Energy & Buildings 336 (2025) 115496

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Courtyards as passive climate buffers: Enhancing thermal comfort and preventive conservation in mediterranean climates

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ARTICLE INFO

Keywords:
Hygrothermal comfort
Mediterranean climate
Climate change
Heat mitigation
Passive strategies
Heritage conservation

ABSTRACT

This study examines the role of Mediterranean courtyards as passive systems for mitigating extreme climatic conditions while enhancing thermal comfort and preserving architectural heritage. Using the Courtyard of the Maidens in the Royal Alcázar of Seville as a case study, the research includes a three-year monitoring campaign (2020–2023) to collect ambient temperature and relative humidity data, assessing seasonal variations and the impact of heatwaves.

Key findings demonstrate that the courtyard moderates extreme temperatures, reducing reliance on active cooling and heating systems, and contributes to improved comfort levels for users. Additionally, the study highlights the courtyard's role in minimising environmental stress on heritage materials, particularly its ability to maintain conditions favourable for the conservation of plasterwork and other decorative elements.

The study underlines the importance of integrating passive architectural strategies, such as courtyards, into urban planning to promote sustainability and resilience in Mediterranean climates increasingly affected by climate change. It offers valuable insights into how historic architectural features can address contemporary environmental challenges.

1. Introduction

Climate change, primarily driven by human activities, has emerged as a critical global issue with far-reaching consequences. Rising temperatures disrupt ecosystems, threaten biodiversity, and alter climate patterns, leading to more frequent heat waves (HW) and droughts. These phenomena jeopardize natural resources, food security, human health, and even the preservation of architectural heritage. The interplay between climate change and cultural heritage conservation has become a pivotal area of study, emphasizing the need to adapt preservation practices to evolving environmental conditions.

Since the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 [1], comprehensive assessments have underscored the rising greenhouse gas (GHG) emissions and the depletion of natural resources [2–4]. Concurrently, the building sector has sought solutions to mitigate its environmental impact by transitioning toward nearly zero energy buildings (NZEB). Such standards aim to drastically reduce energy consumption [5–9] while enhancing thermal comfort, even in historic buildings through retrofitting [10]. However, implementing NZEB standards in Southern Europe poses unique challenges [11], including the risk of summer overheating [12] and the pervasive Urban Heat Island (UHI) effect, which intensifies heat waves and increases energy demand for cooling [13]. These challenges, coupled with energy poverty and economic barriers, highlight the complexity of achieving sustainable urban environments [14,15].

In parallel, preserving built heritage in the face of climate change demands innovative approaches and tools. International initiatives like *HeritageCare* have introduced integrated methodologies for the preventive conservation of historical buildings across Portugal, Spain, and France [16–19]. Geographic Information Systems (GIS) [20,21] and software tools such as *BuildingsLife* and *Art-Risk 5.0* [22–26] have advanced maintenance strategies by enabling precise monitoring, cost estimation, and durability modelling [27–29],. These technologies enhance the understanding of material degradation under specific environmental conditions, fostering more informed conservation strategies.

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https://doi.org/10.1016/j.enbuild.2025.115496
Received 29 November 2024; Received in revised form 3 February 2025; Accepted 18 February 2025
Available online 27 February 2025

Nomenclature

AEMET	State Meteorological Agency of Spain
AR	Aspect Ratio
BPSTs	Building performance simulation tools
CT	Courtyard Air Temperature
CTE	Spanish Technical Code
DHR	Diurnal Humidity Range
DTR	Diurnal Thermal Range
GHG	Green House Gases
H	Height
HMR	Heritage Microclimate Risk index
HW	Heatwave
IPCC	Intergovernmental Panel on Climate Change
MRT	Radiant Tempe
NZEB	Nearly Zero Energy Consumption
PET	Physiologically Equivalent Temperature Index
PRD	Predicted Risk of Damage index
R_2	Coefficient of determination
RAS	Royal Alcazar of Seville
RCP	Representative Concentration Pathway
RH	Relative Humidity
RITE	Regulation of thermal installations in buildings
SD	Standard Deviation
ST_c	Heat Index, From the Spanish 'Sensación Térmica de Calor'
T_a	Air temperature
T_{DAMP}	Thermal Dampness
T_{LAG}	Thermal lag
TG	Thermal Gap
W	Width

Prolonged exposure to specific environmental conditions can cause irreversible deformations or cracking in materials, potentially leading to structural failure if their capacity for deformation is exceeded [30]. This highlights the importance of monitoring campaigns that document variables such as temperature and relative humidity. For instance, studies conducted at sites like the Royal Alcazar of Seville have provided crucial insights into the durability of materials such as plaster [31], wood, and ceramics [32,33]. These investigations not only reveal how past environmental conditions have shaped material resilience [34–37] but also guide future conservation efforts in light of projected climate scenarios [30].

Research has increasingly focused on the environmental factors influencing heritage conservation, analyzing their impact on construction materials and the valuable items housed within historical structures [35,38–40] Studies spanning decades have employed non-destructive techniques to assess conservation states, identify degradation causes, and develop preventive strategies [41–43]. In this context, the monitoring and analysis of specific environmental conditions and their impact on built heritage, as well as future vulnerabilities due to global warming [44–51], present significant challenges.

2. Research objectives and key questions

Climate change poses significant challenges to the conservation of architectural heritage. The integration of advanced tools, long-term monitoring, and interdisciplinary research is essential to mitigate risks, ensure the durability of historic materials, and adapt preservation practices to current and future climatic conditions. Understanding and addressing these vulnerabilities will be pivotal in safeguarding our cultural heritage for generations to come. In this context, this study aims to address two questions:

2.1. Do courtyards help mitigate climate change while ensuring hygrothermal comfort?

Addressing hygrothermal comfort in the context of climate change requires adaptive solutions. Semi-open spaces, such as verandas, overhangs, and courtyards, play a key role in mitigating climate fluctuations and improving urban resilience, particularly in Mediterranean regions [44]. These passive conditioning systems help reduce energy consumption and GHG emissions, contributing to enhanced thermal comfort, especially during summer [45–49].

Previous studies have quantified the energy-saving potential of Mediterranean courtyards, showing that savings in cooling demand range from 8 % to 18 %, depending on the courtyard's aspect ratio (AR) [50]. In hot-arid climates, optimized courtyards have been shown to reduce annual energy consumption by over 11 % compared to conventional building forms. Additionally, factors like courtyard geometry, orientation, water features, vegetation, and material properties can influence their efficiency in filtering solar radiation, promoting natural ventilation, and improving microclimates [44,46,50–62].

2.2. To what extent do courtyard climatic conditions affect claddings conservation?

The preventive conservation of architectural heritage is vital for preserving cultural assets for future generations [63,64]. Maintenance programs based on long-term planning and continuous assessment are necessary to protect these assets [32]. Tools like Geographic Information Systems (GIS) and software such as BuildingsLife and Art-Risk are increasingly being used to optimize heritage conservation by monitoring environmental conditions and predicting material degradation.

International standards, such as UNI 10829 [65], UNE-EN-15757 [66], and ASHRAE 55–2020 [67], provide guidelines for indoor air quality in heritage buildings, specifying acceptable ranges for temperature and relative humidity to prevent material deterioration. Likewise, the EN-16096:2016 standard addresses the inspection and reporting of built cultural heritage, offering recommendations for preventive conservation, maintenance, immediate repairs, and more detailed planning [68]. However, these standards are designed for fully enclosed indoor environments and do not address the unique challenges posed by semi-open spaces like courtyards. Currently, no regulatory framework defines appropriate climatic parameters for the preservation of materials in such spaces, despite their significant role in heritage conservation.

The absence of specific guidelines for semi-open environments has motivated recent research efforts aimed at understanding how these spaces impact material degradation. Studies are increasingly focusing on the microclimates of courtyards and similar semi-open areas, investigating how fluctuating environmental conditions —such as exposure to outdoor humidity and temperature changes— affect the longevity and deterioration of claddings and other building materials. This line of research is essential for developing conservation strategies tailored to the unique climatic dynamics of semi-open spaces.

Materials exposed to variable conditions in courtyards can suffer irreversible deformations and cracking due to prolonged temperature and humidity fluctuations. This is particularly problematic in intermittently heated or unheated spaces typical of Southern Europe. Monitoring key environmental variables, such as temperature and relative humidity (RH), in courtyards is vital for assessing their impact on materials like plaster, wood, and ceramics. In the case of the Royal Alcazar of Seville, continuous monitoring has been crucial in identifying potential risks to material conservation.

Ongoing research into the specific climatic conditions of semi-open spaces aims to bridge the gap in current standards and provide new insights into how these environments influence material degradation. Understanding the effects of climate on courtyards will be key to establishing more robust conservation strategies for historic heritage in semi-open settings.

This study presents a novel approach by integrating long-term microclimatic monitoring with a focus on both thermal comfort and the preventive conservation of historic materials. Unlike previous research, which primarily examines the energy-saving potential of courtyards, this work explicitly quantifies their role in mitigating extreme temperature fluctuations and humidity variations over an extended period. The use of multiple sensors in all four corners of the courtyard ensures a comprehensive spatial analysis, with the selection of the north corner justified due to its exposure to direct solar radiation. Additionally, the study incorporates a comparative framework with similar case studies, reinforcing the broader applicability of our findings. By addressing the intersection of passive cooling strategies and heritage conservation, this research contributes critical insights into the resilience of courtyard microclimates under future climate change scenarios.

The objective of this study is to examine whether courtyards can enhance urban comfort and mitigate extreme environmental conditions, as well as to determine whether interior courtyards play a role in preserving architectural heritage from temporal degradation. Through this exploration, the research aims to provide insights into the potential of courtyards to contribute to more resilient and sustainable urban environments.

3. Case Study – The courtyard of the Maidens

The case study selected was the Courtyard of the Maidens, a traditional Mediterranean court located in the Royal Alcazar of Seville (hereinafter, RAS) (Fig. 1), considered a world heritage site by the UNESCO since 1987.[1] It is situated in Seville (37.3831° N, 5.9902° W, 34 m.a.s.l.), a Spanish city located in the Csa zone according to the Köppen climate classification [69]. This area is characterized by hot and dry summers, and mild winters. It is worthwhile to highlight that there is no cooling or heating devices in the case study, neither inside the building or in the courtyard.

This is a 21*15 m courtyard, bordered by 7.85 m heigh galleries on the ground floor and more than 4 m heigh on the second floor. Thus, the aspect ratio (AR) range that links the height (H) and widths (W_1 and W_2) is less than 1.0.

The central area of the courtyard is composed by a pit with vegetation on the floor, orange trees and a water fountain that refresh the space. Additionally, this courtyard façade is composed of a brick and lime wall of 60 cm thickness to improve the thermal inertia and natural cross ventilation is ensured thanks to three high dimension doors and several windows that remain opened during the day and close during the night (Fig. 2).

4. Materials and method

The main objective of this work is to validate the effect of the courtyard with bioclimatic elements as a buffer of external environmental conditions through a three-year longitudinal study and examines its influence in cladding conservation. Taking into account the historical climatological records and climate trends in this location, it is vital to reduce temperatures during the hottest seasons not only to avoid health risks for the population and prevent the loss of cladding cohesion. For this purpose, a descriptive statistical analysis of the hygrothermal comfort in a semi-outdoor space during a three-years-period was conducted (i.e., three consecutive years from 23/09/2020 to 22/09/2023), together with the analysis of temperatures during extreme HW periods and the consequent impact on the cladding deterioration.

