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Cross-evaluation of thermal comfort in semi-outdoor spaces according to geometry in Southern Spain

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ABSTRACT

Climatic events in Mediterranean cities, such as heat waves, directly affect their inhabitants. As a result, outdoor thermal comfort in urban spaces is gaining increasing research attention because it is associated with the quality of life in these cities. Significant improvements have been achieved in the adaptation of buildings; however, a similar level of resilience to climate is not observed in urban spaces.

This research proposes quantifying thermal comfort in semi-outdoor enclosed spaces according to EN16798, UTCI and PET. The study is carried out in different cities in southern Spain, employing 20 courtyards with different geometries. Results reveal courtyards as liveable rooms during most hours of the day in summer. The influence of its geometry considering AR is decisive since the impact of outdoor climate on the microclimate of the courtyard depends on it, exceeding values of 60% comfort hours (PET and EN16798) in all case studies during the warm season. When AR > 3, the courtyard reaches comfort 90–100% of the hours of the day and approximately 70–80% when the AR 2–3. In the case of the most common geometries in Mediterranean cities, with AR 1–2, >70% of the hours the courtyards are within the limits of comfort.

1. Introduction

The increase in global average temperature and the increasingly frequent heat waves, coupled with the agglomeration of 70% of the world's population expected in urban areas by 2050 (Organization UN, 2018), create the need to ensure the habitability of citizens in the urban environment. Urban overheating and the urban heat island effect (UHI), results of global warming, cause discomfort to users. However, the porosity of cities, the voids in the built mass, is particularly prominent in the traditional urban fabric of warm climate cities and has been a more comfortable space supporting social relationships since ancient times, generating a more comfortable microclimate for users. These are spaces with very different geometrical parameters (Ali-Toudert and Mayer, 2007). The built and unbuilt spaces regulate solar radiation during the day, but hinders the dissipation of accumulated heat during the nights by increasing the UHI (Lizana et al., 2022). Transitional elements such as courtyards, increasing urban porosity, generate a more comfortable microclimate for users (Shahlaei and Mohajeri, 2015). Previous literature reviews have analysed and quantified the tempering potential of these spaces in hot climate zones, as well as the influence of parameters such as shape, orientation or the impact of different

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Nomenclature

UHI	Urban Heat Island
TG	Thermal Gap
DTR	Diurnal Thermal Range
CS	Case Study
T_a	Air Temperature
WD	Wind Direction
SVF	Sky View Factor
CT	Courtyard Temperature
θ_{rm}	Outdoor Running mean temperature
MRT	Mean Radiant Temperature
PET	Physiologically Equivalent Temperature
UTCI	Universal Thermal Climate Index
CTE	Código Técnico de la Edificación
RH	Relative Humidity
WS	Wind Speed
AR	Aspect Ratio
OT	Outdoor Temperature
θ0	Operative Temperature

passive strategies applicable to courtyards (Zamani et al., 2018; Rivera-Gómez et al., 2019). The Intergovernmental Panel on Climate Change IPCC report considers global warming a profound universal problem during the last decade, intensified in the most densified areas, affecting the comfort and health of citizens (IPCC, 2018). The evaluation of thermal comfort in extremely hot climates has received increasing attention in recent years, as well as its direct relationship with society and economy (Aljawabra and Nikolopoulou, 2009). An extensive literature review on thermal comfort (Sharma et al., 2021) shows the inadequacy of a large number of thermal comfort indices, detecting the importance of quantifying the thermal environment and the shortcomings of previous studies in the field of adaptive comfort (Lin et al., 2017).

The large built-up mass in increasingly densified cities accentuates the effects of climate change due to the UHI (The European environment — state and outlook, 2020), a phenomenon that does not allow cities to cool down at night due to the high thermal capacity of materials that act as heat sinks (Oke, 1995). This urban overheating contrasts with the cooling of rural areas (Voogt and Oke, 1997), with a difference of several degrees between the two scenarios (Taleghani, 2018). Comfort standards must be adapted to the new times, considering the adaptability of users, and considering the morphology of urban architecture of the past in coexistence with that of today. In this context, the urban form configures different microclimates that generate thermal comfort for the citizens.

This paper focuses on thermal comfort in courtyards, analysing a large number of case studies covering the main typologies of courtyards in different climate locations in Southern Spain (see Fig. 1). Using the extensive database developed as part of the BETTER

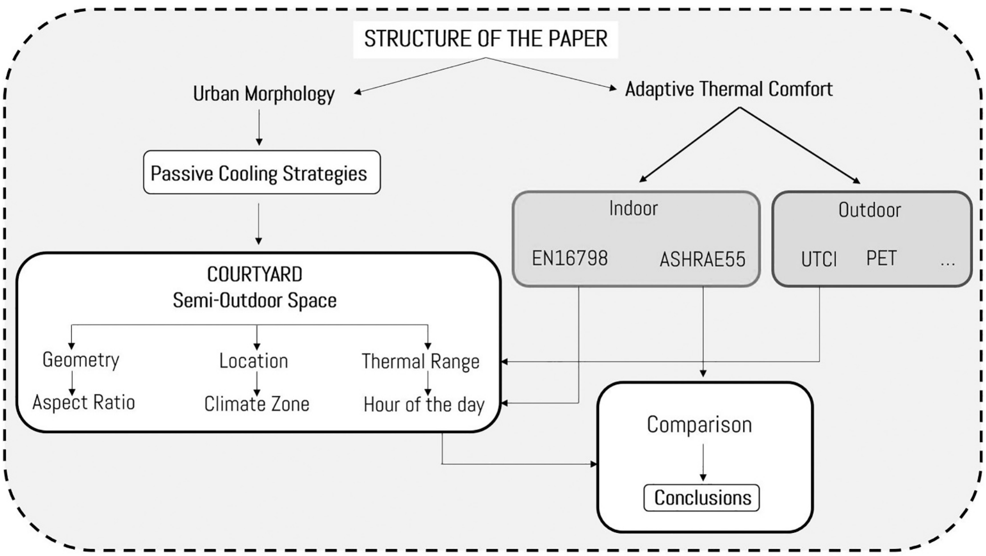


Fig. 1. Structure of the paper.

project, it analyses thermal comfort as a function of courtyard characteristics, such as shape and climatic location. Given the transient nature of courtyards, both indoor and outdoor comfort indices will be used, as previous research from the team (Diz-Mellado et al., 2021a) highlighted small differences between the application of indoor and outdoor indices in such spaces.

1.1. Urban morphology: Courtyards

In cities, different microclimates are generated due to differences in materiality, vegetation, and the urban morphology itself (Ibrahim et al., 2021). The streets or urban canyons are different from each other, as well as other urban voids such as courtyards, with characteristics that define them according to their geometry (Krüger et al., 2010), orientation, materiality, etc. (Jamei et al., 2016). The geometric configuration, the external environmental parameters (air temperature, humidity, wind speed and direction, and solar radiation), as well as the specifics of each location, generate differences in the resulting microclimate (Grimmond et al., 2010). The geometry of these spaces along with the climatic region in which they are located are the most determining aspects in defining the microclimatic conditions (Johansson, 2006).

In vernacular architecture, courtyards have been used as the nucleus of social relationships in buildings in Mediterranean cities for centuries. Furthermore, courtyards constitute the main element in terms of defining the architectural spatiality of most of these homes. For this reason, the courtyard is of great social and cultural significance in cities with a Mediterranean climate, while allowing for a closer relationship with the outside (Martinelli and Matzarakis, 2017). On the other hand, due to the temperate microclimate generated by their shape (Carnielo and Zinzi, 2013), courtyards are considered to be effective buffer spaces in cold, temperate, and warm climates (Soflaei et al., 2017a). However, until recently, these transition spaces have been neglected in building energy codes.

