Enhancing Urban Microclimates Towards Climate-Resilient Cities: The Potential of Courtyards

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Abstract The increasingly urgent phenomenon of global warming has a critical epicentre in the topic of urban thermal comfort, which is significantly influenced by the urban heat island effect. In this built environment, creative thinking is required to shape pleasant, healthy, and sustainable microclimates, and not only urban planners and designers but also researchers and software developers are all involved in the search for feasible solutions, tools and opportunities. This chapter evaluates the potential use of one of the most dominant urban configurations in historic Mediterranean cities, the courtyard, as a promising thermal tempering solution to mitigate the impact of climate-related events. The methodology to evaluate the potential of the courtyard microclimate as a climate-responsive strategy follows a top-down approach. Firstly, the relevance of courtyards at city-scale is evaluated in two historic city centres in Spain, Seville and Cordoba. Secondly, six representative courtyards are characterised and monitored to evaluate their thermal benefits. Thirdly, alternatives to improve courtyard performance are discussed and tested in two scenarios. Finally, an urban CFD software to support efficient courtyard design is evaluated in case studies. The results show that this building configuration is highly representative of both historic urban contexts, with approximately 80% of existing plots having inner courtyards. Moreover, the monitored data demonstrates the potential thermal benefits of courtyard microclimates, which can reduce outdoor peak temperature from 6.8 up to 14.3 °C during the hottest days. The analyses show that courtyards with a height/width relation (aspect ratio) above 3 perform better, especially with additional shading devices to reduce solar gains. Finally, the study demonstrated the need to develop more procedures to accurately simulate the specific microclimate of these deep, small-scale spaces as a climate-resilient strategy for buildings and cities, to efficiently mitigate the impact of extreme heat wave events.

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1 Introduction

Human activity is estimated to have already caused approximately 1.0 °C of global warming above pre-industrial levels, which is likely to reach 1.5 °C between 2030 and 2052 (IPCC 2018). Changes in many extreme weather and climate events in Europe have been observed since them, and in particular after 2000, including heat waves, which now occur more often and last longer (IPCC 2014; European Environment Agency 2019). Moreover, the projected frequency of heat waves is greater for southern and south-eastern Europe, especially in the Mediterranean areas (Cramer et al. 2018, 2019), where the effects will be exacerbated in large cities due to the urban heat island effect (European Environment Agency 2019), whose magnitude ranges from 0.4 to 11 °C (Garshasbi et al. 2020). Such heat waves will reduce work productivity, and increase morbidity (e.g.: dehydration, heat stroke and heat exhaustion) and mortality (IPCC 2014; WMO and WHO 2015). Urgent actions to strengthen resilience to climate-related hazards in vulnerable hot-dry cities are required, in line with Sustainable Development Goal 13 (SDG13) defined by the (United Nations 2015). Climate-resilient pathways should be addressed from building-scale to urban planning in order to mitigate climate risks and improve the comfort and well-being of citizens (Garshasbi et al. 2020).

In this context, the tempering and mitigation potential of specific urban technologies began to receive greater attention in the last decade, in the development of climate-resilient urban solutions, including the production of highly reflective materials, cool pavements, water-based technologies, urban greenery or green roof technologies, among others (Akbari et al. 2016). However, most of these solutions focused on outdoor public spaces (Akbari et al. 2016), with few studies evaluating the mitigation potential of semi-outdoor spaces, or the inner courtyards of building blocks arranged as buffer spaces (Yang et al. 2020). Inner courtyards represent an important, representative feature of Mediterranean cities, especially in the case of historic city-centre layouts.

Courtyards are an efficient strategy to improve the thermal and microclimatic conditions of urban spaces (Zamani et al. 2018). Moreover, they play an essential role in the buildings´ environmental performance because they create specific microclimates that differ markedly from regular outdoor climatic conditions (Naboni and Havinga 2019). The courtyard acts as storage for cool air during the night when the temperature drops to minimal values. The cool air is then distributed around the indoor space during the hotter periods of the day (Hassan et al. 2016). The thermal performance of the courtyard also depends on proportion, orientation, geometry, opening characteristics and materials (Zamani et al. 2018). Deep courtyards perform better thermally than shallow courtyards in hot, dry areas (Johansson 2006). Temperatures are lower in and around the courtyards due to a decrease in sun exposure compared to the surrounding areas (Naboni and Havinga 2019). Furthermore, this effect can be improved if the courtyard is surrounded by a balcony or an arched portico, or by the presence of vegetation, water and shading devices (Aldawoud 2008; Zamani et al. 2018). In addition, the shaded areas provided by the courtyard to the building have a considerable impact on indoor cooling energy demand due to the reduction of solar gains (Cantón et al. 2014).

Recent studies have demonstrated the benefits of courtyard blocks compared to other block typologies. Natanian et al. 2019 applied an automated parametric analysis to evaluate the performance of different urban building configurations. The results highlighted the courtyard archetype as the most favourable urban building design in hot climates. Chi et al. 2020 demonstrated the potential use of a courtyard as a passive cooling and heating strategy to reduce energy consumption by 23%. Almumar 2019 showed how positioning the courtyard within the land plot so that main façades receive sun in the winter and block out most of it in the summer contributed to the natural heating and cooling of the house. Asfour 2020 evaluated the optimal configuration of courtyards and atriums to improve daylighting performance while reducing energy demand. The results showed how the most efficient, balanced alternative was the courtyard or atrium configuration, with a window-to-wall ratio of 30%, together with shading devices. (Guedouh et al. 2019) demonstrated that courtyard depth, opening ratio and orientation remain crucial elements in optimizing the balance between courtyards' thermal and luminous environments. Rodríguez-Algeciras et al. 2018 highlighted the aspect ratio (AR) as the most important parameter influencing courtyard thermal conditions.