4.1. The experimental campaign and subsequent statistical analysis

To monitor ambient conditions, a Lascar thermohygrometer (model EL-USB 2 LCD) with two recording channels, a temperature range of −35 °C to 80 °C, and a relative humidity range of 0 % to 100 %, with a resolution of ±0.5 °C and ±3 % relative humidity, was used. The obtained dataset collects hourly information from September 2020 to September 2023, beginning and ending on September the 23rd to get a complete seasonal measurement (sample size: n = 26,280).[2] Thus, a general review of the annual ambient conditions in the courtyard could be obtained and a specific assessment of the thermal conditions during HW periods. In this regard, Seville is characterised by range of maximum severity in summer and low severity in winter seasons [71]. This fact was considered when the location of the thermohygrometer was decided, and the north corner of the courtyard was selected due to ensure the assessment of the area that receive more direct solar radiation along the year.

It is important to note that the study did not rely on a single sensor. Identical sensors were deployed in all four corners of the courtyard to ensure comprehensive data collection. The north corner was selected for detailed analysis due to its higher temperature and humidity variations, resulting from receiving the most direct solar radiation throughout the year. This corner experiences higher temperatures and lower relative humidity during peak hours, while at night, the temperature minima and relative humidity maxima align closely with the readings from the other three corners, confirming consistency in the data.

This robust technical campaign provides hourly measurements of ambient temperature (T_a) and relative humidity (RH) in the selected corner of the courtyard. Minimum and maximum T_a and RH were stated per seasons, as well as monthly T_a and RH mean were determined together with their standard deviations (SD). It was also calculated the Diurnal Thermal Range (DTR) (Eq.1), the mean of daily thermal difference between the maximum (T_{max}) and the minimum (T_{min}) T_a values during each period and consequently, the Diurnal Humidity Range (DHR) (Eq. (2).

$$DTR = Tmax - Tmin \tag{1}$$

$$DHR = RHmax - RHmin \tag{2}$$

Comparison between data retrieved from the three years analysed was carried out to understand annual historical data and reveal the trend of environmental conditions in the nearest years. Similarly, monthly ambient conditions during the three-years period were analysed to demonstrate which months suppose potential risk for human healthy and architectural preservation.

To conclude this statistical study, the correlation between T_a and RH was examined by calculating the linear regression and the R^2 value. Additionally, an analysis of the frequency distribution of both variables was conducted.

4.2. Comparative study of ambient conditions: Outdoor environment versus the courtyard

The temperature in the courtyard was robustly evaluated by comparing it with the outside temperature over a three-year period, utilizing hourly data from the State Meteorological Agency of Spain (hereinafter, AEMET). Specifically, data was retrieved from meteorological station coordinates 37°25′0″N, 5°52′45″W, 34 m.a.s.l. Thus,

[1] https://whc.unesco.org/en/list/383.

[2] September 23rd is the first day of the Autumn season in Spain and other cities from the EU.

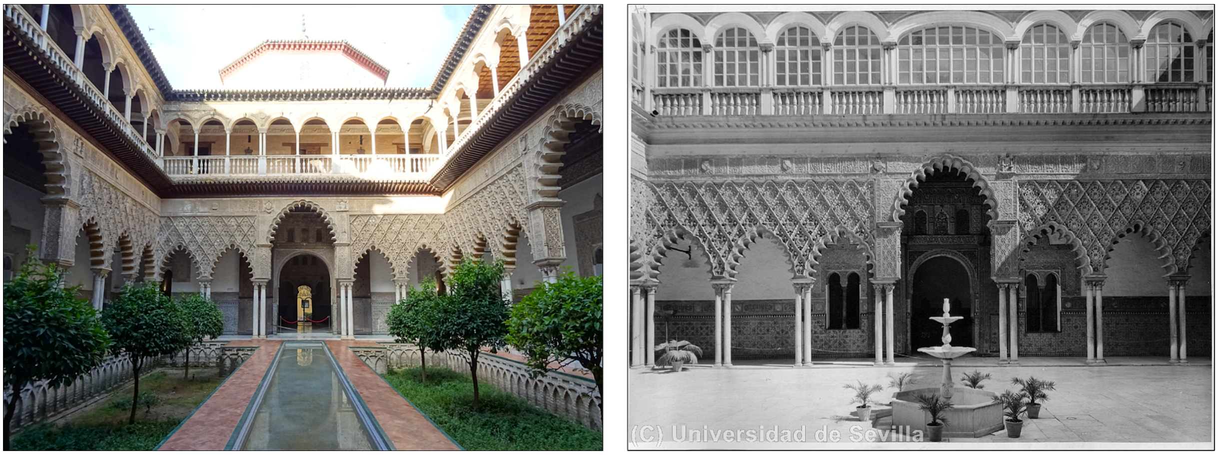

Fig. 1. General view of the Courtyard of the maidens: current state (left) [Image owned by the authors] and historical photograph in the 19th century (right). [Retrieved from the University of Seville].

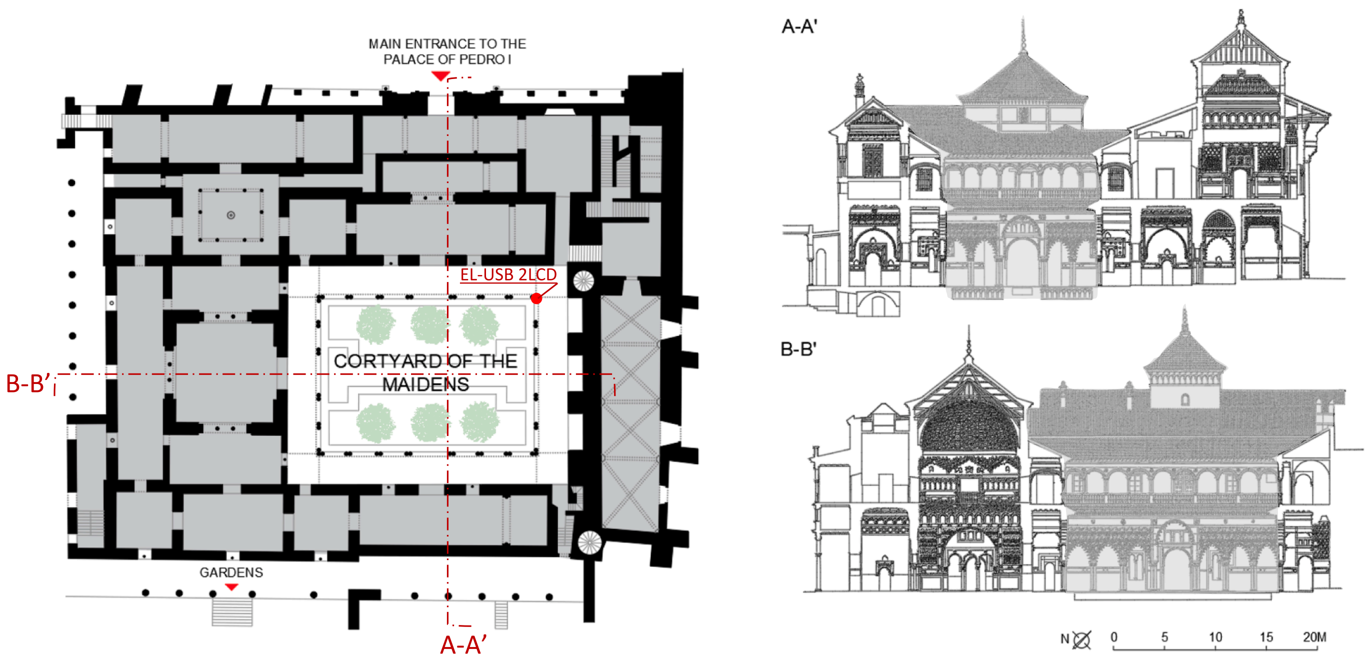

Fig. 2. Plan and cross sections of the Courtyard of the maidens. Retrieved from Almagro Gorbea 2000 and edited by authors [70].

graphical comparisons between variables measured inside and outside the courtyard were depicted and possible correlations were studied.

Furthermore, the ambient conditions during the HW periods were studied thoroughly (Table 1). Subsequently, temperatures recorded outdoor by AEMET during HW days were compared to those recorded by the thermohygrometer situated in the Courtyard of the Maidens. This comparison encompassed an assessment of the thermal gap (TG), the thermal lag (T_{LAG}), and the thermal dampness (T_{DAMP}). It is worth to highlight that the Fisher test and the t-student test were previously conducted to determine whether the variance of these two variables was equal or not ($\alpha = 0.01$).

4.3. Hygrothermal comfort: PET & ST_c indices

This study will focus on comparing outdoor comfort and courtyard comfort over a three-year period, particularly during heat wave (HW) periods. Thus, the Olgyay bioclimatic chart, created by combining climate conditions of T_a and RH and widely validated in previous studies across different climate zones was used [72–75]. Additionally, the Physiologically Equivalent Temperature index (PET), developed by Matzarakis and Mayer [76], was analysed [50]. This index has been adopted for this research due to its suitability to Mediterranean climate and latitude, previously validated in semi-outdoor spaces studies in southern Spain [77,78], considering the PET ranges for Western and Central Europe [47] (Table 2).

To conclude the hydrothermal study, the Heat Index (ST_c), an index that combine T_a and RH to determine how heat is perceived, was calculated (Eq. (3)). This index is especially relevant in hot and humid climates and can warn about situations of excessive heat that could be dangerous to health [79].

$$
\begin{aligned}
ST_C = & -8,78469476 + 1,61139411 \cdot T + 2,338548839 \cdot RH \\
& - 0,14611605 \cdot T \cdot RH - 0,012308094 \cdot T^2 - 0,016424828 \cdot RH^2 \\
& + 0,002211732 \cdot T^2 \cdot HR + 0,00072546 \cdot T \cdot RH^2 - 0,000003582 \cdot T^2 \cdot RH^2
\end{aligned} \tag{3}
$$

Table 1
Heatwaves periods in Andalusia according to AEMET from 23 to 09-2021 to 23–09-2023.

Designation	Year	Date	Duration (days)	Anomaly of the HW	T_{max} in Seville (°C)
HW_1	2021	21st to 23rd July	3	2.0	39.7
HW_2	2021	11st to 16th August	6	4.1	44.8
HW_3	2022	12nd to 18th June	7	3.2	42.6
HW_4	2022	9th to 26th July	18	4.5	44.8
HW_5	2022	30rd July to 14th August	16	3.5	41.0
HW_6	2023	9th to 12nd July	4	3.2	41.7
HW_7	2023	17th to 20th July	4	3.4	41.7
HW_8	2023	6th to 13th August	8	3.3	43.7
HW_9	2023	17th to 25th August	9	3.9	42.6

Table 2
PET index comfort intervals.