In recent years, documented overheating in new buildings suggests the need for a revisit of cooling regulations and strategies (Adekunle and Nikolopoulou, 2016). If courtyards could be integrated into regulations, it would support the design of buildings in a free-running mode for longer periods of the year. Previous studies by the team have shown that the courtyard can reduce the cooling demand of buildings by >7%, having a direct impact on the economy and the environment (Sánchez de la Flor et al., 2021). Advanced analysis through the use of machine learning techniques has allowed us to predict the temperature of these spaces based on their shape and the outside temperature (Diz-Mellado et al., 2021b), enabling the geometry of the courtyard to be controlled during the building design process for different climate zones. Additionally, our research highlighted the high thermal gap, of >15 °C during heat waves, identified between courtyards and outdoors, while the implementation of added passive strategies within these spaces such as vegetation or shading elements was shown to improve thermal conditions further in transitional spaces (Diz-Mellado et al., 2022). All these can encourage the use of courtyards as a design strategy for contemporary buildings, improving comfort and energy savings in Mediterranean climates.

1.2. Thermal comfort

Citizens interact with their environment, adapting to it over time (Godoy, 2012). Thermal comfort is affected by environmental parameters, i.e. air temperature, humidity, radiation, wind speed, as well as the type of clothing and activity that is performed (He et al., 2022). Current standards regulate the comfort of most buildings with automated controls, with a fully controlled environment (Nicol and Humphreys, 2010). On the other hand, there are two standards that regulate adaptive indoor comfort in free-running buildings, the European (EN16798 (Technical Committee CTN 100, 2020)) and the American (ASHRAE55 (ASHRAE-55, 2017)). Surveys conducted in previous studies show the adaptive comfort of users when the indoor temperature rises as the outdoor temperature rises in free-running buildings (Lai et al., 2020). Moreover, buildings in which users feel that they are able to adapt are perceived as more satisfactory (Shooshtarian et al., 2018).

In terms of outdoor comfort, users of urban spaces such as streets (Sözen and Koçlar, 2019), squares (Marçal et al., 2019), or parks (Chan and Chau, 2021) often perceive thermal comfort through their direct contact with the outdoors, which is a pleasant experience for citizens (Nikolopoulou and Lykoudis, 2006). This feeling is influenced by the season, cold or warm, as well as by activity levels or clothing (Xiong and He, 2022). There are different outdoor comfort indices to estimate the comfort of users, notably the Universal Thermal Climate Index (UTCI) (McGregor, 2012), or Physiologically Equivalent Temperature (PET) (Mayer and Höppe, 1987; Matzarakis et al., 1999; P. H, 1999). In the case of the UTCI, it has become the most widely used index by meteorologists worldwide (McGregor, 2012). PET, on the other hand, is a widely used index for assessing comfort perception in different climates, derived from human energy balance (Matzarakis et al., 1999). Both indices assess the comfort of people according to a heat stress scale. In addition, PET is an outdoor comfort index that can be adapted to different climate zones, which makes it more similar to the model for calculating indoor comfort standards.

Research on adaptive thermal comfort has mainly focused on the study of comfort in indoor or outdoor spaces, without highlighting the analysis of comfort in transitional spaces. Recent research (Diz-Mellado et al., 2021a) has focused on thermal comfort in the unique nature of transitional spaces borrowing methodologies from these two disparate fields. The selection of comfort indices used in this research is based on the Metamatrix Thermal Comfort (Migliari et al., 2022). The section identifying historical and geographical information and performance indices related to climatic factors, physical factors and meteorological conditions has been considered the most relevant for use in this research. PMV*, PET or UTCI stand out as the most complete indexes. Recent researches (Ma et al., 2021) have incorporated coupling models using comfort indices as a function of experimental values such as pavement porosity (Liu et al., 2022), humidity, etc. Although studies in semi-outdoor spaces such as courtyards are limited, in recent years the number of publications studying the microclimatic conditions of these spaces, using simulation tools, monitored experimental data or both (Taleghani et al., 2015), has increased.

1.3. *Research issues and aim*

Given the lack of standards and indices for thermal comfort in semi-outdoor spaces such as courtyards, this research aims to incorporate existing thermal comfort standards for indoor spaces and comfort indices for outdoor spaces (Diz-Mellado et al., 2021a), to determine the influence of courtyard geometry on thermal comfort, using several case studies. For the analysis it employs both indoor comfort models, such as the EN 16798 standard, as well as outdoor comfort models, such as the PET and UTCI comfort indexes. Previous research (Diz-Mellado et al., 2021a) has helped us to confirm the possible use of indoor comfort standards in transitional spaces such as courtyards. This could be the first step in establishing new adaptive comfort parameters for courtyards.

The high number of case studies evaluated will enable a robust comparison for a range of geometries, which can inform the discussion on how best to evaluate comfort and which of the indices is better suited to semi-outdoor spaces.

The main aim of this research is to establish a suitable approach capable of determining the potential of courtyards as thermally comfortable spaces, as well as the influence of their geometry on their ability as thermal regulators in terms of adaptive comfort. Given their hybrid nature as semi-outdoor spaces, the microclimate analysis has been performed by jointly exploring the results of standards for indoor spaces such as EN 16798 and comfort indices for outdoor spaces such as PET and UTCI.

The main novelty of this research is, besides taking a new step towards establishing new adaptive comfort indices for semi-outdoor spaces, to unravel the importance of the geometry of these semi-outdoor spaces in Mediterranean cities in the thermal comfort perception of users.

2. Materials and methods

2.1. *Overall methodology*

The methodology is divided into several sections. Firstly, the case study profile. The different selected climatic zones are defined, as well as their zoning criteria according to the *Código Técnico de la Edificación Documento Básico de Ahorro Energético* (CTE-DB-HE) (Documento Básico E, 2017) Moreover, the selected case studies are defined and characterised, divided into different ranges according to their shape (Fig. 2). Subsequently, the methods of monitoring campaigns carried out in each of the case studies are defined as well as the content of the data, methods and calculations of the comfort indices according to EN 16798, UTCI and PET. As courtyards are semi-outdoor spaces, both, the indoor comfort calculation model and the outdoor ones, are simultaneously used for analysis and comparison.

2.2. *Case studies profiling*

A set of 20 case studies located in four cities in southern Spain, characterised by high summer temperatures, were analysed. The courtyards were monitored in the summer for a minimum period of two weeks. The number of case studies made it possible to analyse and deduce the thermal comfort conditions of these transition spaces, which are widely used in the Mediterranean climate. The monitoring results were analysed in terms of the temperate potential of the courtyard as a function of the outdoor climate and its geometry, presented in a previous paper (Ibrahim et al., 2021).

2.2.1. *Climate analysis*

Four cities were selected in different climatic zones, including coastal and non-coastal areas. The cities are Seville (Seville, 37° 22′58 ″N 5° 58′ 23″ W, elevation 16 m. above sea level), Cordova (Cordova, 37° 53′ 30″ N 4° 46′ 22″ W, elevation 106 m. above sea

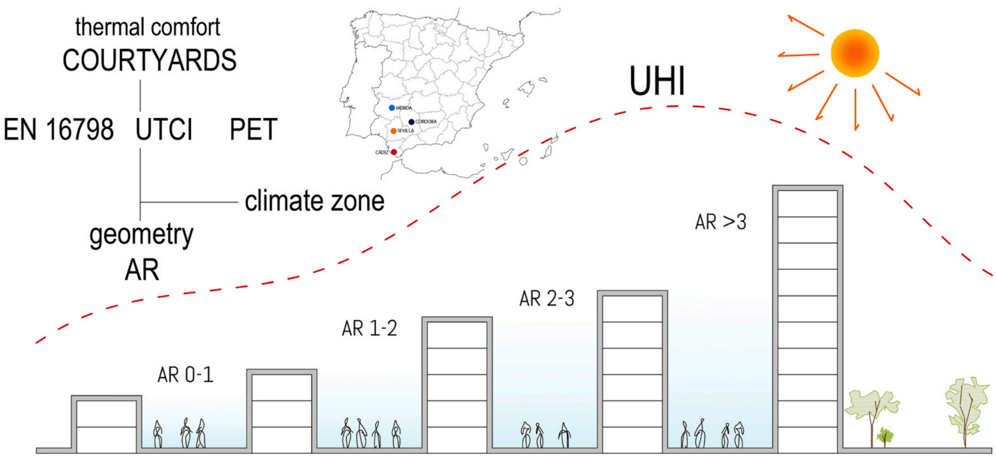


Fig. 2. Overview of the methodological evaluation.

