This resulted in a TG of up to 11.8 °C, while night-time overheating in the courtyard was reduced to just 0.8 °C. According to PET, the analysed case study was able to ensure thermal comfort conditions 24 h a day during a heat wave period.

Unlike most previous research which tested individual passive strategies in courtyards in specific climate scenarios, this analysis explores the combination of strategies in different thermal ranges. It was confirmed that the implementation of shading elements in courtyards resulted in a TG of over 10 °C. This investigation yielded a TG of 11.8 °C, in line with a previously recorded TG of 13.7 °C [87]. Minor variations may be attributed to the selection of a different representative courtyard geometry for this study or differences in courtyard materials and orientations. TG achieved by shading device is significantly higher than TG caused by tree shading in courtyards, which previously achieved up to 3.3 °C [55]. Thermal comfort improvement due to the implementation of shading devices was 12 °C in previous research [79], while in this case study it achieved 16.2 °C. In terms of comfort hours, the shading element in campaign B achieved 79%, a 37% improvement compared to campaign A (without shading). This contrasts with other experiments where improvements of up to 66% were achieved [87].

Ulpiani et al. [74] confirmed the effectiveness of the misting strategy in all three climate scenarios, all above 30 °C and never exceeding 70% RH. However, the 15 °C improvement achieved in other studies [78] was not matched here, as the maximum TG due to the misting effect was 10.1 °C. In terms of comfort, previous research showed a reduction of 2.2 °C (SET*) due to misting [79], and in this experiment the outdoor wind chill was reduced by up to 14.8 °C (PET). This highlights the potential impact of these strategies on different microclimates. Nevertheless, the main novelty of this research lies in the flexible combination of both strategies (shading elements and misting system) during the day/night cycle, leading to the significant optimization and reliability of the results. These results confirmed the improvements evaluated in previous research by implementing each strategy. Moreover, this research addressed the different seasonal temperature ranges (from 30 to above 40 °C) characteristic of most cities in the Mediterranean basin and many other locations around the globe, by combining both strategies, improving the results of temperature reduction and increased comfort in the courtyard.

5. Conclusion

In this study, direct experimental results on the microclimatic conditions in a courtyard under different thermal ranges have been obtained by implementing combinations of passive cooling strategies. The main research innovation lies in the potential for identifying how courtyards can upgrade their climate resilience under a global warming scenario, adapting to different temperature ranges in hot and warm dry climates, by using easy-to-implement passive approaches.

A dynamic combination of strategies was found to be most beneficial during the various field monitoring campaigns, particularly as the outdoor temperature increased. The results emphasized the importance of removing the shading element at night to cool the courtyard. In light of the research objectives.

- Both strategies were tested separately and in combination under different outdoor climatic conditions, reaching a TG of up to 11 °C.
- In addition, variations were made during the 24-h cycles to analyse the optimal combination, with TG increasing by almost 2 °C during the day, and overnight overheating being reduced by up to 3 °C.
- The implementation of the shading device during the daytime period (12 h), combining with a 24-h misting system, was the best strategy for the courtyard microclimate, achieving 24 h of thermal comfort in the courtyard. This not only substantiates the traditional practice of shading during the day and uncovering and watering courtyards at sunset in old town dwellings, but also quantifies the improvement in comfort, arguing for the adoption of these strategies in new residential constructions.

The research therefore addresses the objective of improving thermal comfort conditions in the courtyards by implementing strategies to modify the radiation and humidity in this microclimate. Both strategies were assessed individually and jointly, and the necessary modifications were made to achieve the optimal combination to ensure 100% of comfort hours in a typical Mediterranean courtyard during a heat wave period.

While this study involves limitations inherent to single case studies, such as the construction characteristics of the envelope and its thermal inertia, the proposed methodology can be applied to the analysis of other courtyards in different climatic zones and with varying geometric configurations. The application of this methodology could facilitate the creation of guidelines for managing basic passive cooling strategies, focusing on two key parameters: courtyard geometry and climatic boundary conditions. Accordingly, future research should apply this comparison to courtyards with different geometries and locations to identify the most suitable passive strategy for each type of courtyard and climate. Additionally, further analysis considering other strategies such as vegetation or albedo variation is deemed essential. Finally, feedback on user comfort or subjective experiences through surveys could provide a more holistic understanding of the effectiveness of strategies implemented in future research.