PET (°C)	Thermal perception	Grade of physiological stress
< 4.0	Very cold	Extreme cold stress
4.1 – 8.0	Cold	Strong cold stress
8.1 – 13.0	Cool	Moderate cold stress
13.1 – 18.0	Slightly cool	Slight cold stress
18.1 – 23.0	Comfortable	No thermal stress
23.1 – 29.0	Slightly warm	Slightly heat stress
29.1 – 35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
> 41.0	Very hot	Extreme heat stress

AEMET calculates Heat Index values by taking into account T_a readings above 26 °C and RH readings above 40 %. If the T_a is below 26 °C or the RH is below 40 %, the apparent temperature (STc) is considered equal to the actual temperature [80]. When Ta values range from 27 °C to 32 °C, caution is advised due to the potential negative effects of prolonged exposure or physical activities. If Ta falls between 33 °C and 40 °C, extreme caution is warranted, as the risk of heat exhaustion or heat-stroke increases. For Ta values from 41 °C to 53 °C, there is a significant danger of heat-related illnesses, and temperatures exceeding 54 °C are classified as extreme danger.

4.4. Degradation of coating material

Humidity plays a fundamental role in the conservation of cultural heritage, as many materials and deterioration processes are influenced by its levels and variations. Controlling relative humidity (RH) is a key preventive measure to minimise the risk of damage and reduce the need for future interventions. Hygroscopic materials, such as wood and plaster, absorb and release moisture in response to environmental conditions, which can lead to expansion, contraction, fractures, or deformations if fluctuations are significant. High RH levels also promote mould growth and harmful chemical reactions, whereas low RH increases dust accumulation.

Temperature directly affects conservation and regulates RH; thus, both factors must be considered from a static perspective (acceptable levels) and a dynamic perspective (frequency and duration of fluctuations). Organic materials require a moderate RH range, as extremes can cause severe structural damage. These conditions underscore the importance of rigorous environmental control in preserving cultural assets.

Given that most of the finishes used in the Patio de las Doncellas consist of historic plasterwork, primarily composed of gypsum [81], the guidelines outlined in the UNE-EN-15757:2011 standard were followed to assess temperature and RH conditions with respect to limiting mechanical damage [66].

The seasonal cycle of RH was determined by calculating the central moving average (MA) for each reading. This was achieved by taking the arithmetic mean of all RH readings recorded over a 30-day window, consisting of the 15 days preceding and the 15 days following the date for which the mean value was computed.

$$MA_{ongoing} = \left(RH_{ongoing} + RH_{ongoing} - 1 + [\ldots] + RH_{ongoing} - 360 + RH_{ongoing} + 1 + [\ldots] + RH_{ongoing} + 360\right)/721 \tag{4}$$

The upper and lower limits were defined using the 7th and 93rd percentiles of the recorded fluctuations during the monitoring period. This approach excluded 14 % of the most extreme fluctuations, effectively trimming the peaks and troughs of relative humidity to minimise the influence of excessively wet or dry conditions.

4.4.1. Heritage microclimate index and predicted risk of damage

In this case study, the methodology established by Fabbri and Bonora [82] was followed to calculate the Heritage Microclimate Risk index (HMR) (Eq. (5) based on the T and RH parameters previously analysed in this work. An HMR value of minus one (−1) indicates a risk condition related to the 'lower threshold', while an HMR value of plus one (+1) signifies a risk condition associated with the 'higher threshold'. Furthermore, the Predicted Risk of Damage index (PRD) (Eq. (6) was also calculated according to the HMR index and the material type (inorganic, organic, paintings, etc.) [82].

$$HMR_{hs} = \frac{HMR_{env} + HMR_{osc}}{2} \tag{5}$$

$$PRD = 1 - 0.95e^{\left(-a \cdot HMR_{hs}^{4} - b \cdot HMR_{hs}^{2}\right)}(\%) \tag{6}$$

where 'env' refers to HMR environmental, 'osc' refers to HMR oscillations, and 'hs' indicates historical value. Additionally, 'a' and 'b' values were determined on an empirical basis from the standards reported by UNI 10829 and EN 15757 [83,84].

4.4.2. Preservation of historical plasterworks

The method proposed by Torres-González et al. [81] was used to assess the conservation status of the most representative coating material in the courtyard, the plasterworks (Fig. 3). All the anomalies developed by this material are widely explained in previous works by the authors [33,85,86] and conclusions indicated that the optimal ambient conditions for the best preservation of this material are those inside the region shaded in yellow in Fig. 3, thus favouring the

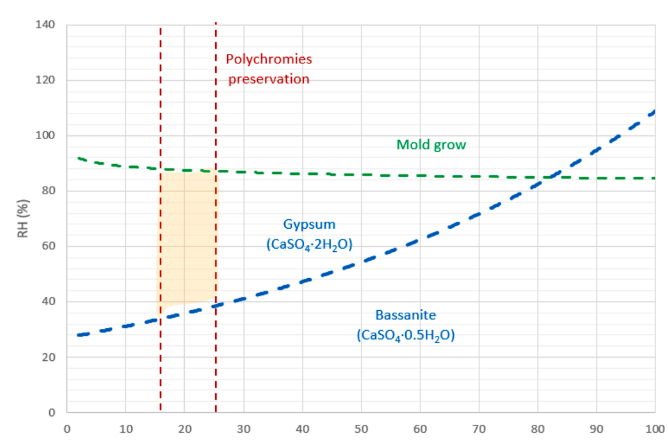

Fig. 3. Conditioning factors for the durability of plasterwork (Retrieved from [81]).

mechanical resistance of the plasterwork.

To complete the study, the correlation between Ta and surface temperature on the plasterworks cladding was analysed during the HW_6 period [87–89]. For this purpose, thermographic images (IRT) were taken with the testo868 camera at 8am, 4 pm and 8 pm, taking into consideration a 0.93 emissivity degree [90]. The QA/QC process for using the TESTO 868 IRT camera involves the verification of correct calibration of the camera and the measurement of surface temperature of the material. For this purpose, the TESTO 905-T2 surface thermometer was used on-site to compare results with those obtained with the TESTO 868 IRT. The IRT was lately post-processed and analysed thanks to Testo IRSoft Analysis software.

5. Discussion and results

The monitoring campaign provides a data set composed by 26,280 records of T_a and RH in a semi-outdoor space, namely the Courtyard of the Maidens. A general overview of the climatic conditions recorded for three-years-period has been depicted in Table 3. and Fig. 4.

The main conclusion drawn from the environmental measurements of the courtyard is that the T_a shows a slight linear increasing trend, with an approximate rise of 1 °C per year, further confirming the reality of climate change (Fig. 4). Consequently, RH demonstrates a notable decreasing trend of approximately 3 % over the past three years (Fig. 4).

When analysing the results per month, July is the month that reaches the highest T_a, being the monthly temperature mean around 30 °C, and January is the coldest month, dropping temperatures to a mean of 12 °C (Fig. 5). A trend in the increase in T_a as the years go by in almost all months – except February and March – was observed, confirming the climate change forecasts in future scenarios (i.e., RCP2.6, RCP4.5, and RCP8.5 scenarios for the years 2050 and 2100 in mediterranean countries [91]), increasing the mean monthly temperature by ~1 °C (Fig. 4). This result validates previous research that states that the climate in Seville will tend to be drier in the coming year [92].

Regarding RH, the results are more disparate and there is no clear trend during the three years monitored. July is the driest month, with a mean relative humidity of 45 %, and December is the wettest month, reaching mean relative humidity of 75 % (Fig. 5). In general terms, Fig. 5&Fig. 6 indicate that mean monthly T_a and RH values inside the courtyard are within the limits commonly accepted almost the entire year. Thus, strategies implemented in this courtyard (i.e., pond, trees, grass, galleries, openings, etc) slightly favour the feeling of optimal comfort for the user.

Although the curves of the means of T_a and RH (Fig. 5) seem to indicate that there is a relationship between both parameters – the higher the T_a, the lower the RH, and conversely – a linear analysis corroborates the great dispersion between the monitored data (R^2: 0.4005).

Table 3
Descriptive analysis from T and RH measured (n: 1,095 days – i.e., 3 completed years).

Period analysed	Variable measured	T (°C)	RH (%)
Spring and Summer *(from March 21st to September 22nd)*	Daily Mean (±SD)	25.61 ± *4.45*	51.39 ± *10.25*
	Daily Min. Mean (±SD)	22.79 ± *4.33*	39.41 ± *9.93*
	Daily Máx. Mean (±SD)	29.05 ± *4.59*	61.15 ± *10.85*
	Daily Mean DTR / DHR (±SD)	6.26 ± *1.26*	21.74 ± *6.71*
Autumn and winter *(from September 23rd to March 20th)*	Daily Mean (±SD)	17.25 ± *4.38*	63.75 ± *13.09*
	Daily Min. Mean (±SD)	14.60 ± *4.23*	47.75 ± *17.05*
	Daily Máx. Mean (±SD)	24.92 ± *7.21*	71.68 ± *11.96*
	Daily Mean DTR / DHR (±SD)	10.32 ± *6.35*	23.94 ± *10.36*

5.1. Assessment of the courtyard mitigation effect

In the context of the T_a variable throughout the analysed three-year period, the initial hypothesis was validated. It was observed that the courtyard serves as a mitigating factor for both warm and cold extreme temperatures. An exemplar representation is presented in Fig. 6, illustrating a typical year from the sample, with a sample size of n:8760. The mean TG recorded was 4.06 °C ± 2.43 °C. This corroborates the TG values reported in previous research conducted in the same city, although over a one-week monitoring period [46]. In this study courtyard, thermal behaviour can be identified through two different outdoor temperature intervals. In the first case, below 30 °C, the tempering behaviour of the courtyard is low with thermal gaps, regarding outdoor temperatures, up to 5 °C. However, parallel to the rise in outdoor temperatures, the thermal tempering potential of the courtyard increases coming to be reached, while outdoor temperatures above 42 °C, a thermal gap up to 12 °C less inside the courtyard. Additionally, this study examines the thermal behaviour of the courtyard during nighttime and extreme summer heatwaves. Specifically, on heatwave days, while outdoor temperatures drop overnight, the courtyard retains heat, maintaining temperatures approximately 10 °C higher than the surroundings.

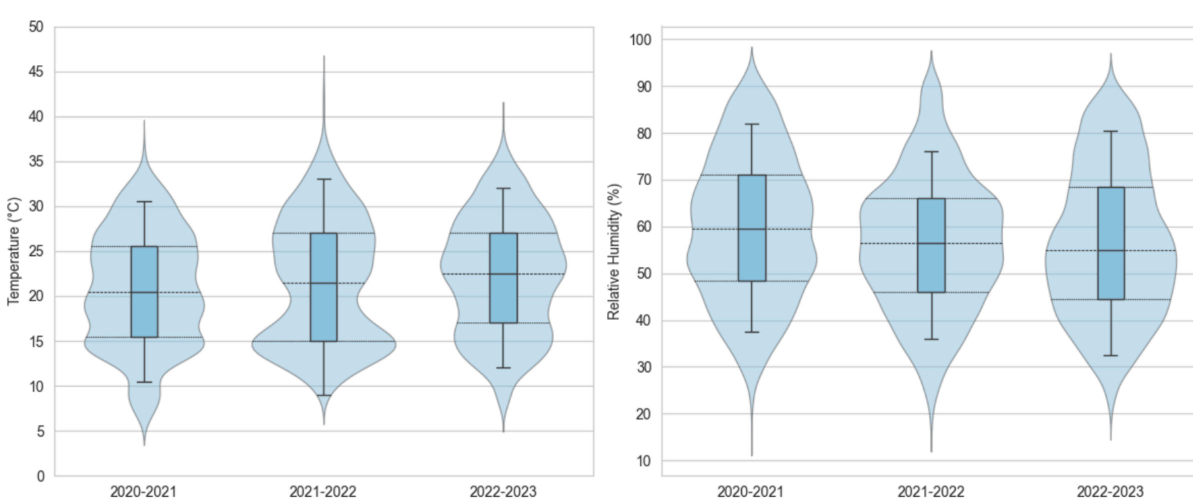

Fig. 4. Violin and box plots indicating temperatures (left) and relative humidities (right) recorded during three-years-period.