level), Mérida (Badajoz, 38° 54′ 57 ″N 6° 20′ 37″ W, elevation 229 m. above sea level), and Cádiz (Cádiz, 36° 31′ 47″ N, 6° 17′ 40″ W, elevation 11 m. above sea level). This was done in order to assess the thermal comfort potential of the courtyards as a function of the existing outdoor temperature in each selected city. According to the Köppen classification (Kottek et al., 2009), the analysed regions are in category Csa, with dry summers and warm temperatures, as well as low rainfall.

For a more detailed definition of the climate zones to which the selected cities belong, the climate zoning categorized by the Spanish regulation (CTE-DB-HE) (Documento Básico E, 2017) is used. The letters A-E reflect winter climatic severity, while numbers 1–4 indicate summer severity.

Considering Spain's climate zoning, the interior cities of Seville and Cordova (Andalusia), B4, Merida (Extremadura), with climate zone C4, and the coastal city of Cadiz (Andalusia), A3, were selected. All selected sites were classified as 3 or 4, the range of maximum summer severity, with a very hot summer climate. The alphanumeric code of the selected climate zones reflects that the climate severity in the regions of Seville and Cordova is low in winter and very harsh in summer, the same as in Merida, where it is medium in winter, and the climate in the coastal region of Cadiz is very mild in winter and medium-high in summer.

The daily mean temperature is often used as a universal measure for climate studies. However, the mean temperature is not sufficient to reflect all daily climatic variations and even to identify daily thermal hotspots hazardous to health (Braganza et al., 2004), as it can result from very different maximum and minimum temperature peaks (Sun et al., 2006). In addition, previous studies show how the difference between the maximum daily temperature and the minimum daily temperature, known as Diurnal Thermal Range (DTR), influences the human and environmental health of citizens (Easterling et al., 1997). For this reason, DTR is an important meteorological index related to global climate change and weather variation. The historical temperature values collected in the Spanish Meteorological Agency (AEMET (Agencia Estatal de Meteorología - AEMET, n.d.)) database show a normalised DTR of 18–20 °C in the non-coastal cities of the research, which is 10–16 °C in the case of the coast. The thermal stress caused during 24-h cycles is even more accentuated in urban areas. Given that the AEMET temperature data is recorded by weather stations located in the periphery of the cities, they are not affected by the UHI phenomenon.

2.2.2. Case studies description

A set of 20 case studies of buildings with courtyards were selected, to provide a wide sample for analysis. These are mainly residential buildings, although there are some educational buildings due to the importance of the courtyard in these buildings. The floor area of the selected courtyards ranges from 6.4 to 650.3 m^2, which covers a broad range of possible configurations.

The radiation and ventilation processes change according to the urban geometry, generating each specific microclimate (Hang and Chen, 2022), and modifying the comfort conditions of people (Chatzidimitriou and Yannas, 2017). Previous research shows the influence of the aspect ratio (AR) on the air flow pattern inside courtyards (Diz-Mellado et al., 2021b). The AR is essential for assessing the thermal performance of courtyards (Soflaei et al., 2017b). In other microclimates such as urban canyons, it has been found that air temperature decreases (and PET improves) when AR increases (Taleghani et al., 2015). Other studies in hot climates found that an urban design with deep canyons is suitable for the warm season. Conversely, in winter a wider canyon is more favourable for solar heating (Johansson et al., 2014). This makes it possible to assess the thermal comfort potential of the courtyards as a function of their geometry. AR is related to the sky view factor (SVF), which represents the proportion of visible sky that can be seen from a specific point in the urban space. Aspect Ratio (AR) is defined as the ratio between the average height (H) and width (W) of the courtyards (Eq. 1). AR (I and II) have been defined, one for each of the two main dimensions of the courtyard plan (W_1 and W_2).

$$AR = H/W \tag{1}$$

where H and W of each courtyard were measured at the cornice of the inner courtyard (Fig. 3).

In this work, courtyards' AR range presented a wide variation from 0.2 to 7, to understand the importance of this factor. The 20 courtyards that made up this group were monitored over a two-week period in the cities. The number of variables was reduced by selecting courtyards with similar orientations and construction characteristics, as well as the absence of excessive vegetation or water features that could modify the results (Ibrahim et al., 2021). The courtyards are described in Tables 1 and 2. The case studies have been ordered according to their geometry, from the lowest AR to the highest AR.

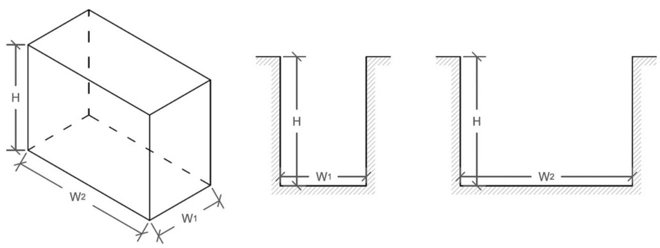
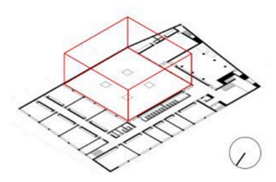
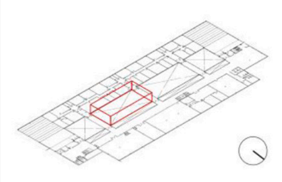
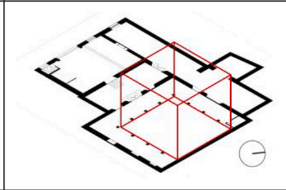
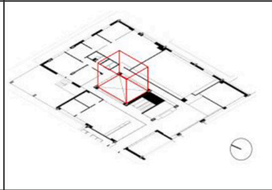
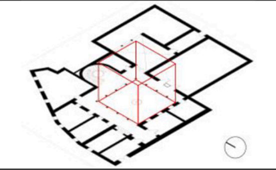
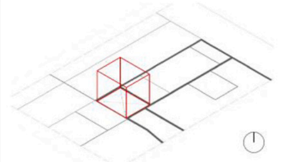
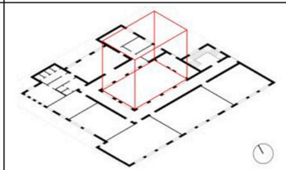
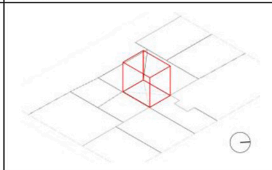
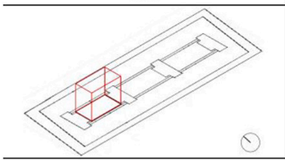
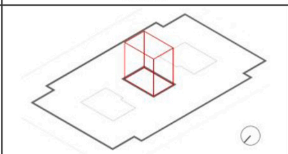
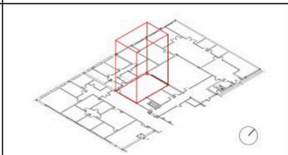
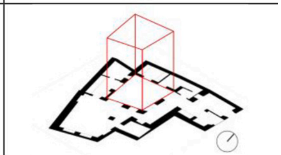
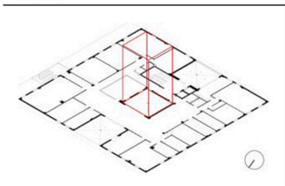
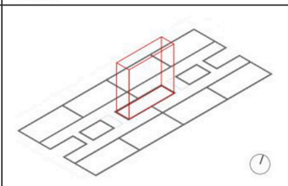
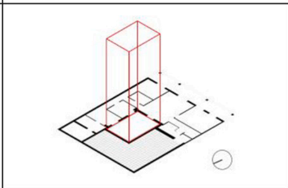
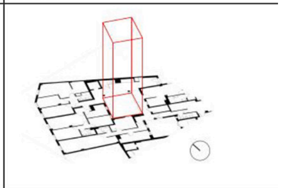
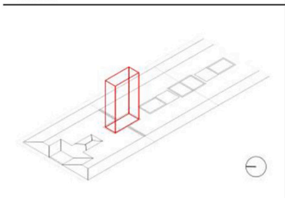
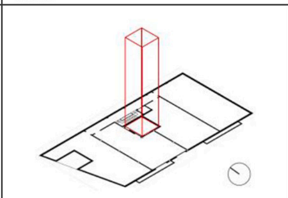
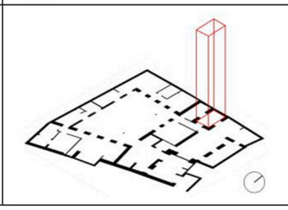
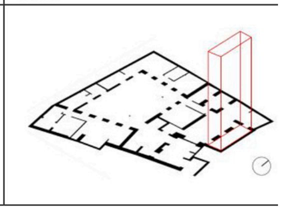