However, the area required and the associated urban land cost are the major reasons for rejecting the internal courtyard technique, despite its beneficial function as a thermal regulator (Hassan et al. 2016). Further studies are still required to evaluate and highlight the importance of this vernacular building configuration, and to provide design guidelines and decision-support tools to enable correct implementation of these strategies to enhance the climate-resilient capacity of buildings and cities that will experience extreme climate-related events. Currently, no urban modelling tools exist to evaluate the benefits of these urban microclimates. Moreover, current building energy simulation (BES) tools do not consider the tempering potential of these buffer spaces, opting for historical weather data that fail to take into account the urban microclimate effects. New procedures are needed to evaluate the urban climate implications in building performance (Shen et al. 2019) and the potential thermal interactions of buildings with specific urban microclimates (Samuelson et al. 2020).

This paper evaluates the peak-temperature mitigation potential of traditional courtyards in two historic Spanish cities in the Mediterranean area, Seville and Cordoba. The aim is to quantify the benefits of these building typologies and define decision-support criteria for future urban planning in order to mitigate the impact of heat waves in hot climates. The relevance and impact of these urban microclimates are evaluated from city-scale to specific courtyard configuration and simulation in order to emphasize the function of these traditional spaces in historic urban contexts, quantify their benefits and identify the optimal courtyard configuration.

The chapter is structured as follows. First, the methodology is described. Material and methods for each assessment scale are detailed, and urban case studies are characterised. Second, the results are presented and discussed in five sections: courtyard relevance at city-scale; performance of representative courtyards; testing of improvement techniques; validation of simulation tools; and limitations of the study. Finally, future research activities to satisfy existing needs in the implementation of these urban microclimates are reported.

2 Methodology

The methodology to evaluate the potential of courtyards as a climate-responsive strategy to mitigate the impact of extreme heat events in cities consisted of a top-down approach. The evaluation procedure was divided into four steps, from city-scale to specific courtyard monitoring, testing and simulation. An overview of the methodology is illustrated in Fig. 1.

The methodological steps were: the evaluation of the relevance of courtyards at city-scale in two historic, non-coastal cities in southern Spain; the characterisation and monitoring of six representative courtyards to evaluate their thermal benefits; the testing of alternatives to improve courtyard performance in two case studies; and, the validation of existing urban CFD tools for courtyard simulation in two scenarios. The materials and methods used in each methodological step are detailed in Sect. 2.1. Finally, the urban contexts used as a case study are defined and characterised in Sect. 2.2.

2.1 *Materials and Methods*

In the first step, the existence and relevance of courtyards in the selected urban cities were evaluated using the QGIS geographic information system (QGIS 2017) according to the methodology defined by Rojas-Fernández et al. (2017). Data for urban context characterisation was collected from a Spanish government database capable of generating shapefile vector files (Gobierno de España 2017). These files

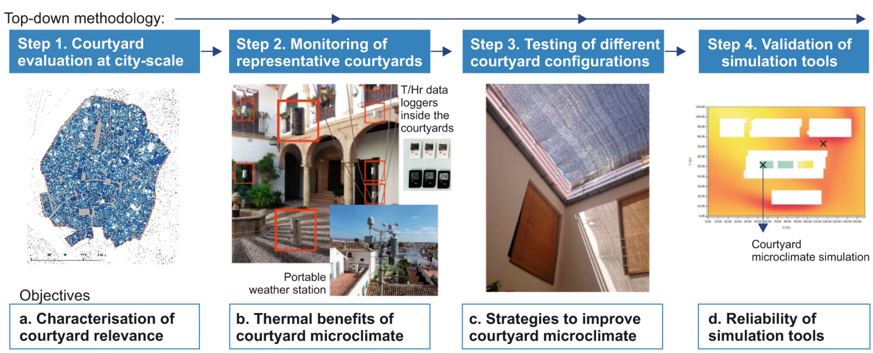

Fig. 1 Overview of the methodological top-down assessment

follow the infrastructure for spatial information provided by the European Union's INSPIRE directive (EU 2007). Then, the percentage of plots with courtyards in the urban context studied, the plot porosity index (PI) and net plot porosity index (NPI) were calculated. PI is the ratio between the void area and total plot area, considering all urban plots in the studied area according to Eq. (1). NPI provides the mean percentage of the courtyard surface using the mean ratio between void area and plot area, considering only the urban plots with courtyards according to Eq. (2). Finally, the number of courtyards per size and the most representative courtyard geometry were obtained through the mean ratio of height and width according to Eq. (3), namely the aspect ratio (AR). AR is an indicator that characterizes courtyard geometry, widely used in the literature, with another common parameter, the sky view factor (SVF), which shows the fraction of visible sky according to Eq. (4) (De Wolff 2008; Dirksen et al. 2019).

$$PI = \frac{\sum \text{Void area per plot}}{\sum \text{Total area of plot}} \tag{1}$$

where

PI Plot porosity index

$$\text{NPI} = \frac{\sum \text{Void area per plot}}{\sum \text{Total area of plot with courtyard}} \tag{2}$$

where

NPI Net plot porosity index

$$AR = \frac{H}{W} \tag{3}$$

where

AR Aspect ratio
H Courtyard height
W Courtyard width

$$SVF_{2D} = \cos\left(\arctan\left[\frac{H}{0.5W}\right]\right) \tag{4}$$

where

SVF Sky view factor

H Courtyard height
W Courtyard width.