CRediT authorship contribution statement

Eduardo Diz-Mellado: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Victoria Patricia López-Cabeza:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Carlos Rivera-Gómez:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Emanuele Naboni:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Carmen Galán-Marín:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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Carmen Galan-Marin reports equipment, drugs, or supplies was provided by Spain Ministry of Science and Innovation. Carmen Galan-Marin reports financial support and article publishing charges were provided by Spain Ministry of Science and Innovation. Carmen Galan-Marin reports financial support and equipment, drugs, or supplies were provided by Junta de Andalucía Consejería de Obras Públicas y Vivienda. Eduardo Diz-Mellado reports financial support was provided by Ministry of Education and Culture.

Data availability

Data will be made available on request.

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Appendix

To obtain the mean radiant temperature inside the courtyard, the case study was modelled using Ladybug Tools, a set of plugins for Grasshopper linking the energy modelling software EnergyPlus and Radiance to the modelling interface in Rhinoceros. The weather file for the simulation was a TMYx file from Seville modified with the monitored weather data recorded during the monitoring campaigns.

An energy simulation was performed by the Honeybee plugin using the model in Rhinoceros and the modified weather file data to obtain the surface temperature information needed to calculate the MRT with the corresponding Ladybug Tools component.

Energy simulation input parameters include aspects such as the thermal properties of building construction materials, internal gains and schedules, infiltration, and ventilation rates. Internal loads are divided into occupants, lighting, and equipment (Table A1). The values used are introduced considering the building to be unoccupied during the campaign period due to the summer holidays. The thermal properties of the construction materials and the elements of the base case are shown in Table A2.

Table A1
Energy modelling parameters.

Parameter	Value
Program and schedules	Unoccupied (summer holidays)
Infiltration	0.0001 m^3/s per m^2 façade
Minimum ventilation	0.0002 (area) + 0.001 (person) $m^3/s.m^2$
Natural ventilation	Activated if: 15 °C < indoor temperature <35 °C; fraction of operable window: 50%; Discharge coefficient: 0.17
Heating and cooling	Not conditioned
Solar distribution	Full interior and exterior (with reflections)

Table A2
Base case construction thermal and optical properties in the courtyard.

Type	Description	Thickness (mm)	Density (kg/ m^3)	Thermal conductivity (W/mK)	Specific Heat Capacity (J/kgK)	U-value (W/ m^2K)	Albedo/ Transparency
Walls	Brick	110	1920	0.567	790	1.38	0.6/0
	Air gap	50	1204	0.31	1008		
	Brick	60	1800	0.432	790		
	Plaster	20	1440	0.4	970		
Windows	Single Pane					U = 5.8 SHGC = 0.8	0.8/0.8
Shadow device	PVC canvas	2	70	–	–		0.9/0.75
Floors	Concrete	200	2300	1.32	880	6.60	0.6/0

Table A3
Percentage of hours of thermal comfort according to PET in Thermal Range 1 (24 h).

Thermal Comfort (PET)	A	B	C	D
	No strategies	Shade	Misting	Shade and Misting
Slightly cool	0%	4%	4%	0%
Neutral	63%	92%	88%	88%
Slightly warm	21%	4%	8%	12%
Warm	17%	0%	0%	0%
Hot	0%	0%	0%	0%

Table A4
Percentage of hours of thermal comfort according to PET in Thermal Range 2.

Thermal Comfort (PET)	A	B	C	D
	No strategies	Shade	Misting	Shade and Misting
Slightly cool	0%	0%	0%	0%
Neutral	50%	46%	33%	63%
Slightly warm	13%	33%	33%	25%
Warm	38%	21%	33%	13%
Hot	0%	0%	0%	0%

Table A5
Percentage of hours of thermal comfort according to PET in Thermal Range 3.

Thermal Comfort (PET)	A	B	C	D
	No strategies	Shade	Misting	Shade and Misting
Slightly cool	0%	0%	0%	0%
Neutral	13%	38%	21%	63%
Slightly warm	29%	33%	33%	21%
Warm	29%	29%	33%	17%
Hot	29%	0%	13%	0%

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