Fig. 3. Definition of the different ranges of AR.

Table 1
Overview of the schematic plan for twenty courtyards analysed as case studies.

CS1	CS2	CS3	CS4
			
CS5	**CS6**	**CS7**	**CS8**
			
CS9	**CS10**	**CS11**	**CS12**
			
CS13	**CS14**	**CS15**	**CS16**
			
CS17	**CS18**	**CS19**	**CS20**
			

2.3. Methods

2.3.1. Field monitoring campaigns

Monitoring campaigns were conducted during the summer months to analyse the thermal performance of the 20 selected case studies. Following the established protocols, the minimum period was two weeks, recording data outside the building, with measurements of the urban environment, and inside the courtyards. Data collection was carried out during a period of high outdoor temperatures in the warmest season. In these conditions, staying outdoors is difficult because outdoor temperatures often exceed 40 °C during the central hours of the day and remain close to 30 °C at night.

Outdoor weather data (air temperature (T_a), relative humidity (RH), wind direction (WD) and wind speed (WS)) were recorded by placing a portable weather station model PCE-FWS − 20 on the roof of the buildings (Fig. 4a). Additionally, meteorological data provided by the Spanish Meteorological Agency (AEMET (Agencia Estatal de Meteorología - AEMET, n.d.)) were used to cross-check the data.

Moreover, temperature data inside the courtyards were recorded by the TESTO 174H sensors (Fig. 4b) at the lower level + 1.00 m (temperature and humidity), and the TESTO 174 T model (temperature), placed at the upper levels (+2.00 m, +5.00 m and + 8.00 m) to study the thermal stratification of the courtyards. Following the protocol mentioned above, the data loggers were protected with radiation shields to minimise the overheating effect of direct sunlight. The sensors were placed on the north-facing façade and were installed at a certain distance from the wall to avoid possible contamination of the data by surface temperature. Furthermore, they were placed away from the windows to avoid the air-flow conditions caused by them. For the thermal comfort analysis, data from

Table 2
Case studies location and geometry description.

Case Study	City	Climate Zoning	Floor (m^2)	Dimensions (m)		Height (m)	AR I	AR II	AR
CS1	Cadiz	A3	650.3	25.5	25.5	10.7	0.42	0.42	0.42
CS2	Seville	B4	816.6	63.8	12.8	12.0	0.19	0.94	0.57
CS3	Cordova	B4	65.5	8.4	7.8	6.8	0.81	0.87	0.84
CS4	Seville	B4	35.9	6.9	5.2	5.0	0.72	0.96	0.84
CS5	Cordova	B4	86.4	9.6	9.0	8.1	0.84	0.90	0.87
CS6	Merida	C4	34.1	5.2	6.5	5.9	1.14	0.91	1.03
CS7	Seville	B4	75.9	11.0	6.9	8.9	0.81	1.29	1.05
CS8	Merida	C4	34.7	5.2	6.7	6.3	1.21	0.95	1.08
CS9	Seville	B4	99.0	13.2	7.5	10.7	0.81	1.43	1.12
CS10	Merida	C4	25.2	4.1	6.1	6.3	1.54	1.04	1.29
CS11	Seville	B4	49.4	5.9	8.5	11.7	2.00	1.38	1.69
CS12	Cordova	B4	14.6	4.3	3.4	6.3	1.47	1.85	1.66
CS13	Seville	B4	48.2	7.3	6.6	14.0	1.92	2.12	2.02
CS14	Merida	C4	36.5	3.2	11.5	10.8	3.41	0.94	2.18
CS15	Cadiz	A3	35.0	7.0	5.0	17.7	2.53	3.54	3.03
CS16	Cadiz	A3	22.7	5.4	4.2	14.3	2.65	3.40	3.03
CS17	Seville	B4	22.9	7.4	3.1	13.6	1.84	4.39	3.11
CS18	Seville	B4	12.3	3.5	3.5	15.9	4.54	4.54	4.54
CS19	Seville	B4	11.0	5.5	2.0	14.2	2.58	7.10	4.84
CS20	Seville	B4	6.4	3.2	2.0	14.2	4.44	7.10	5.77

sensors located at +1.00 m, according to ISO 7726 (ISO 7726:2021-03, 2021) for sitting and standing subjects, and + 2.00 m, considering the official temperature at screen level established by the WMO (Guide to Meteorological Instruments and Methods of Observation, 1983), were selected for the analysis.

The accuracy of the sensors is ±0.5 °C and ± 3% for temperature and relative humidity, respectively, according to manufacturer technical specifications in accordance with EN 12830 (EN 12830, 2019). The recording interval was defined every 15 min and quality control procedures were applied during the monitoring campaigns.

Finally, for the analysis of thermal comfort, the operative temperature is required. To obtain it, the mean radiant temperature (MRT) has been previously estimated.

The MRT is one of the fundamental variables for the evaluation of comfort, especially in hot climate zones (Mayer and Höppe, 1987). There are different methods to determine the MRT, the most accurate being by integral radiation measurements and the calculation of angular factors (Thorsson et al., 2007). However, the instrument setup is complex and can cause errors (Thorsson et al., 2007). Another simpler method is the one developed by the German guideline (Beuth, 2008), using a pyranometer and a pyrgeometer mounted on a movable axis. Another way to determine MRT is by using a globe thermometer and has proven to be accurate and economical (Thorsson et al., 2007). The response time of the globe must be short, so it must be small size and have a small heat capacity. Finally, MRT simulation with different software using meteorological data as input and modelling the environment is another widely used method (Beuth, 2008).

In this research, the MRT has been estimated as suggested by ISO 7726 (ISO 7726:2021-03, 2021), through the globe thermometer monitored data, using QUESTemp 34/36 to record the temperature of the black globe in the centre of the courtyard (Fig. 4c). Black globe temperature monitoring was not possible in all case studies due to the limitation of the equipment available. The estimated MRT data were used to calibrate a simulation model in LadyBug (Ladybug Tools | Butterfly, n.d.) and obtain MRT data for the 20 case studies. The technical data for each of the measuring instruments used during the field monitoring campaigns are shown in Table 3.