In the second step, the performance of the most representative courtyards was evaluated during a one-week monitoring campaign, following the procedure reported by Rivera Gómez et al. 2019. A set of six courtyards was selected, all located inside buildings. Selection criteria were based on the most representative characteristics in terms of the courtyard area, geometry and surface albedo. The selected courtyards had AR values ranging between 0.8 and 7.1. The outdoor urban temperature in each urban context was recorded by a portable weather station (model PCEFWS) located on the roof of each building; and the courtyards' indoor temperature was monitored by data loggers protected from direct solar radiation (model TESTO 174 T) placed at different heights (1 and 2 m). The final courtyard temperature obtained was a mean value between both measurements. Different monitoring campaigns were carried out in the courtyards throughout the summer season with a minimum duration of one week each.

In the third step, the improvement potential of courtyard performance through the implementation of shading devices was tested in two case studies in Seville and Cordoba, following the criteria reported by (Lopez-Cabeza et al. 2020). Two courtyards were selected in Seville and Cordoba with an AR value of 0.72–0.96 and 1.57–1.46, respectively. Both courtyards have a similar wall finish, white mortar coating and some windows. The same shading device was installed in both cases, a black canvas mesh installed at the top of the courtyard, with some separation from the walls to allow ventilation. The fabric of the canvas cover was black polyethylene of 60–70% UV filter and 70 g/m^2 density. The equipment and procedure for data collection were similar to the previous campaign. Both courtyards were monitored with, and without, the shading devices during a full summer day, with peak temperatures at over 40 °C.

Finally, the effectiveness of powerful calculation software, based on computational fluid dynamics (CFD), to simulate the performance of these specific microclimates was evaluated in two courtyard scenarios. ENVI-met software was selected as the most suitable tool to evaluate the performance of outdoor spaces (Acero and Herranz-Pascual 2015; Ketterer and Matzarakis 2015). ENVI-met can simulate interactions between buildings, soil, vegetation and air. The effectiveness of this CFD tool in the prediction of the thermodynamic performance of courtyards was evaluated by comparing field data with simulated results in two case studies in Seville, following the procedure defined by (López-Cabeza et al. 2018). The selected courtyards had an AR value of 4.1 and 1.4. The equipment and procedure for data collection were similar to those previously defined in step 2. The case studies were modelled and calibrated through a manual iterative calibration process. Finally, different standardised statistical indices were calculated to ascertain the accuracy and reliability of the proposed tool for simulating the courtyard microclimate. The indices selected were Root Mean Square Error (RMSE), Systematic Root Mean Square Error (RMSEs), Unsystematic Root Mean Square Error (RMSEu) and the coefficient of determination

(R2), widely used in the literature (Coakley et al. 2014). Two temperature indicators were compared using these statistical indices in each case study: one inside the courtyard and another in the building surroundings.

2.2 Study Areas

Two historic urban contexts in Seville and Cordoba (Spain), illustrated in Fig. 2, were selected to evaluate the existence and performance of traditional Mediterranean courtyards. These two historic city centres are characterised by narrow streets of irregular shape, and building topologies based on traditional and vernacular architecture, influenced by the Roman, and later Muslim, historic periods. Their climates are similar, both are located in the valley of the Guadalquivir river, with relatively mild winters and very hot summers.

These scenarios were selected due to the marked presence of the traditional Mediterranean courtyard, and to the increase in heat wave events during last decade (AEMET 2019), which registered temperatures higher than those previously recorded for the 2003 heat wave that affected southern and central Europe, or for the 2010 heat wave that hit eastern Europe (European Environment Agency 2019). Moreover, the projected monthly mean temperature in the twenty-first century for these Andalusian regions is set to rise by up to 4.2 and 4.8 °C (Fig. 3), for Seville and Cordoba, respectively (Junta de Andalucía 2019), considering the A1B scenario of the IPCC's Fourth Assessment Report (IPCC 2007).

3 Results and Discussion

The results are presented as follows. First, the relevance of courtyards in the selected urban cities is shown. Second, the performance of the most representative courtyards

Fig. 2 **a** Historic urban context of Seville. **b** Historic city centre of Cordoba

is analysed. Third, strategies to enhance courtyard performance are evaluated. Fourth, courtyard performance is simulated using a CFD urban modelling tool, highlighting the needs and requirements for efficient courtyard installation for climate-resilient cities. Finally, limitations of the study are discussed.

3.1 The Relevance of Courtyards in the Two Mediterranean Cities

The results of the percentage of plots with courtyards and the total courtyard surface in the selected urban contexts are summarised in Table 1. The porosity index (PI) and net porosity index (NPI) were also calculated. PI provides the percentage of the void area considering all urban plots. NPI shows the percentage of the void area considering only plots with courtyards.