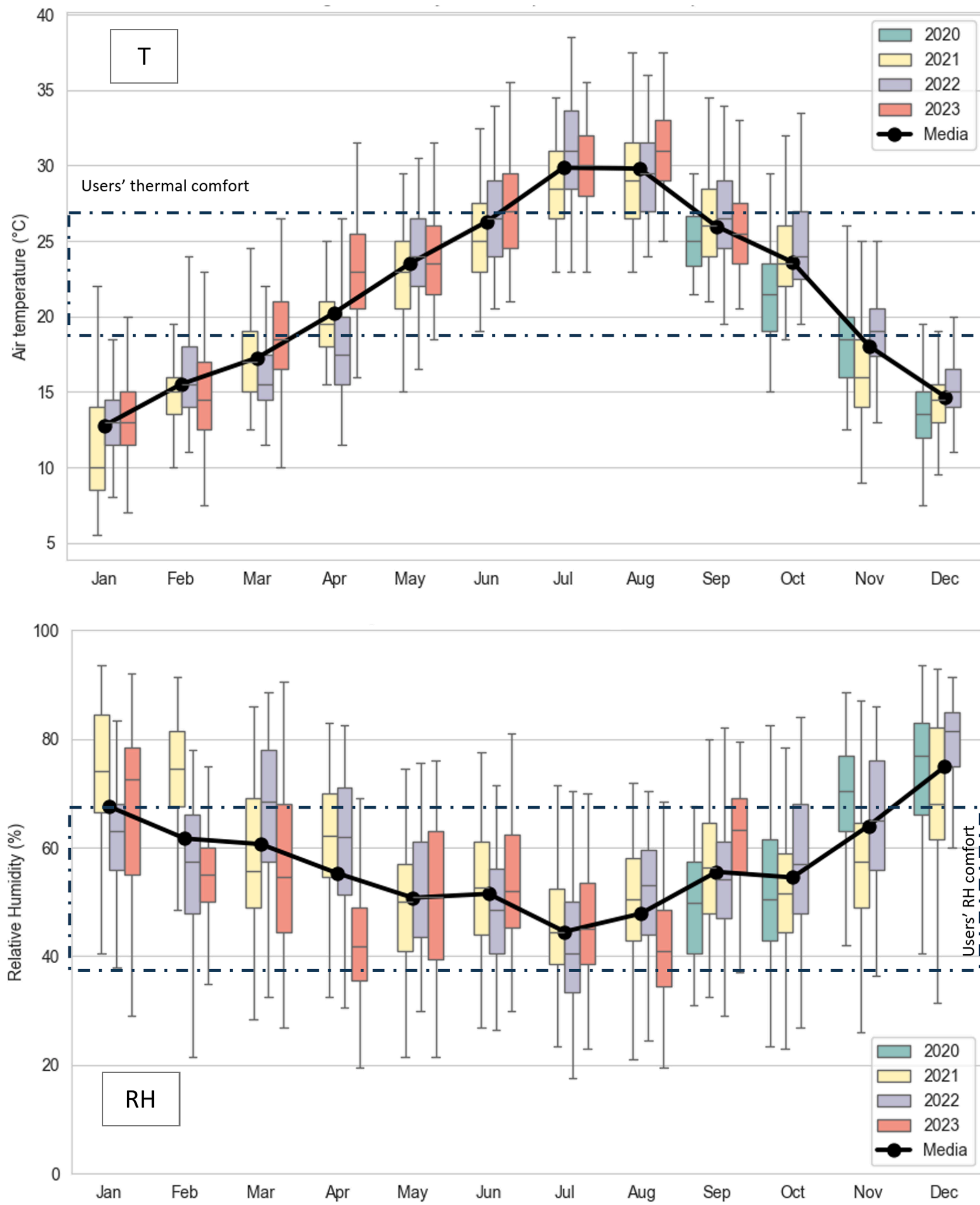

Fig. 5. Monthly T and RH from September 23rd, 2020, to September 23rd 2023 period.

Exposure to excessively high levels of RH can lead to various health issues, such as respiratory discomfort, the exacerbation of allergies, and an increased risk of respiratory diseases such as asthma, as well as the increment in the proliferation of mold and fungi. In this case, it was observed that the courtyard significantly reduces the high RH levels recorded during the autumn and winter months (Fig. 6).

The coefficient of determination R^2 of 0.7029 indicates that approximately 70.29 % of the variability in indoor temperature can be explained by the variability in outdoor temperature using the applied regression model. This suggests a significant relationship between both variables, implying that outdoor temperature has a considerable influence on indoor temperature (Fig. 7 – left). Similarly, the relationship between the hourly RH outside and inside the courtyard was positive but weaker, with an R^2 value of 0.5949 (Fig. 7 – right).

These findings corroborate previous studies on the positive impact of courtyards in reducing energy demand [46], but also provide new evidence regarding their heat retention capacity during the night and during heatwaves. These results highlight the importance of

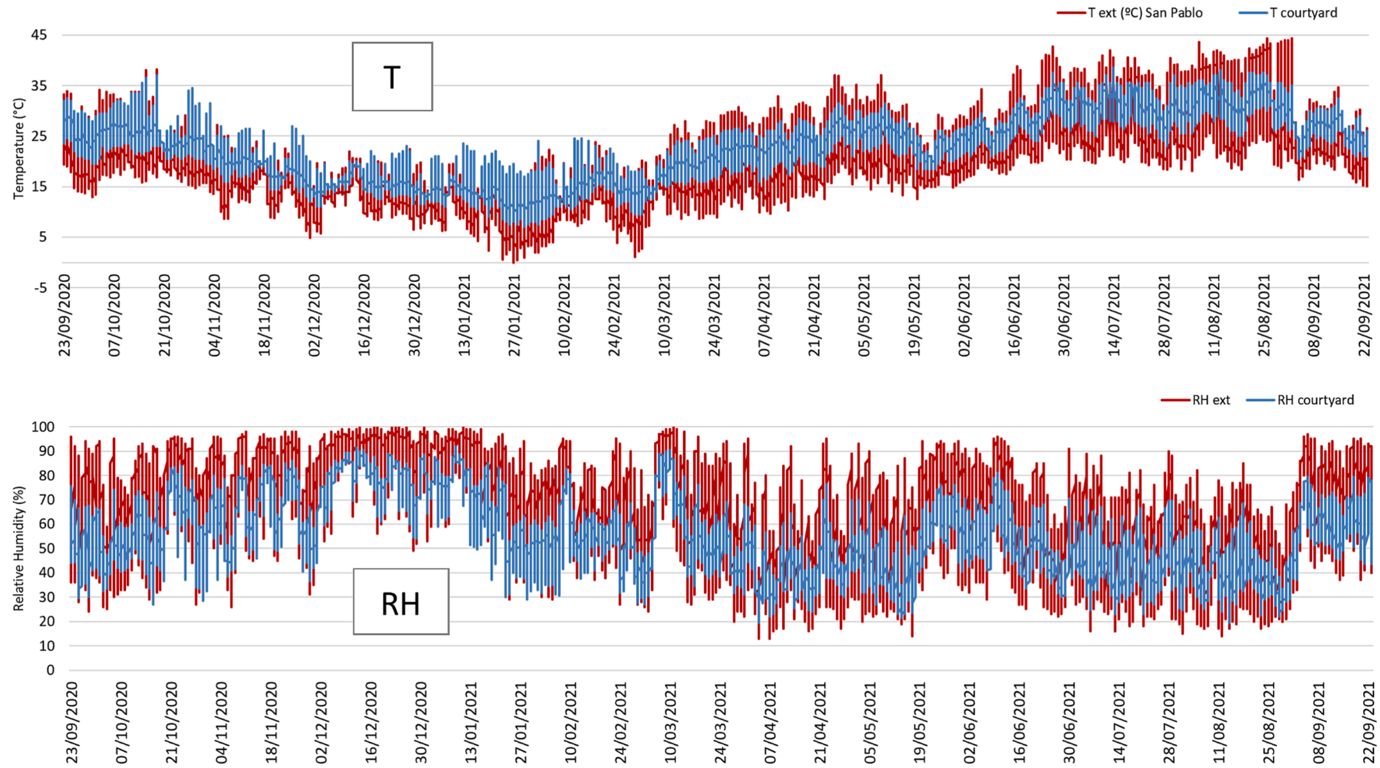

Fig. 6. T and RH during a year period (from September 23rd, 2022 to September 22nd, 2023).

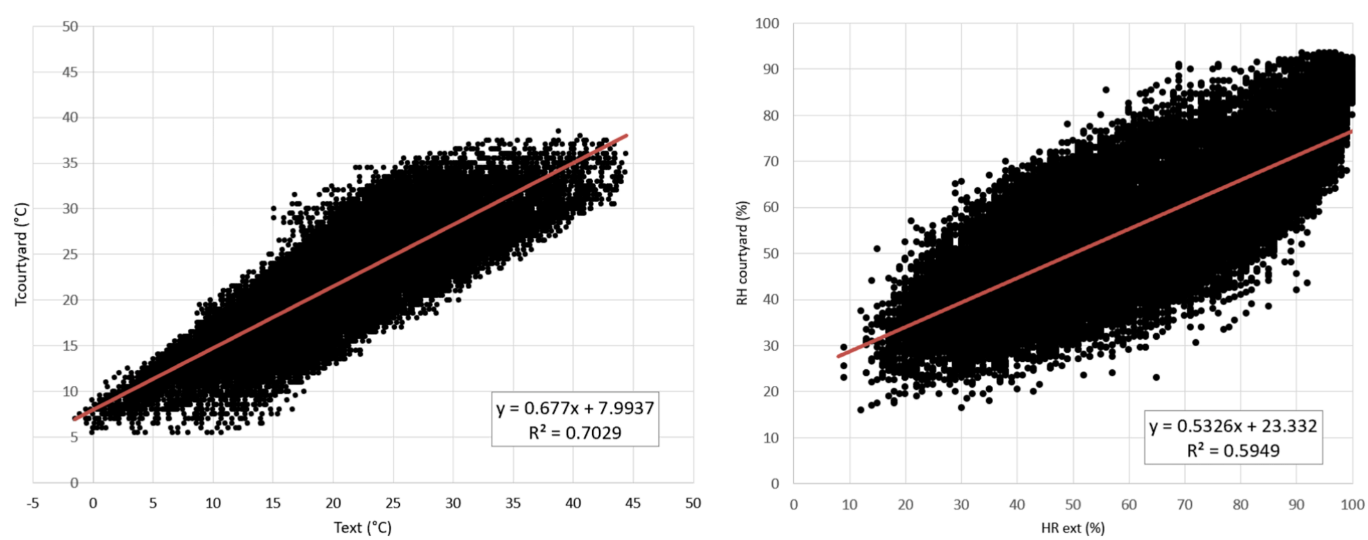

Fig. 7. Three –years period T and RH analysis (from September 2020 to September 2023).

incorporating seasonal variations in future research on passive design strategies in warm climates.