2.3.2. Adaptive thermal comfort in courtyards according to EN 16798

As these are transitional spaces, there is no standard to regulate comfort in these spaces. Recent work by the authors, focused on the potential to extend and interpret the existing calculation models for the adaptive indoor thermal comfort standards, to determine thermal comfort in courtyards, using two different courtyards in Cordova (Diz-Mellado et al., 2021a). In the current work, this methodology is extended for the 20 selected case studies, using the model described by EN 16798, based on the PMV and PPD comfort indices.

For the mathematical model, the Outdoor Running mean temperature (θ_{rm}) (Eq. 2) and the inner Operative Temperature (θ_0) (Eq. 3) of the courtyard data are required.

$$\theta_{rm} = (1-\alpha)\,\theta_{ed-1} + \alpha \cdot \theta_{rm-1} \tag{2}$$

where α is a constant value and $\theta_{ed\text{-}1}$ is the average daily outside temperature of the previous day (24 h) and $\theta_{rm\text{-}1}$ is the Outdoor Running mean temperature of the previous day.

$$\theta_0 = (CT + MRT)/2 \tag{3}$$

where CT is courtyard temperature and MRT is mean radiant temperature.

By extending the limits of the categories defined by the standard, it is possible to check whether the operative temperature data inside the courtyards complies with the limits set by the European standard.

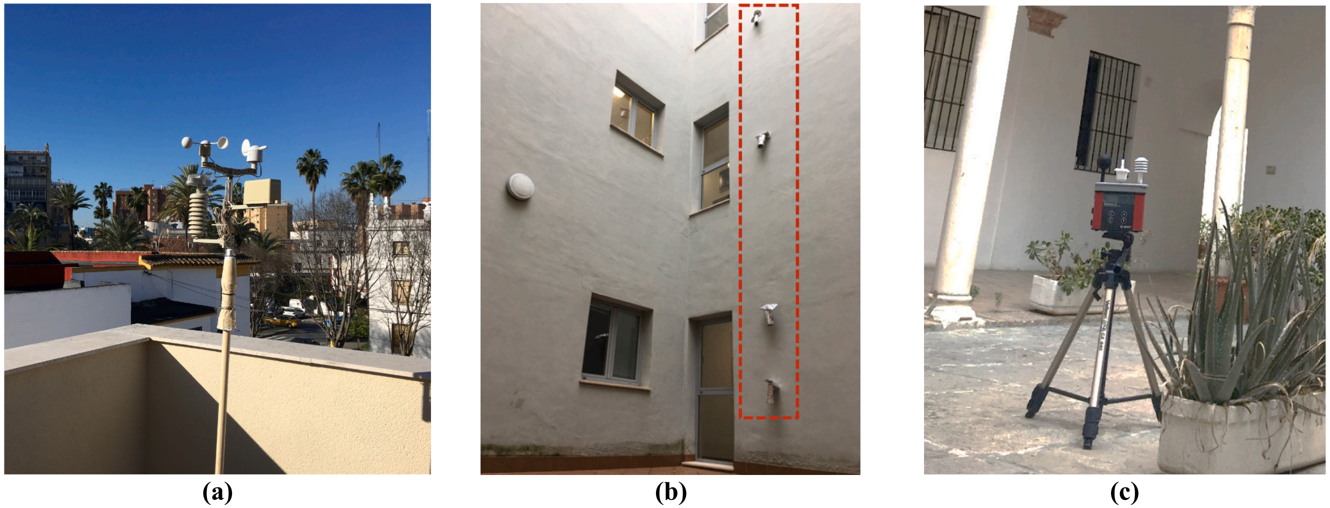


Fig. 4. Field monitoring campaigns. (**a**) PCE-FWS 20; (**b**) TESTO 174H/T; (**c**) QUESTemp 34/36.

Table 3
Technical data of the measurement instruments.

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

2.3.3. Adaptive thermal comfort in courtyards according to the outdoor indexes

As this study is carried out in semi-outdoor spaces, the research does not intend to limit the results to the exclusive analysis of the standards for indoor spaces. This section analyses the thermal comfort in courtyards according to the UTCI and PET outdoor comfort indexes, which are the most widely used (Binarti et al., 2019; Lopez-Cabeza et al., 2022) and the best indices for this research according to Part IV of Metamatrix Thermal Comfort (Migliari et al., 2022). This study has used the Rayman software (Matzarakis et al., 2007; Matzarakis et al., 2010; Matzarakis and Fröhlich, 2018; Fröhlich et al., 2018; Matzarakis et al., 2021), which can calculate radiation fluxes as a function of parameters like wind speed, air temperature, RH and MRT in different environments.

2.3.3.1. UTCI index. UTCI (McGregor, 2012), is a common index that is currently used worldwide by meteorologists. This outdoor comfort index considers different parameters such as air temperature (Ta), relative humidity (RH), wind speed (WS) or mean radiant temperature (MRT). In addition, non-climatic factors related to users such as height and weight, as well as age and clothing. The values monitored and calculated according to the previously presented methodology have been added as data in the input file in the Rayman software for the calculation of UTCI. The location has been indicated in the software and the date and time, Ta, RH, WS and MRT have been incorporated in the input file for the calculation.

2.3.3.2. PET index. Next, the PET index is used to analyse comfort in the 20 case studies. It is a previously calibrated index for different climates (Zhao et al., 2021; Yang et al., 2017), hence a priori allows a better comparison for the Mediterranean climate than the UTCI. The physiologically equivalent temperature (PET) outdoor comfort index is derived from the human energy balance. It is an index with the capacity to adapt to different climate scenarios to assess the perception of thermal comfort by users of urban space. Previous literature reviews have established several PET scales for different climate zones (Potchter et al., 2022; Potchter et al., 2018). There are three scales developed for the Csa climate zone, developed for Rome (Italy), Tel Aviv (Israel) and Crete (Greece). On the other hand, Cohen et al. (Cohen et al., 2013) establishes different scales, among them, the PET scale for Tel Aviv, with a neutral comfort range of 19–26 °C, which has been established for this research, being the most similar to our climate and latitude. This scale has been previously used to analyse comfort in semi-outdoor spaces in southern Spain (Diz-Mellado et al., 2021a; Diz-Mellado et al., 2022). As for the outdoor comfort index above, the data has been added as data in the input file of the Rayman software for the PET calculation.

3. Results and discussion

3.1. Courtyard behaviour

The data obtained from the monitoring campaigns were previously analysed and filtered to exclude meteorological anomalies that are not representative of the climate of each location.

To determine the tempering potential of the courtyard, and following the protocols established, the thermal gap (TG) between the temperature monitored in the courtyard (CT) and the temperature measured by the outdoor (OT) weather station has been calculated (Eq. 4).

$$TG = OT - CT \tag{4}$$

Maximum TG values are usually found during the hottest hours of the day, being negative during the early morning hours due to the air pocketing produced inside the courtyards. This thermal behaviour corresponds to the urban heat island effect. The geometry of the courtyards provides the necessary shading so that during the maximum outside temperature the maximum cooling occurs in the courtyard. Accordingly, the mean T_a in courtyards is significantly lower during the day as the walls block incident direct solar radiation (Muhaisen and Gadi, 2006). However, at night, they limit the loss of long-wave radiation and hot air is trapped in these spaces, producing the opposite effect (Lopez-Cabeza et al., 2022). The results of the monitoring are shown in Fig. 5, represented in terms of TG during a 24-h cycle for each of the case studies (vertical lines). In addition, this figure represents TG of all case studies (grey lines), the mean (median) TG for the case studies with lower AR (0–1) (dark line) and the cases with higher AR (>3) (orange line).

Between 17.00 and 19.00 h is usually the maximum daily temperature during the monitoring, and when the TG is higher. The TG follows a cyclical trend depending on outside temperatures, increasing with daytime temperatures and decreasing until it becomes negative during the night.