Courtyards are highly representative of both these historic city centres due to their Mediterranean tradition. Seville and Cordoba are characterised by a large number of plots with courtyards, exceeding 6000 and 3000 inner courtyards, respectively. The percentage of plots with a courtyard ranges between 77 and 82%. Moreover, the mean surface percentage of courtyards is higher in Cordoba (NPI: 19%) than in Seville (NPI: 16%).

Figure 4a illustrates the plot porosity index (PI) in both urban contexts, Fig. 4b is a zoomed picture of each urban context, and Fig. 4c shows the most typical size of courtyards in each historic city centre.

The historic urban context of Seville is characterised by a mean plot porosity of 12%, lower than the historic urban context of Cordoba, with 15%. The relevance of courtyards can easily be identified in the zoomed picture of each urban context (Fig. 4b), where each white inner square represents existing inner courtyards. The right bar graphs (Fig. 4c) also show that the most representative courtyard surfaces range between 5–10 m^2 and 10–15 m^2, whose mean AR values are 3.7 and 3.1 for Seville and Cordoba, respectively.

Table 1 Porosity and percentage of plots with courtyards in the selected urban contexts

	Seville	Cordoba
Total urban context size (m^2)	2,853,558	1,830,447
Total urban plots	8139	4625
Plots with courtyard	6263	3790
Percentage of plots with courtyards (%)	77%	82%
Total courtyard surface (m^2)	384,504	267,956
PI (%)	12%	15%
NPI (%)	16%	19%

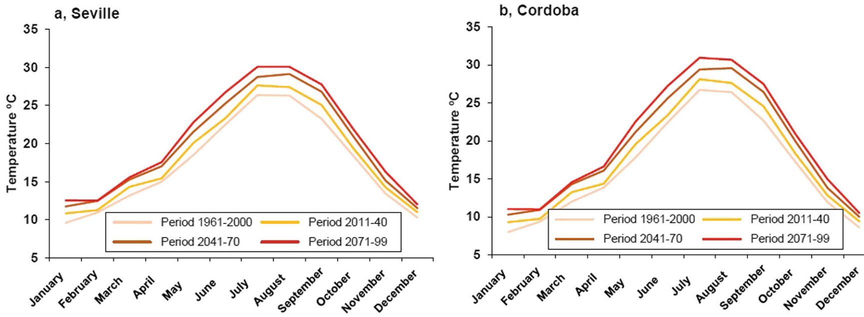

Fig. 3 Projected monthly mean temperature throughout the twenty-first century. Data collected from the (Junta de Andalucía 2019). **a** Region of Seville. **b** Region of Cordoba

3.2 The Benefits of Courtyard Microclimate as a Passive Cooling Solution

The performance of six representative courtyards was evaluated to assess their benefits as a passive cooling strategy. The schematic plans and sections of the selected case studies are illustrated in Fig. 5. Table 2 summarises the characteristics of the courtyards.

The selected case studies were monitored on different days, with a minimum of one week during summer, with maximum temperatures always higher than 40 ºC. Figure 6 shows the evolution of maximum and minimum daily temperatures throughout the monitored period inside the courtyard compared to outside urban temperature oscillation.

The results show that maximum peak temperature reduction was obtained during hotter days. Seville courtyards reduced peak temperature by up to 14.3, 14.8 and 9.7 ºC for CSA1, CSA2 and CSA3, respectively, during day 4, which had the maximum peak temperature of 42.8 ºC. Cordoba courtyards reduced peak temperature by up to 7.3, 8.9 and 6.8 ºC for CSB1, CSB2 and CSB3, respectively, during day 7.

The mean temperature reduction during the monitored period of the courtyards ranged between 7 and 10 ºC for the Seville case studies, and between 4 and 7 ºC for Cordoba. The better performance of the Seville courtyards seems to relate mainly to the higher AR value of these configurations (AR between 2.58 and 7.10) and worse outside climate conditions, which enhances the advantages of courtyards. The results demonstrate that deep courtyards, which have a high AR value, perform better thermally than shallow courtyards.

Courtyards are indicated as a key element in mitigating heat wave effects and improving the passive conditioning of buildings and cities since, for all the case studies analysed, the outdoor peak temperature decreased by a mean value of 7 ºC during the week monitored, ranging from 6.8 to 14.8 ºC. The data obtained highlight how these urban microclimate configurations can play an important role in diminishing the impact of heat waves on urban overheating and building performance. In