5.1.1. *Thermal conditions during HW periods*

The study of hourly temperatures of the courtyard alongside the HW periods in comparison with the temperatures of these days outside – retrieved from AEMET open source database[93] – was depicted in Figs. 10 and 11. A t-student test was conducted to determine whether the variance of these two variables was equal or not. For this purpose, the Fisher test was conducted ($\alpha = 0.01$), rejecting the null hypothesis, and indicating that temperature variances of both groups are not equal. The *t*-test for two samples assuming unequal variances, with a significance level of $\alpha = 0.01$, indicated that there is a significant difference between both variables [$t(-2.747) = 2.578$, $p = 0.00$]. In both statistical analyses, the size of the sample was 1,800 (i.e., hourly temperatures retrieved from 75 days of HW).

Previous studies have shown that the courtyard temperature was between 3 °C and 15 °C lower compared to the exterior temperature during peak heat hours [50]. Similarly, Sánchez de la Flor et al. have shown that when the T_a is below 30 °C, TG is approximately 5 °C, whereas if the outside temperature exceeds 42 °C, TG increases to 12 °C. Consequently, greater fluctuations in outside temperature result in a more pronounced effect within courtyards, leading to a reduction in maximum temperature [46]. In other words, the building design seeks to prevent overheating when highest T_a outside. This point was corroborated by previous research in the field, which indicated that the efficacy of Mediterranean courtyards as passive systems increases as outdoor temperatures rise [77]. However, despite extensive research on the thermal behaviour of courtyards, no comprehensive study has previously analysed their environmental conditions specifically during heatwave periods. This study addresses this gap by evaluating how extreme summer conditions influence temperature retention and

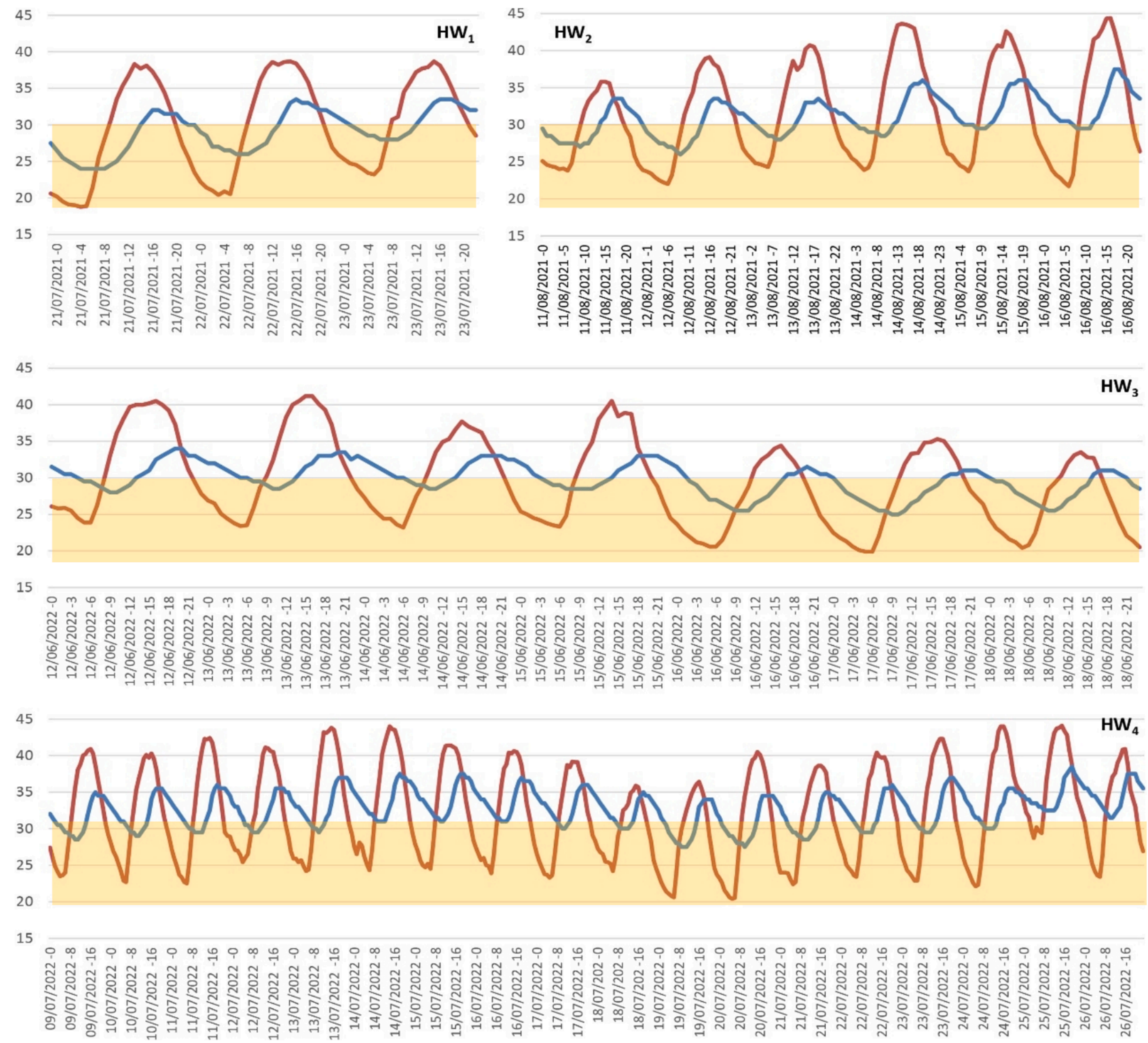

Fig. 8. Daily T recorded during HW periods: HW$_1$ to HW$_4$.

Table 4
Analysis of Tdamp and Tlag considering Tmax and Tmin during HW periods.

Designation of the period		T max				T min			
		Thermal damp	**SD**	**Thermal lag**	**SD**	**Thermal damp**	**SD**	**Thermal lag**	**SD**
Specific analysis of each HW	HW$_1$	5.57	0.64	4.00	1.00	5.20	0.40	1.33	1.53
	HW$_2$	6.03	1.95	2.50	1.52	4.85	1.70	2.67	0.82
	HW$_3$	5.16	2.12	6.00	2.16	4.97	0.40	3.00	1.53
	HW$_4$	4.82	1.83	3.06	1.16	6.28	1.15	3.94	1.00
	HW$_5$	2.37	1.43	2.00	0.89	5.54	0.96	3.88	1.59
	HW$_6$	6.15	1.42	2.00	1.15	5.68	1.61	2.50	1.00
	HW$_7$	5.50	0.98	2.25	1.26	4.65	1.37	2.50	0.58
	HW$_8$	5.93	1.96	1.75	1.67	6.10	1.48	2.38	0.92
	HW$_9$	5.91	1.03	1.56	1.13	5.99	0.63	2.00	0.71
In total	75 HW days	**4.81**	**2.06**	**2.68**	**1.76**	**5.67**	**1.20**	**3.08**	**1.38**

dissipation within the courtyard.

Different conclusions can be drawn from the Fig. 8, where red lines indicate the outside T_a, blue lines represent the T_a in the courtyard and yellow shadows highlight the optimal T_a range: i) the TG is much greater outside than in the courtyard; ii) when temperatures decrease noticeably outside (see days 4, 5 and 6 of HW_2 in Fig. 8) the T_a in the courtyard is cushioned and does not drop so abruptly, iii) the greater the TG outside, the more relevant the heat sink effect of the courtyard is.

When analysing the thermal conditions in the courtyard during the heat wave (HW) in the studied period (Fig. 8), it becomes clear that the highest temperature peaks in the courtyard consistently occur in the late afternoon, between 6 and 7p.m. In contrast, outdoors, the maximum temperature typically occurs earlier, between 2 and 4p.m. The noteworthy observation is that within the courtyard, the peak of maximum T_a is delayed, and the TG decrease by approximately 5 °C under extreme hot conditions and almost 6 °C when T_{min} is considered (Table 4). Essentially, the courtyard's heat-dissipating effect is more efficient under extreme weather conditions, as long as they are not prolonged. This implies that the courtyard's effectiveness might diminish if extreme environmental conditions persist. Over the past 3 years, the peak of highest temperature in the courtyard typically occurs between 6 and 7 in the evening, while the peak of lowest temperatures occurs between 8 and 9 in the morning. Indeed, the thermal lag (T_{lag}) for T_{max} usually occurs with a delay of 2 h relative to the peak of T_{max} outdoors and with over 3 h of delay in the case of the peak of T_{min} outdoors (Fig. 9). This observation facilitates improved management of users and events within the premises.

5.1.2. Hygrothermal comfort. PET & ST_c indices

The comfort zone proposed by Olgyay, with a T_a range of 19.5 °C to 27.8 °C and a RH range of 35 % to 65 %, provides a foundational guideline for achieving thermal comfort in both buildings and urban spaces. In Mediterranean climates, practical applications require flexibility and adaptive strategies to ensure comfort across varying conditions. By adjusting the temperature range to account for seasonal variations in humidity and employing bioclimatic design principles, such as proper orientation, shading, and natural ventilation, it is possible to extend the comfort zone. This adaptability enhances the

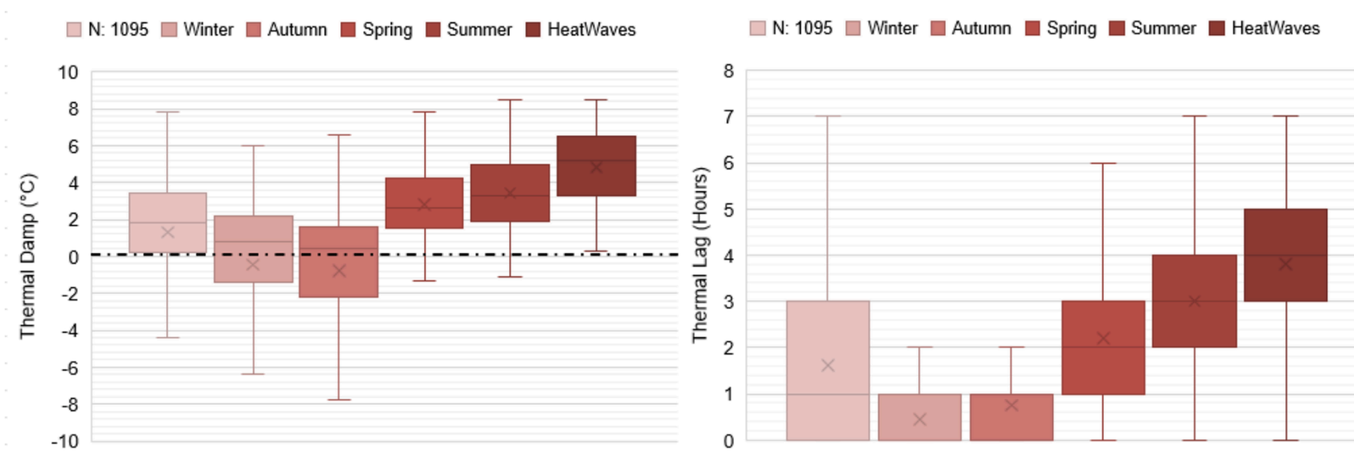

Fig. 9. Analysis of daily Thermal Damp and Thermal Lag during 3-years-monitoring.