The positive TG values range between 3 °C in locations with non-extreme outdoor temperatures (Cádiz), reaching 13 °C when the

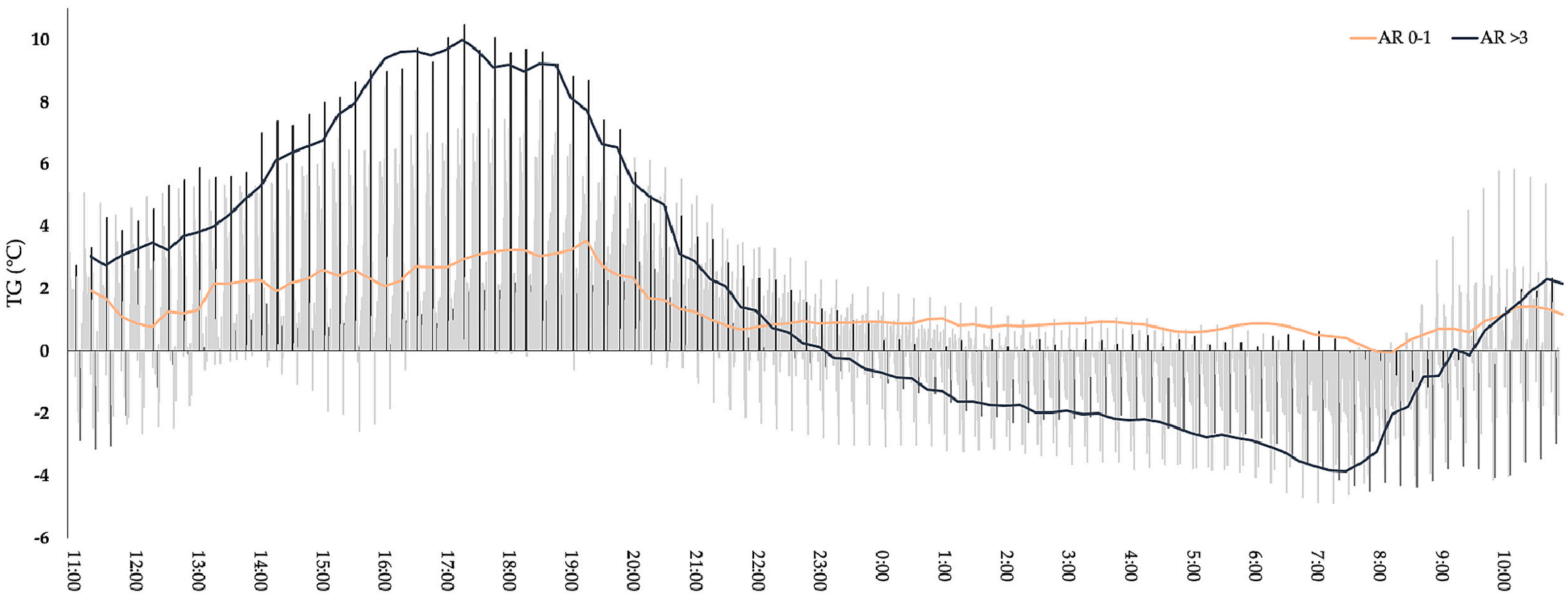


Fig. 5. Average TG over a 24-h cycle for the 20 case studies.

outdoor temperature exceeds 40 °C. These results are also related to the geometry of the courtyard, with higher TG being reached in courtyards with higher AR, the opposite effect being the case at night (orange line). Courtyards with AR <1 are more influenced by the outside temperature, heating up during the day and cooling down at night (dark line), while those with AR > 3 have a much lower DTR, being thermally more stable.

3.2. Adaptive thermal comfort results according to indoor standards

Fig. 6 shows the 24-h courtyard temperature over a representative period of one week for each case study. The results are shown divided according to the average AR range of each case study to check the influence of the geometry on the comfort capacity of the courtyards. The AR ranges are as follows: AR 0–1, AR 1–2, AR 2–3, and AR >3. Fig. 6 also shows the different comfort ranges (Cat I, II and III) established by the European standard.

Fig. 6a shows the results for CS1–4 with the lowest AR, representing the first range of AR 0–1. The results show a wide range of operative temperature values during the day due to the greater influence of the outdoor temperature on this courtyard geometry. Despite being the lowest AR, an average of 63% of the daytime hours during the selected period, the courtyards with AR 0–1 are within the comfort limits according to EN 16798.

The next range of AR 1–2 is the most representative of the selected case study sample, with eight case studies for CS5–12 (Fig. 6b). The results obtained still show very heterogeneous values of the operative temperature inside the courtyard. However, the higher the Outdoor Running mean temperature, the lower the amplitude of the maximum and minimum values of the operative temperature. An average of 67% of the hours of the day, the courtyards are considered as comfortable, for the most frequent typology in the south of Spain.

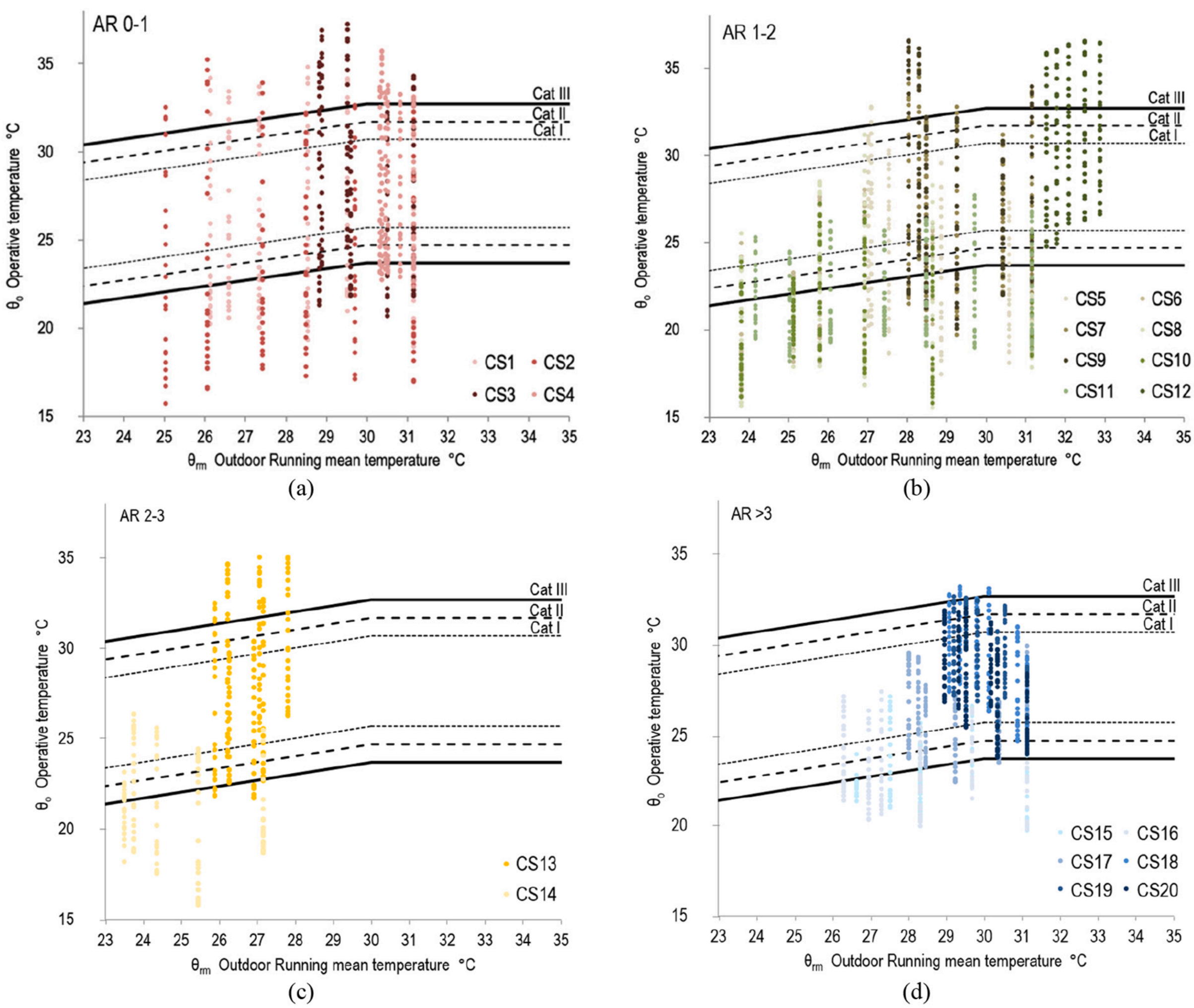


Fig. 6. Adaptive thermal comfort range in courtyards according to EN 16798. (a) AR 0–1, (b) AR 1–2, (c) AR 2–3 and (d) AR >3.