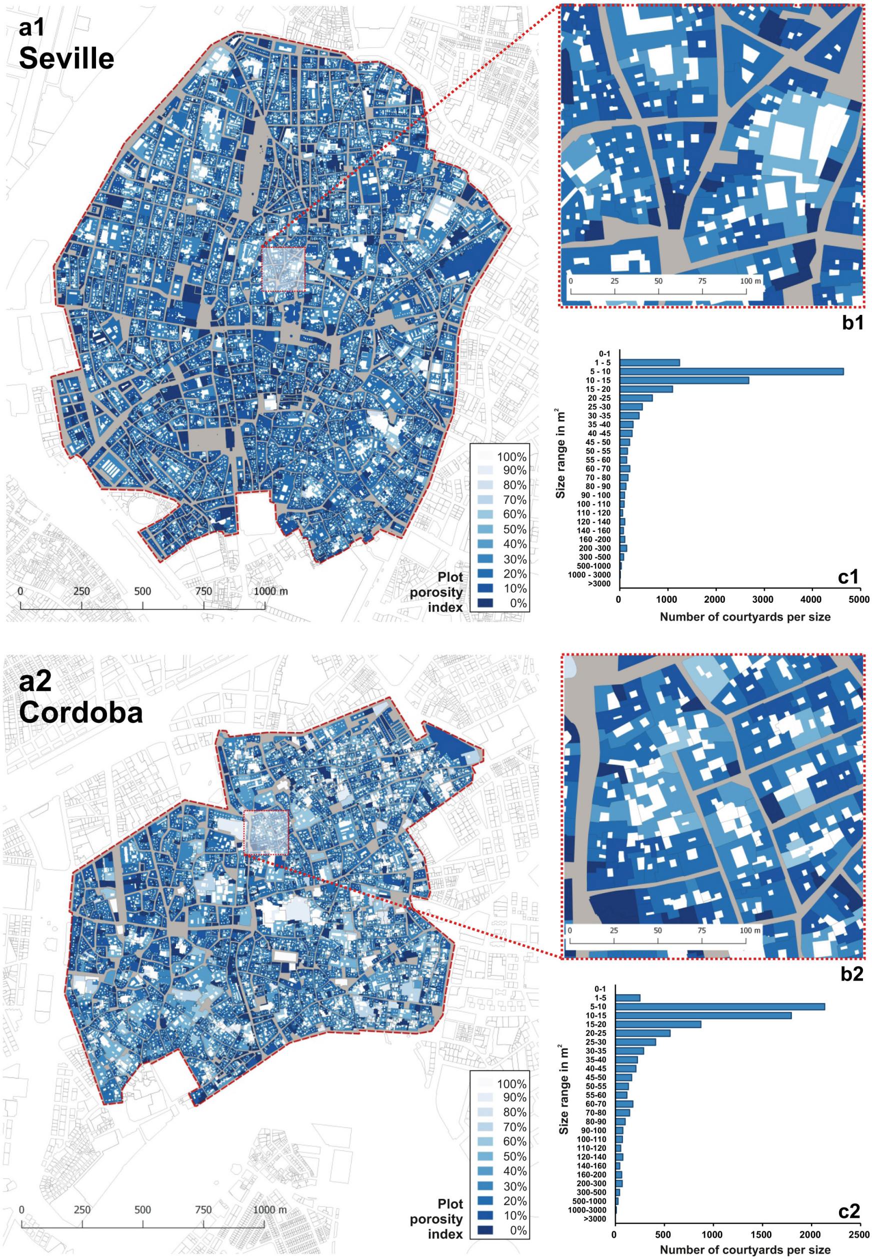

Fig. 4 Distribution and number of courtyards in the city centres of Seville and Cordoba. **a1-2** Illustration of the plot porosity index in the studied area, **b1-2** zoomed picture of each urban context, **c1-2** bar graphs illustrating the number of courtyards according to size

Table 2 Characterisation of the selected courtyards

Case study	Surface (m^2)	Dimensions (m)	Height (m)	AR I	AR II
a. Seville					
CS1A	6.4	3.2 × 2.0	14.2	4.44	7.10
CS2A	11.0	5.5 × 2.0	14.2	2.58	7.10
CS3A	12.3	3.,5 × 3.5	15.9	4.54	4.54
b. Cordoba					
CS1B	14.6	4.3 × 3.4	6.3	1.47	1.85
CS2B	65.5	8.4 × 7.8	6.8	0.81	0.87
CS3B	86.4	9.6 × 9.0	8.1	0.84	0.90

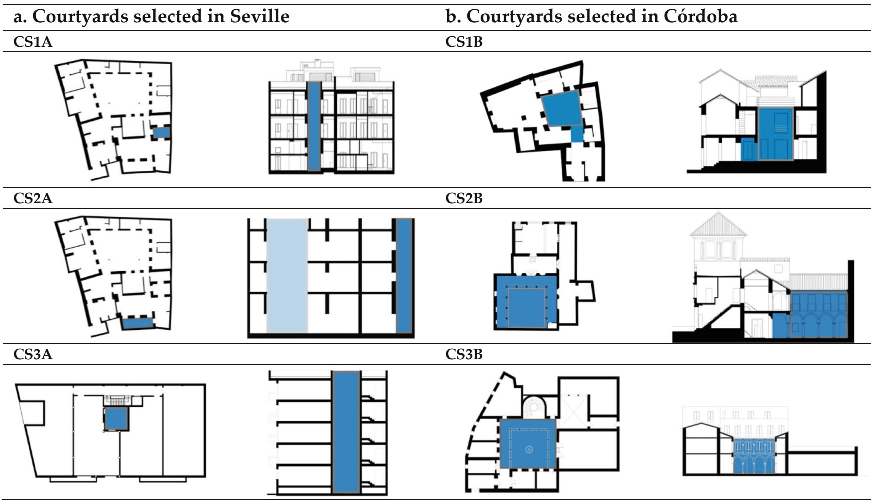

Fig. 5 Overview of the schematic plans and sections of the representative courtyards. **a** Case studies selected in Seville city centre. **b** Courtyards selected in Cordoba city centre

the next section, different solutions to improve the reported benefits are discussed and tested.