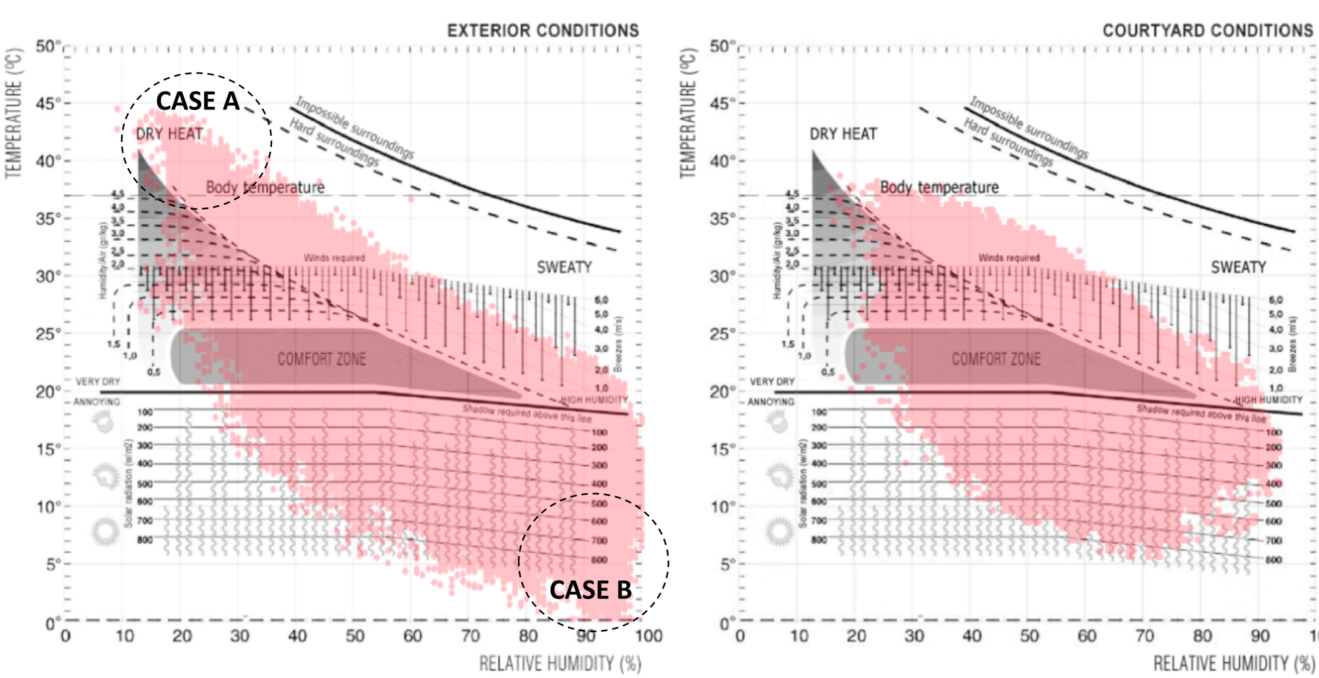

Fig. 10. Olgyay diagram applied to the Courtyard of the Maidens: Conditions during three-years period outside (left) and inside the courtyard (right).

overall well-being of users in both indoor and outdoor urban environments, ensuring comfort without significant disturbances in Mediterranean climatic conditions.

The analysis of environmental conditions records shows that only the 10.67 % of the records fulfil with the ideal for human comfort (i.e., 2,804 points out of 26,280). However, comfort values are better than those obtained in other Mediterranean courtyards without bioclimatic passive elements [92] and Fig. 10 demonstrated that the courtyard is an element that significantly reduces extreme uncomfortable situations (i.e., ambient conditions of 40 °C and an RH around the 20 % or 5 °C together with an RH of 90 %):

- CASE A: Environments identified by high T_a and low RH values promote heat stress, dehydration, respiratory problems, and a decrease in physical and mental performance. In this point is relevant to mention that the courtyard effect implies a reduction in a 3 % these situations (477 records out of 26,280).
- CASE B: Highly humid environments, with a RH above 80 % can lead to various health problems such as respiratory difficulties, fatigue, discomfort, skin irritations, or even dehydration. The proliferation of mold and fungi can also worsen indoor air quality, affecting respiratory health and triggering allergies. Not to mention the preservation issues of materials at these humidity levels (e.g., plasterwork). It is crucial to take measures to control humidity, such as using dehumidifiers and proper ventilation, to mitigate these risks and maintain a healthier environment. Fig. 10 indicates a reduction of the 7 % of this type of extreme comfort situation (1,765 records out of 26,280).

Similarly, the climatic conditions observed outside and inside the courtyard during HW periods reveal significant conclusions regarding their impact on individuals' comfort and the effectiveness of such passive bioclimatic strategies. Meanwhile outside temperatures exceed 40 °C and a RH of 20 %, inside the courtyard the maximum T_a is 35 °C and the RH is 25 %. Thus, the risk of dehydration decreases and a more tolerable and safer environment for individuals is created for users (Fig. 11).

The results highlight the importance of taking measures to improve environmental conditions in this specific case study. This could involve adjustments to heating, cooling, ventilation systems or the implementation of more efficient architectural design strategies in terms of hygrothermal comfort. For instance, a fabric covering the courtyard during summer months will provide shade to mitigate the perception of heat [94], while incorporating radiant flooring in the perimeter galleries could enhance thermal comfort during winter.

The sensation of comfort fluctuates over time [76], and individuals' satisfaction is contingent upon their expectations and influenced by past experiences or previous situations [95]. While the perception of optimal temperature varies among users, previous studies have determined that in Mediterranean climates, the optimal temperature range is 24 °C–28 °C in summer and 18 °C–22 °C in winter. Similarly, the comfortable relative humidity during summer ranges between 40 %–60 %, while in winter it varies between 50 %–70 %. Therefore, it is important to establish transition zones (i.e., courtyards or galleries), facilitating a seamless transition from areas where individuals feel comfortable to less neutral environments. Moving from an uncomfortable zone to a more comfortable one is easier to accept even if the change is abrupt.

In this specific case study, results indicate a clear predominance of slightly cool, comfortable, and slightly warm perceptions, reaching a 77 % of the total recorded hourly temperature (n: 26,280). The thermal sensation is comfortable mainly during autumn and spring seasons, almost 20 % of the total recorded hourly temperature. On the contrary, during the summer season, moderate heat stress stands out (8.27 % of the total recorded hourly temperature) (Fig. 12). Thus, measures to mitigate these ambient conditions should be taken to prevent insolation or heatstroke.

Regarding the ST_c (Fig. 13), almost the 30 % of the records indicate an ST_c index less than 25 which mean, problems related to dehydration or heatstroke will hardly ever occur. Almost a 16 % of the records reveal an ST_c index between 30 and 35, indicating a low risk. In the contrary, only a 6 % of the measurements indicate an elevate ST_c, recommending short time exposition.

Considering that Cohen et al. [96] defined the 'neutral' range of thermal sensation in the Mediterranean climate between 19 and 26 °C, the courtyard only overheats during the hottest hours in summer and up until the early hours of the night during HW (i.e., the 27 % of the total sample [n:26,280]).

When comparing the results obtained from the analysis of the PET index and the STC index both in the courtyard and the exterior, it becomes evident again that the courtyard mitigates extreme temperatures, reducing both the intensity of cold and heat, while also tending to increase average temperatures.

5.2. Architectural heritage conservation from the point of view of ambient conditions

By applying criteria established in UNE-EN 15757:2010, a general analysis of the RH variable was undertaken and the subsequent graphical representation was depicted in Fig. 14. The permissible ranges of relative humidity (RH), based on historical measurements, should be between the lower and upper limits defined by the 7th and 93rd percentiles. In the analysed case, the upper RH limit is occasionally exceeded throughout the 3-year period, without significant impact on the conservation of building materials. However, the lower RH limit is consistently surpassed during prolonged periods, primarily in the summer months, indicating the need to regulate humidity through passive or active conditioning strategies during these intervals.

The $HMR_{hs}(T_a)$ index calculated tanks to T_a values monitored during 3-years-period in the courtyard and outside the courtyard was –0.04262 and the one corresponding to RH [HMR_{hs} (RH)] was 0.05362 (Fig. 15). Negative values for the HMR_{hs} index indicate that the mean temperatures are nearer to the lower bound of the time series data, suggesting that the risk is more associated with low temperatures than with high temperatures. In this case, both results indicate low risk of damage.

In relation to PRD indices (Fig. 15), they were also calculated for T_a and RH inputs, and results indicate PRD indices among 0.051 and 0.055, depending on the material (See Table Embedded in Fig. 14). PRD index is used to assess the likelihood of damage based on certain environmental factors, such as T_a or RH. A value close to 0 suggests a low risk of damage, while higher values would indicate a greater risk. In this case, values between 0.051 and 0.055 suggest that the materials are at minimal risk from the ambient conditions being measured.

The Courtyard of the Maidens stands out due to decorative plasterwork corresponding to different architectural styles, along with the wooden carpentries and ceilings, and ceramic tiling on the walls. A brief graphical analysis of T_a and RH parameters indicated that almost the half of the measurement taken during the 3-years-period of monitoring (42 %) fulfil the requirements to preserve the construction materials present in the Courtyard of the Maidens (Fig. 16).

To deeply understand the implications of durability for conservation in these materials, it is essential to identify how ambient conditions affect them and to be aware of the standard ranges or reference values established for their proper preservation:

- When temperatures drop below 0 °C, the processes of freezing and water expansion can cause the swelling of plasterwork and carpentry. To mitigate frost problems, a saturation module (ratio between open porosity and total porosity) lower than 75 % is recommended, as this ensures that the material does not have freezing problems [97]. In this specific case study, there was not $T_a < 0$°C.