The AR 2–3 range is the least represented in the sample (Fig. 6c). In addition, these courtyards are monitored in different locations, which explain why the results are very different for the two case studies. The first one, CS13, is located in Seville, and CS14 is in Merida. Although both cities are in the same climatic zone in summer, outdoor conditions during the monitoring were different. The operative temperature reached is 35.1 °C in CS13 and 26.4 °C in CS14. The first one is more affected by the high outdoor temperatures. Despite this, an average of 72% of the 24-h daily cycle is in thermal comfort.

Finally, Fig. 6d shows the results obtained from CS15–20, with a range of AR >3. These are the courtyards with the least variant behaviour in terms of operative temperature, as the daily thermal oscillations are very low. Most of the case studies are within the

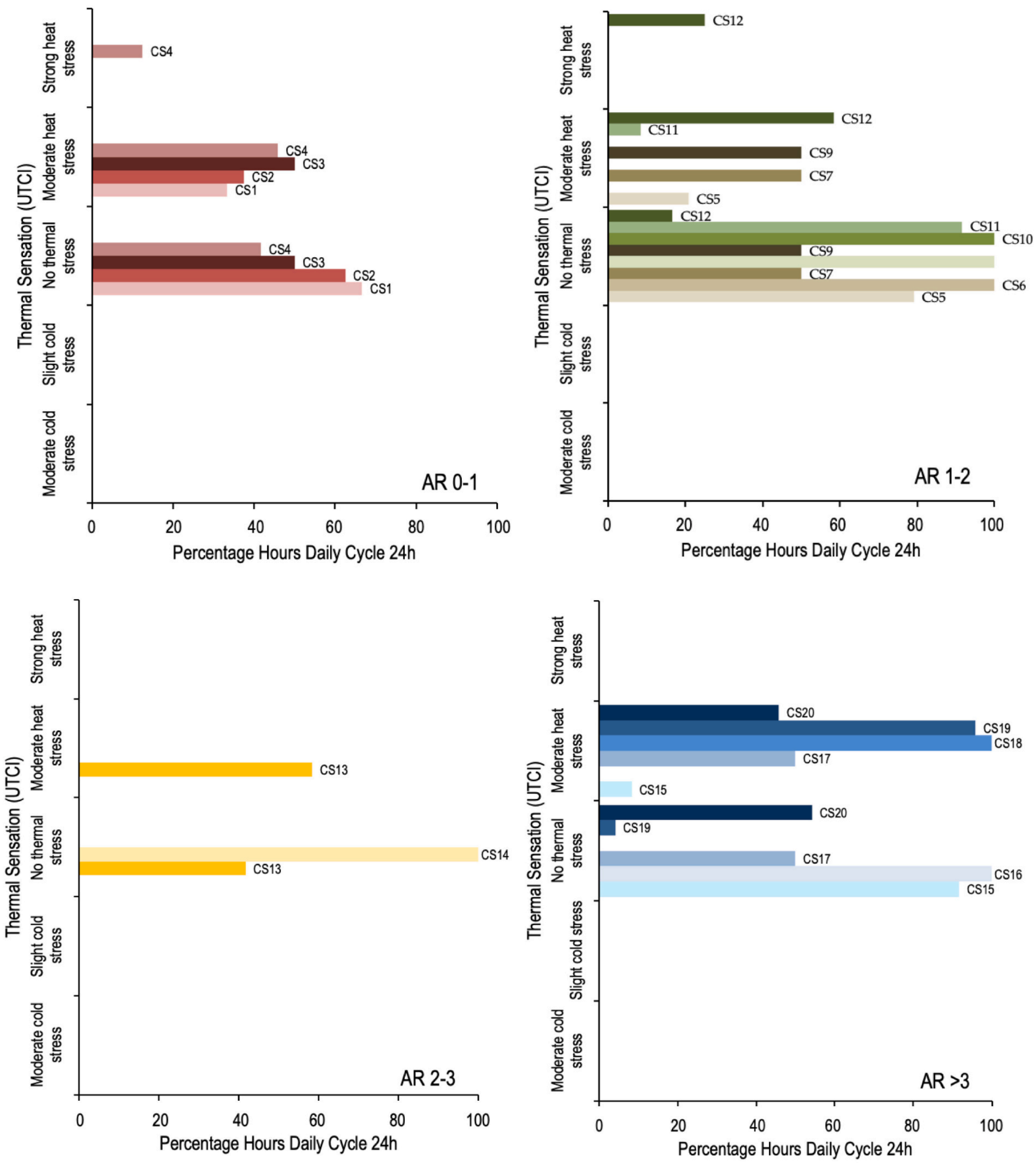


Fig. 7. Adaptive thermal comfort range in courtyards according to UTCI. (a) AR 0–1, (b) AR 1–2, (c) AR 2–3 and (d) AR >3.

comfort zone for a large percentage of the hours of the day, >90%, with very few occasions exceeding Cat III, even though the study was conducted during the warm season.

3.3. *Adaptive thermal comfort results according to outdoor indexes*

3.3.1. *UTCI index*

The result is the thermal sensation felt by the user classified according to an established scale of thermal stress levels (Fig. 7).

The UTCI results have been calculated using the Ladybug Outdoor Comfort Calculator component (Outdoor Comfort Calculator - Ladybug - Component for Grasshopper | Grasshopper Docs, n.d.), which adapts the original Fortran code to Python. The inputs required by the simulation software are the monitored climate parameters defined above.

The case studies classified with AR 0–1 are shown in Fig. 7.a. The results show, on average, a feeling of thermal comfort for 50% of the day, and a feeling of mild heat stress for the other 50%. In addition, in some cases the heat stress is strong. When analysing the results, the heat stress is found in the hours of maximum outdoor temperature, in the interval from 14:00–19:00 h.