3.3 Enhancing Courtyard Performance to Create Climate-Resilient Cities

Many factors influence the thermal performance of courtyards, such as geometry and orientation, thermal mass, the albedo of the courtyard surfaces or the presence of vegetation, water and shading devices. This section evaluates the thermal benefits of shading devices to improve courtyard performance. Two case studies in Seville and

Cordoba were tested for one day during which peak temperatures exceeded 40 °C. The schematic plans and sections of the selected case studies are illustrated in Fig. 7. Table 3 summarises the characteristics of the courtyards.

Figure 8 shows the monitored results of both courtyards with, and without, the installation of shading devices.

Without shading devices, the courtyards show a reduction in outside peak temperature (in red) of 7 °C. The same peak temperature mitigation potential seems to relate to similar geometry and surface albedo in both scenarios. The difference between the maximum and minimum daily temperature, or daily thermal oscillation inside the

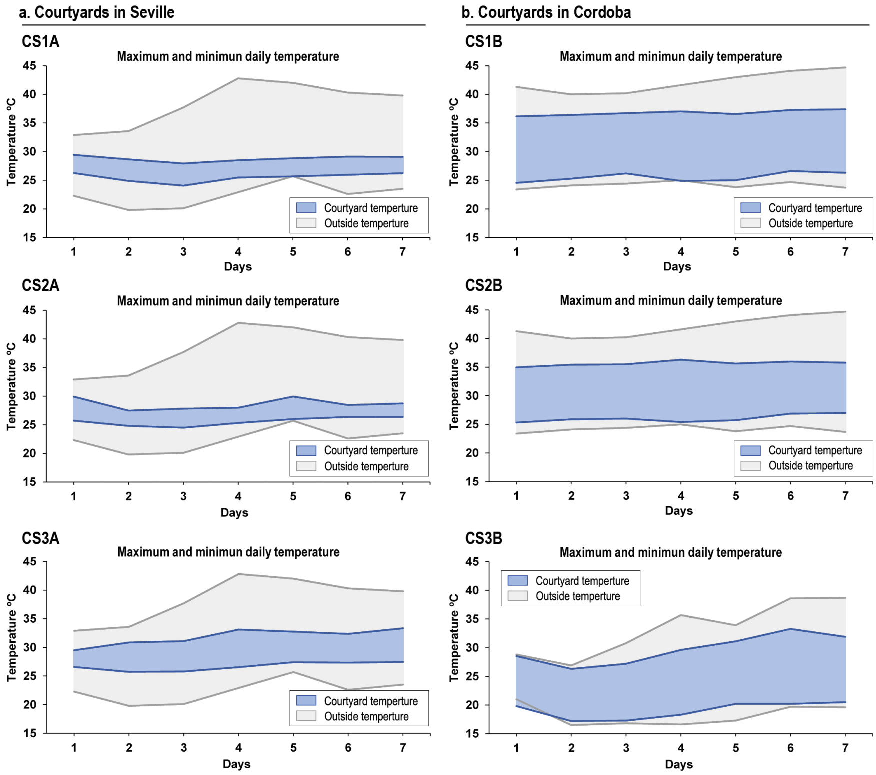

Fig. 6 Maximum and minimum daily temperatures of the courtyards monitored during one summer week, compared to outside urban temperature oscillation. **a** Case studies in Seville city centre. **b** Courtyards in Cordoba city centre

Table 3 Characterisation of the selected courtyards to evaluate the impact of shading devices

Case study	Surface (m^2)	Dimensions (m)	Height (m)	AR I	AR II
a. Seville	35.9	6.9 × 5.2	5	0.72	0.96
b. Cordoba	17.2	4.3 × 4.0	6.3	1.57	1.46

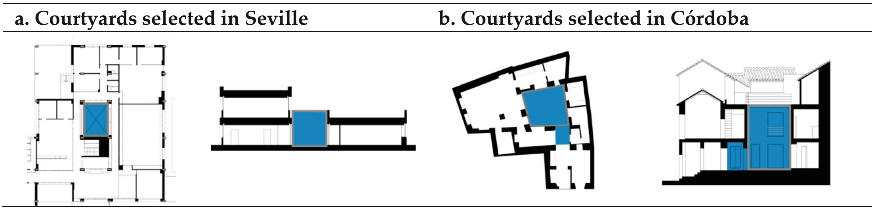

Fig. 7 Overview of the schematic plans and sections of the two case studies to evaluate the impact of shading devices

courtyards (in orange), is 13 and 12 °C, respectively. It can be observed that courtyard b1 performs better throughout the day, which can be explained by its deeper geometry (or higher mean AR value of approximately 1.5) that reduces solar radiation on the courtyard surfaces.

With shading devices, both courtyards show an increased reduction in outside peak temperature by up to 12–13 °C. The thermal oscillation in courtyard a2 is higher than in courtyard b2, which seems to be related to the lower mean AR value of approximately 0.84. However, in both cases the daily thermal oscillation is radically reduced, ranging between 4 °C and 8°, clearly improving the thermal benefits of these microclimates.

The results show the importance of mitigating solar gains inside these inner spaces in order to improve their thermal performance and reduce peak temperatures. It should be emphasized that both shading devices were installed with some separation from the perimeter to enable courtyard ventilation.