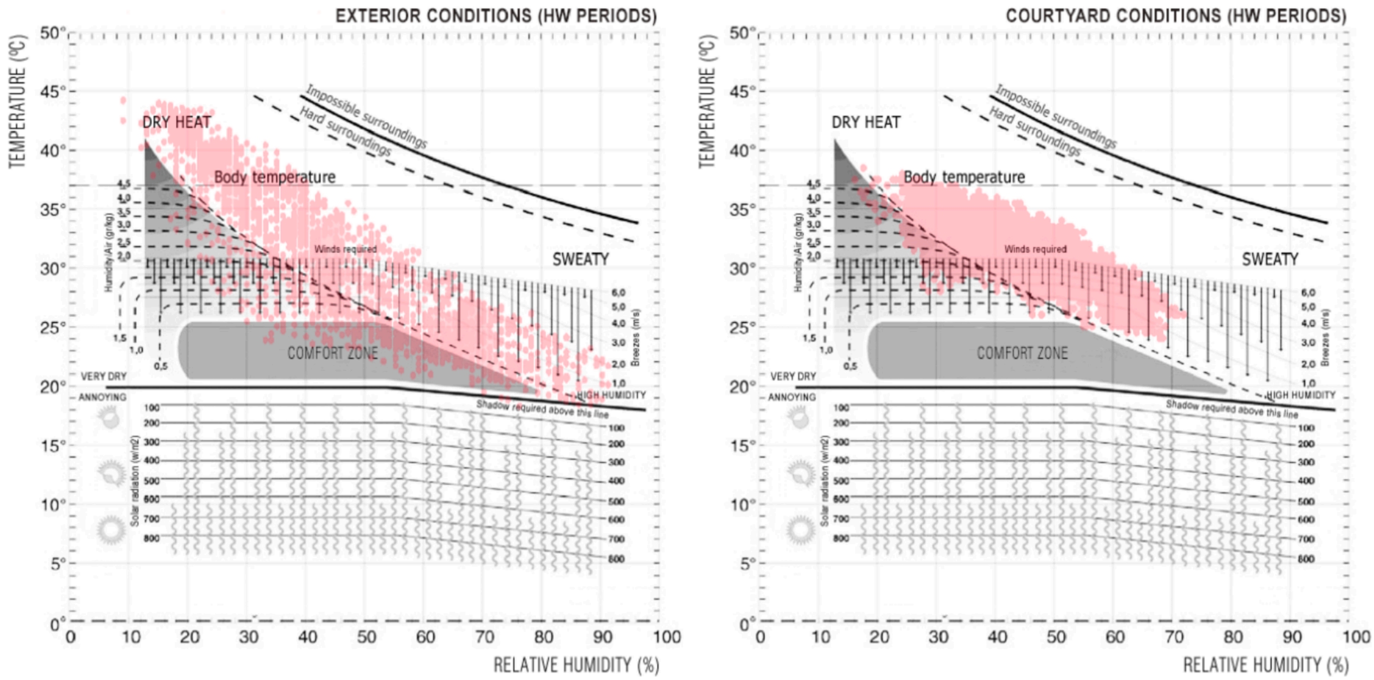

Fig. 11. Olgyay diagram applied to the Courtyard of the Maidens: Conditions during HW period outside (left) and inside the courtyard (right).

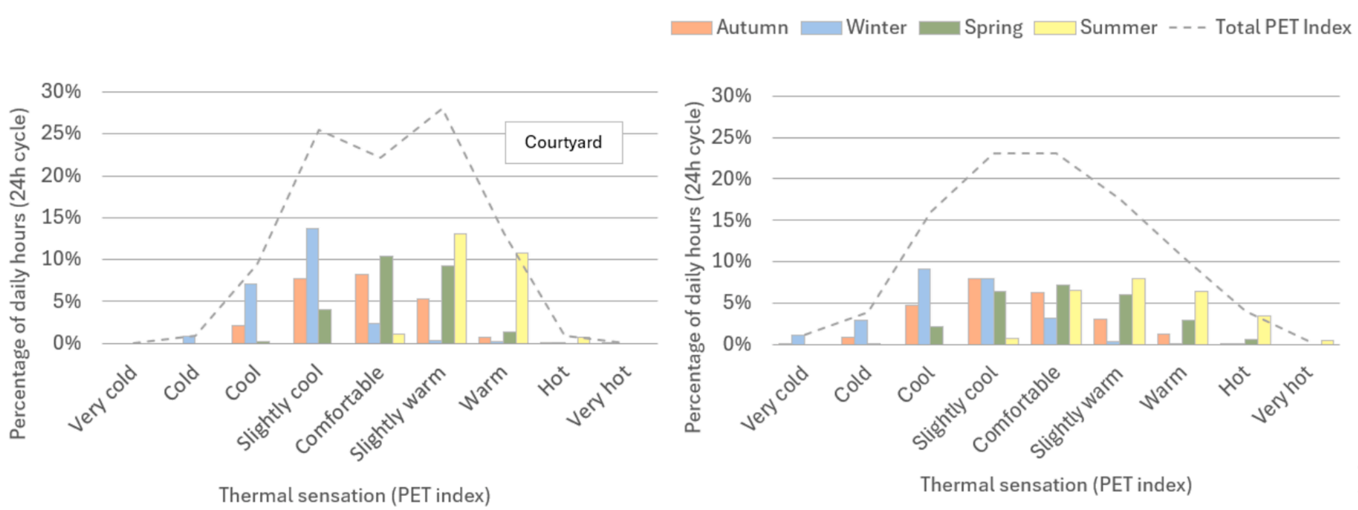

Fig. 12. PET index by seasonal periods during 24 h three-years-monitoring carried out in the Courtyard of the Maidens.

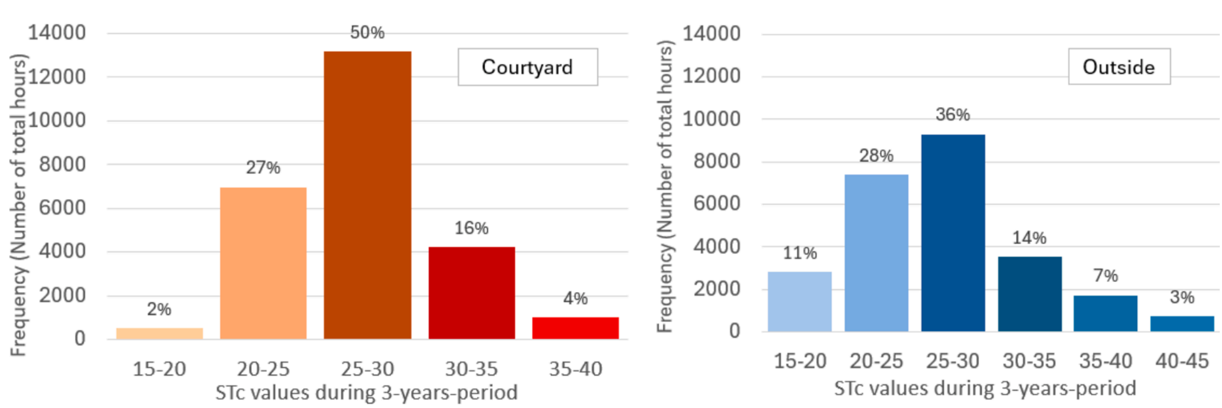

Fig. 13. STc Indices results during 24 h three-years-monitoring carried out in the Courtyard of the Maidens.

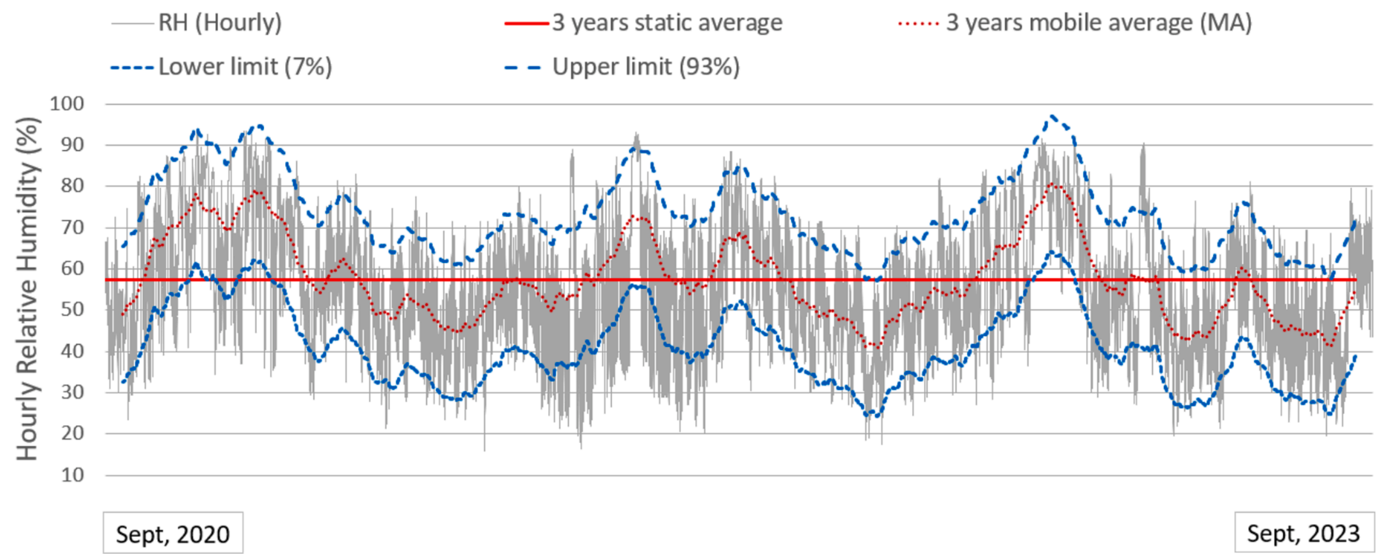

Fig. 14. Preventive conservation limits according to UNE-EN-15757:2011.

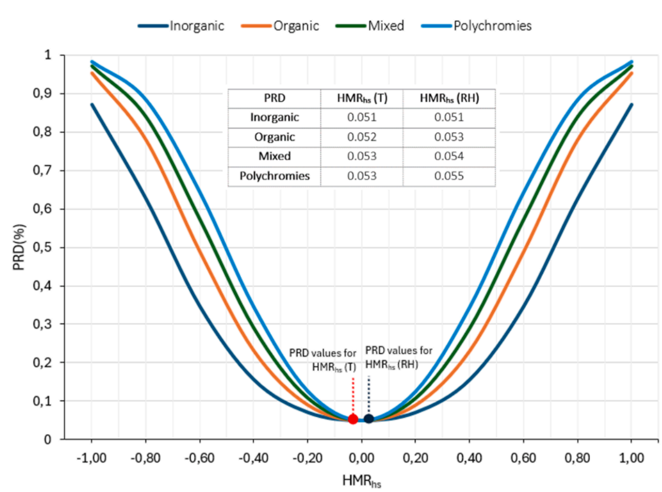

Fig. 15. Results of the HMR and PRD Indices for the Courtyard of the Maidens based on the values of HMR_{hs} (T_a) and HMR_{hs}(RH).

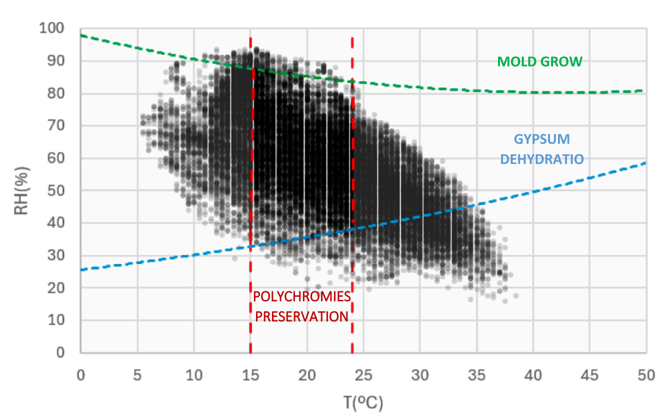

Fig. 16. Dispersion graph of the measurements from 23/09/2020 to 22/09/2023 at the southeast corner of the Courtyard of the Maidens.