3.4 Need for New Approaches for Courtyard Microclimate Simulation

The effectiveness of ENVI-met software to simulate the thermodynamic performance of courtyards was evaluated in two case studies in Seville. The schematic plans and sections of the selected case studies are illustrated in Fig. 9. Table 4 summarises the characteristics of the courtyards.

In both scenarios, two datasets were measured and simulated during a single day, inside the courtyard and in the building surroundings. The results of the monitored data were compared with the simulated data in Fig. 10.

The monitored data in the selected courtyards show the same tempering effect previously reported. Courtyard 1 displays better performance than courtyard 2 since it is deeper and has a higher AR value, of up to 4.1, which prevents solar radiation from reaching the lowest levels. However, courtyard 1 shows a stronger overheating effect during the night due mainly to its depth, since the heat accumulated during the day does not escape easily, and the temperature of the courtyard rises during the night.

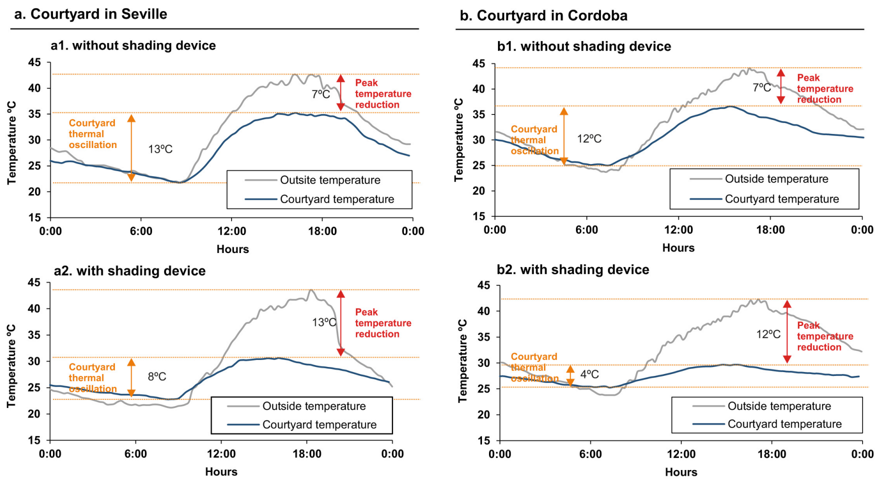

Fig. 8 Evaluation of shading techniques to improve the courtyard microclimate. **a** Courtyard performance with, and without, shading in Seville. **b** Courtyard performance with, and without, shading in Cordoba

Table 4 Characterisation of courtyards to evaluate a CFD urban modelling tool

Case study	Surface (m^2)	Dimensions (m)	Height (m)	AR I	AR II
Courtyard 1	22.9	7.4 × 3.1	12.6	1.70	4.06
Courtyard 2	99.0	7.5 × 13.2	10.7	1.43	0.81

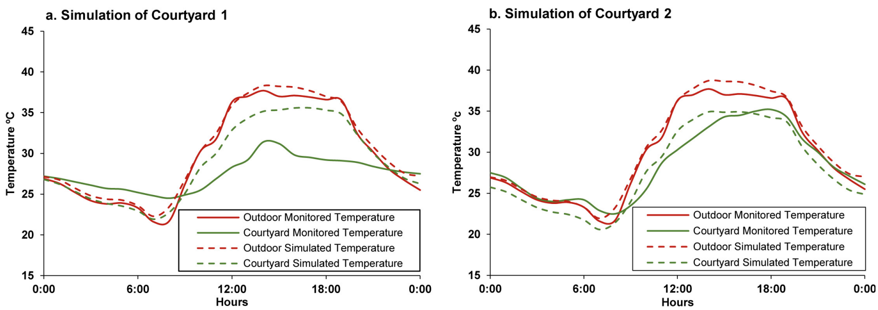

Fig. 9 Overview of the schematic plans and sections of the two case studies to evaluate a CFD urban modelling tool

Comparing the monitored and simulated data, provided in Fig. 10, it can be observed that the measured and simulated outdoor air temperatures have a similar pattern. However, the inner air temperature in courtyards is lower in monitoring than in simulation, above all in the first case, the deeper courtyard. Courtyard 1 shows the maximum divergence between monitored and simulated data, with a difference

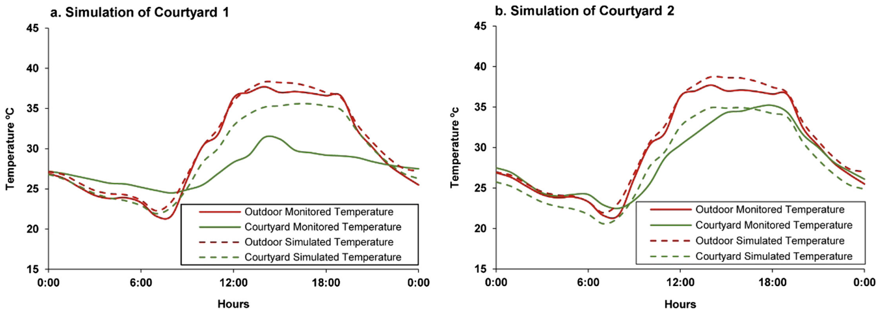

Fig. 10 Evaluation of ENVI-met software to simulate the courtyard microclimate

of up to 6 °C. In this case, ENVI-met was not able to reproduce the daytime courtyard performance. Moreover, in both scenarios, the software failed to consider the overheating effect of courtyards during the night.

The standardised statistical indices of the measured and simulated data using ENVI-met in both cases are reported in Table 5. Statistical indices were calculated for different measured and simulated points outside and inside the building block in order to determine the accuracy and reliability of the software for inner and outer urban microclimates.

The results show a highly accurate simulation of the outdoor temperatures in all models, obtaining a RMSE value of 0.77 and 0.82, and a R2 of 0.99 in both cases. In contrast, the values obtained for the air temperatures in the courtyards, despite displaying a R2 above 0.84, present a RMSE of 3.35 in the worst case. These results highlight the fact that the deeper the courtyard is, the worse the simulated performance obtained. Courtyard microclimates are characterised by small-scale outdoor urban spaces, which represent a limitation for simulation by urban CFD software. Thus, it is necessary to develop additional procedures to accurately evaluate the mitigation potential of peak temperature of these deep, small-scale traditional spaces.

Table 5 Standardised statistical indices of measured and simulated data using ENVI-met

	RMSE	RMSEu	RMSEs	R^2
Courtyard 1				
Outdoor	0.77	1.33	0.62	0.99
Courtyard	3.35	4.50	1.33	0.84
Courtyard 2				
Outdoor	0.82	1.41	0.66	0.99
Courtyard	1.52	2.10	0.88	0.93

3.5 Limitations of the Study

This research has the following limitations. First, the reported results and conclusions on the performance of courtyards are based on the assessment of nine selected representative case studies located in two Mediterranean cities throughout the summer season. Nevertheless, extensive courtyard monitoring of different scale studies and cities in Spain carried out in previous years shows similar results, which are widely detailed in (Rivera Gómez et al. 2019). Further studies with more scenarios and in different climate regions should be carried out to extend the reported conclusions to other climate areas. Second, this study focused on the temperature results at user height. Further research could use measurement points at different heights of the courtyards due to the fact that the microclimate impact of courtyards decreases according to height. Third, the performance of courtyards with and without shading devices was compared on days with peak temperatures higher than 40 °C. However, alternatives were monitored on different days, with different outside hourly temperature profiles, which may have influenced the reported absolute improvement values. And fourth, the simulation of courtyard performance using a CFD urban modelling tool was calibrated through a manual iterative calibration process, which limits optimal model achievement.

4 Conclusions

This paper has evaluated the thermal benefits of inner courtyards to mitigate peak-temperature periods during hot climate events. Courtyard microclimate performance was measured in two historic cities in Spain, Seville and Cordoba, through a top-down approach from city-scale to specific courtyard configuration and simulation in order to highlight the role of these traditional spaces in historic urban contexts, quantify their thermal benefits, identify the optimal courtyard configuration and support decision-making processes towards climate-resilient buildings and cities. Based on the results, it is possible to extract the following conclusions:

At city-scale in the two cities evaluated, Seville and Cordoba (Spain), courtyards are an important feature of both historic urban contexts. Approximately 80% of existing plots have inner courtyards in both cities, with a size ranging from 5 to 15 m^2 in the majority of cases. Moreover, in these cases, the most extended relation between height/width, the aspect ratio (AR), shows a mean value of 3.7 and 3.1 for Seville and Cordoba, respectively.

At courtyard-scale, the monitored results of the six representative courtyards evaluated in both cities highlight the temperature mitigation potential of these inner buffer spaces. Courtyard microclimates can reduce peak temperature from 6.8 °C up to 14.3 °C. The results also show that maximum peak-temperature reduction is obtained during hotter days. Thus, it is demonstrated that this building configuration acts as a powerful climate-resilient strategy to counter the effects of the projected and more frequent heat waves expected in southern and south-eastern Europe due to climate change, especially in the Mediterranean areas. The higher the outdoor temperature, the greater the climate benefit of the courtyard. Furthermore, considering all the courtyards evaluated, the AR value stands out as a representative parameter of the courtyard's thermal tempering potential. Deeper courtyards, with AR higher than 3, provide better thermal regulation than shallow courtyards.

With the aim of improving courtyard performance, this study also demonstrates the high impact of solar radiation on the courtyard microclimate. The use of shading devices boosted peak temperature mitigation during hotter days from 7 to 13 °C. Therefore, courtyard configurations that lower solar incidence will produce a better microclimate performance during hot days.

Regarding courtyard simulation tools, the results obtained confirm that existing urban CFD tools show poor accuracy in simulating the courtyard microclimate. It is demonstrated that the deeper the courtyard, the worse the simulated performance obtained. Courtyards are characterised by small-scale outdoor urban spaces, with specific boundary conditions, which limit simulation by CFD urban modelling software. Thus, additional procedures are needed to accurately evaluate the design of these thermal buffer strategies to mitigate the impact of extreme heat wave events on buildings and cities.

Finally, it can be concluded that the courtyard microclimate is a key urban strategy for mitigating the impact of extreme heat events in cities and buildings, and it could be optimised by a range of strategies to enhance its thermal buffer potential. However, further studies are required to support the efficient implementation of these urban configurations in cities. New research will be carried out to accurately predict courtyard performance and evaluate the impact of these buffer spaces on building performance, with the aim of supporting the decision-making process in the design of these promising spaces towards climate-resilient buildings and cities.

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