- Temperatures below 10 °C can lead to the cracking or stiffening of pictorial layers, while temperatures between 10 °C and 24 °C are ideal for preserving polychromies. As it can be shown in Fig. 16, only 613 records remained below 10 °C (~2.33 % of the total dataset). This figure is not significant for two reasons. Firstly, it represents a very small percentage of the measured points. Secondly, and more importantly, the points with temperatures below 10 °C do not correspond to a continuous timeframe; they are measurements taken at isolated hours over different days or months. As a result, the material does not suffer any damage.
- For ceramic and glazed elements, a temperature range of 15 °C to 25 °C is recommended, whereas wooden heritage objects should be kept between 19 °C and 24 °C [32,98]. Thus, more than the half of the monitored points are within these ranges (55 %), which is a relevant figure to ensure the preservation of ceramic and wooden elements with regards to T_a recorded in the courtyard.
- High RH can lead to the adsorption of water, softening and decohesion of plasterwork, and the proliferation of microorganisms and pollutants in plasterwork and carpentry [32,99,100]. Most moulds thrive when the RH reaches approximately 70 % and temperatures fall within the range of 5 to 45 °C, with the optimal growth temperature being between 25 °C and 30 °C. A critical or high-risk condition for mould development occurs when the humidity exceeds 80 % for a duration of 6 h to 2 weeks [101–103]. In this context, a 14.37 % of the RH values recorded were above the 75 % RH and a relevant 21.64 % indicated a RH higher than 70 %. These results were not concerning since the measurements were again isolated in time and did not occur continuously over several consecutive days.
- For ceramic and glazed materials, fluctuations in temperature should be limited to ± 2°C and RH should be maintained between 45 % and 60 % to avoid damage [32,98]. This point should suppose a serious risk to take into account due to the fact that TG is around 10 °C during HW periods (See Fig. 8) and even higher during winter periods. Moreover, only a third part of the measurement taken are within the range 45 % and 60 % so stakeholders should take measures to combat this situation through passive or active mechanisms that regulate both parameters.
- Finally, low RH combined with temperatures above 40 °C can cause dehydration, transformation into basanite, and loss of mechanical resistance. Thus far, this issue has not posed a threat, as the combination of high temperatures and low relative humidity primarily occurs during heatwaves, which typically last between 4 and 9 days.

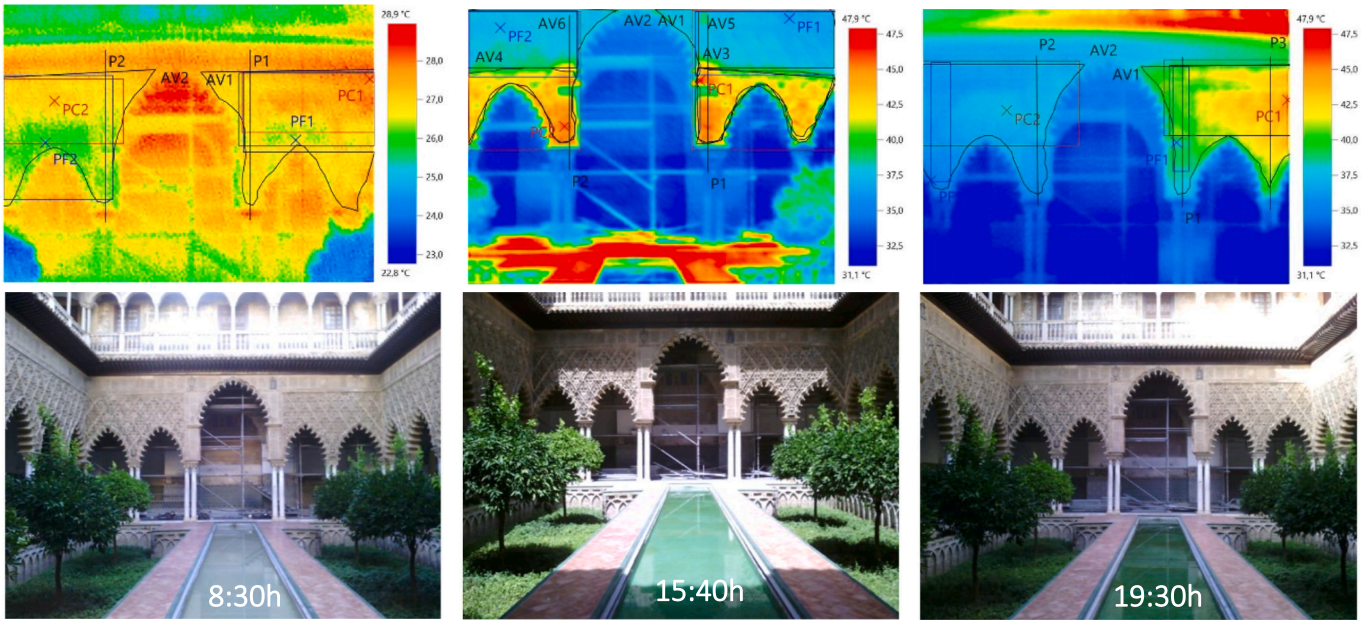

Fig. 17. IRT images taken during the 10/07/2023 (HW_6).

Table 5
Tsup in the plasterwork cladding (HW_6).

Time	T_a (°C)	Area 1				Area 2			
		Min. T_{sup} (°C)	Max. T_{sup} (°C)	AVG. T_{sup} (°C)		Min. T_{sup} (°C)	Max. T_{sup} (°C)	AVG. T_{sup} (°C)	
8:30 h	26	25.70	28.40	27.00	27.00	25.30	27.60	26.50	26.50
15:40 h	45	35.80	46.60	42.00	42.00	36.70	45.80	42.30	37.60
19:30 h	37	37.40	46.30	41.10	41.10	34.30	37.50	36.30	36.30

This combination could be very detrimental to the preservation of the material if exposure to these environmental conditions were to continue for approximately a month. So far, the longest heatwave recorded in the last 3 years has lasted 18 days, which does not pose an immediate risk. However, climate change is gradually increasing temperatures and creating drier conditions, which could present a significant risk to the preservation of the material in the near future.

The results obtained from the thermographic images were presented in Fig. 17 and Table 5, showing the minimum, maximum, and average surface temperatures on the left and right plaster panels of the northeast façade of the courtyard. Although the reached surface temperatures do not pose a risk to the preservation of the plasterwork, it is important to note an increase of 20.90 °C in Area 1 and 20.50 °C in Area 2 over a 24-hour period. This TG in the material is not significant because plaster is a hygroscopic material that adapts to environmental conditions and subsequently regains equilibrium. However, the detected change in surface temperature does affect the mechanical relationship between the plasterwork of the gypsum panels and the wooden support to which they are anchored, as well as the mechanical relationship between the decorative gypsum volumes and the metal nails used for their attachment to the panels, due to the difference in the coefficients of expansion of wood (longitudinal coef.: $\alpha \approx 3$–5×10^{-6} °C^{-1}, radial coef.: $\alpha \approx 20$–30×10^{-6} °C^{-1}, and tangential coef.: $\alpha \approx 30$–50×10^{-6} °C^{-1}), metal ($\alpha \approx 11.8 \times 10^{-6}$ °C^{-1}), and plaster ($\alpha \approx 12 \times 10^{-6}$ °C^{-1}). Consequently, cracking of the plaster and the detachment of fragments become the most significant issues [104].

6. Conclusions

The study conducted in the Courtyard of the Maidens (Seville, Spain) over three years reveals the increasing impact of climate change on Mediterranean regions. The courtyard's microclimate demonstrated a linear increase in air temperature of approximately 1 °C per year, consistent with broader Mediterranean trends. July was the hottest month, with an average temperature of around 30 °C, while January recorded the lowest temperatures at 12 °C. Notably, February and March exhibited deviations from the upward trend, indicating more complex climatic dynamics.

Relative humidity decreased by 3 % over the study period, aligning with the broader drying trend observed in Seville's climate. December exhibited the highest humidity levels at 75 %, whereas July had the lowest at 45 %. Despite these fluctuations, temperature and humidity conditions in the courtyard generally remained within acceptable comfort ranges. Passive strategies such as vegetation, water features, and shaded galleries were effective in maintaining comfort, although extreme heatwaves continued to pose challenges, particularly during the hottest summer months. In autumn and winter, many conditions fell outside of the ideal comfort ranges.

Courtyards proved to be effective thermal buffers, with statistical analysis revealing a strong correlation between indoor and outdoor temperatures. The temperature difference between the courtyard and the outside during heat peaks was 4.06 °C, while during cold spells, it was 5.67 °C. These findings underscore the courtyard's potential to mitigate temperature extremes, thereby reducing reliance on active heating and cooling systems, which in turn contributes to overall energy conservation.

The study also highlights the broader role of courtyards in Mediterranean climates, not only in enhancing indoor comfort but also in facilitating energy conservation. As climate change continues to affect Mediterranean cities, courtyards offer a sustainable, passive solution for urban spaces. The research emphasises their importance in creating more resilient and comfortable environments, ensuring long-term energy efficiency and occupant well-being in the face of rising temperatures.

Courtyards not only contribute to the thermal efficiency of buildings, but also create a more stable and protected environment for the conservation of delicate materials, such as wood and plasterwork. This effect has been historically harnessed in Mediterranean and Islamic vernacular architecture to preserve the integrity of interior and ornamental finishes. Courtyards maintain a more stable thermal gradient, reducing the exposure of materials to extreme fluctuations in temperature and humidity. In this way, excessive expansion and contraction of wood are avoided, reducing the risk of warping, cracking, and decay, while also minimising the occurrence of fissures and detachment caused by abrupt temperature or humidity changes in the case of plasterwork. However, while the passive strategies implemented in the courtyard tend to increase humidity—an adverse factor for the preservation of materials such as wood and plasterwork—the findings presented in this study demonstrate that the environmental conditions to which the various finishes in the Courtyard of the Maidens have been exposed have not contributed significantly to material degradation. According to the HMR and PRD indices, no substantial risk to the materials has been identified. Specifically, the plasterwork has not been affected by the abrupt temperature and humidity fluctuations associated with heatwaves or colder, rainier days. These fluctuations occur on specific days and do not persist for extended periods, meaning that, at present, they do not result in significant damage to the internal structure of the material.

CRediT authorship contribution statement

M. Torres-González: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **L. Rodríguez-Antuña:** Software, Data curation, Conceptualization. **D. Bienvenido-Huertas:** Supervision. **J.M. Alducin-Ochoa:** Data curation, Conceptualization. **M. León-Muñoz:** Visualization, Software. **C. Rubio-Bellido:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the R&D project 'Potential of Positive Energy Buildings for Climate Change Adaptation and Energy Poverty Mitigation' (PID2021-122437OA-I00), funded by the Ministry of Science, Innovation and Universities.

The authors express their sincere gratitude to the Board of Trustees of the Royal Alcázar of Seville for granting permission to conduct this scientific research and for their invaluable collaboration in promoting the history of this UNESCO World Heritage site.

Data availability

Data will be made available on request.

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