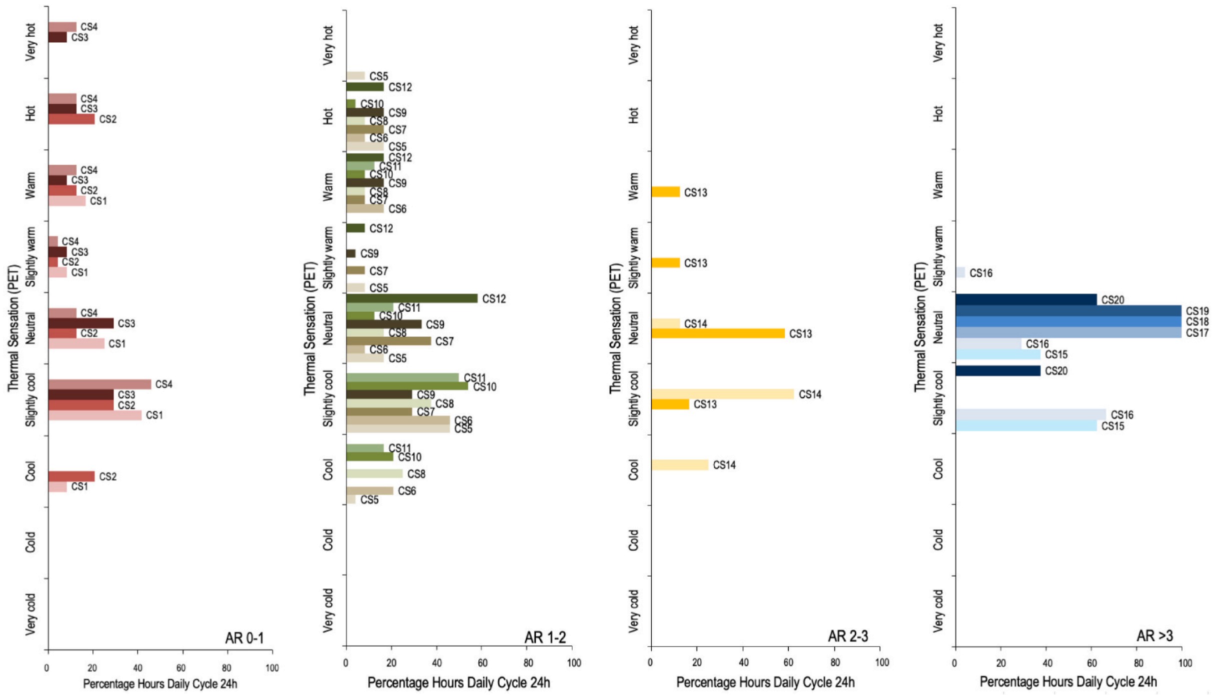
In the case of AR 1–2 (Fig. 7.b), most of the case studies are in thermal comfort 73.4% of the hours of the day. In some cases, moderate heat stress occurs in the central hours of the day. In addition, as in the previous AR range, there is a period of strong heat stress. It is different in the courtyards with AR > 2 in which there is never a strong heat stress. In the courtyards with AR 2–3, with a limited sample size, comfort according to UTCI is complete in one of the two cases, with hours of moderate thermal stress in the other (Fig. 7.c).

Finally, Fig. 7.d with the case studies with AR > 3, shows different results from the rest. The overall UTCI thermal behaviour is less variable throughout the day. This is due to the low thermal variation in the courtyard during the day and night. Typically, there are case studies with no heat stress throughout the day, and case studies with moderate heat stress throughout the day. The influence of the climate zone of each courtyard is important in these results. CS15 and CS16, with >90% of the daytime hours without heat stress according to UTCI, are located in the city of Cadiz, climate zone A3, which is more moderate than the other cities.

3.3.2. *PET index*

Fig. 8a-d show the PET results of the case studies according to the different AR ranges. The thermal comfort according to PET varies depending on the geometry.

In Fig. 8.a of case studies with a smaller AR the comfort sensation according to PET is variable, slightly cold some hours of the day and quite warm at others. An average of 63,5% is in neutral thermal sensation. These are more open courtyards in direct contact with the outside. In contrast, in Fig. 8.d, from case studies with the highest AR, for most of the day the courtyard is in a neutral comfort



(a) (b) (c) (d)

Fig. 8. Adaptive thermal comfort range in courtyards according to PET.
(a) AR 0–1, (b) AR 1–2, (c) AR 2–3 and (d) AR >3.

sensation (100%), with a very slight hot or cold sensation some hours of the day.

3.4. Results discussion according to geometry

The analysis of the results obtained shows the high tempering potential of the courtyards against heat. Depending on its geometry, the larger the AR, the better the courtyard is in terms of thermal comfort against high temperatures according to CAT III of EN 16798 (Table 4). Table 4 represents the percentage of comfort hours of the day and the effective occupancy period of the courtyard defined in a previous investigation (Lizana et al., 2022). The estimated range of occupation is from 9.00 to 15.00 h, and from 17.00 to 23.00 h. In addition, the percentage of heat and cold discomfort in the courtyard is indicated.

The results show that the lower the AR, the more the outdoor climate influences the microclimate of the courtyard. However, in this research the courtyards have also been analysed with an indoor comfort standard, a priori with more restrictions. For this reason, exceeding 60% of the 24 h in thermal comfort indicates that these are very thermally comfortable spaces. The percentage increases to 68.6% in the range of AR 1–2, and up to 72.3% in AR 2–3. Finally, the AR > 3 range shows very comfortable results throughout the day, exceeding 90%.

In the case of the percentage of hours of comfort in the courtyards according to the UTCI outdoor comfort index (see Table 5), there are differences compared to the European standard. The percentage of comfort hours in courtyards with lower AR is lower with UTCI than with EN 16798, being 55% of the hours of the day comfortable. Case studies with AR 1–3 intervals have similar behaviour, with a percentage of hours in comfort between 71 and 73%. The largest difference occurs in the case studies with AR >3, where thermal comfort is reduced to 50%. This is due to the low thermal variability in these courtyards and to the UTCI scale, which has very wide intervals. Most of the case studies with AR >3 are close to 26 °C on the UTCI scale. This value is the limit between no thermal stress and moderate heat stress sensation. In Table 5 is shown the percentage of hours of thermal comfort according to UTCI scale of no thermal stress (9–26 °C).

The comfort results according to PET shown in Table 6 reflect a similar trend for the different geometries and the percentage of comfort hours in the courtyards is comparable to the indoor European standard. According to the protocol established by previous research for the PET scale (Braganza et al., 2004), a comfortable space has been considered from slightly cold to slightly warm. The case studies analysed exceed 63% of daily comfort hours when AR is lower, reaching 100% of daily comfort hours during the entire monitoring campaign when the AR is higher than 3.

Finally, Fig. 9 shows the comparison of the percentages of comfort hours in the courtyards according to their geometry and the standard or comfort index being used.

The results of the investigation show a similar behaviour in the evaluation of thermal comfort in courtyards between the indoor comfort standard EN16798 and the outdoor comfort index PET. On the other hand, the UTCI outdoor comfort index gives significantly different results. Both PET and EN16798 are adaptive comfort evaluation procedures. Besides PET has different evaluation scales adapted to different climate zones. Both cases have a different calculation methodology, but both cases consider the adaptation process of the users. The UTCI, however, does not adapt the scale for different climatic zones and in the current context its use in assessing comfort in transitional spaces such as courtyards is limited. For this reason, the use of UTCI in the current context of assessing comfort in transitional spaces such as courtyards is limited. The 20 case studies, with different geometries, have allowed us to understand the influence of the geometric characteristics on the thermal comfort of transition spaces. Moreover, this methodology confirms the results of previous research with a smaller number of case studies (Diz-Mellado et al., 2021a). The use of EN 16798 and PET is confirmed to be the most successful in analysing the comfort of transitional spaces. In general terms, as shown in Fig. 9, the trend indicates that the higher the AR of the courtyards, the higher the percentage of comfort hours in these spaces. This is because the geometry of the courtyard itself generates more shade inside the courtyard, reducing the radiation in this space, and tempering it. These results in terms of geometry can be extended to other climate zones, as the trend in terms of thermal comfort has been the same in the climate zones analysed. This trend is consistent using the two different evaluation methods for indoor and outdoor, using EN16798 and PET respectively.

The main limitation of the research is the specific climate in which the case studies are located, Mediterranean climate. Additionally, other limitations should be noted, such as the fact that comfort indices were particularly precise for the location of the case studies and that the sample size could have been larger to extend the conclusions to other typologies. To a lesser extent, the orientation of the case studies may also be considered a limitation. According to previous literature reviews (Zamani et al., 2018; Rivera-Gómez et al., 2019), the influence of orientation compared to other parameters such as geometry is not relevant. Moreover, in future research it would be appropriate to analyse comfort in cooler seasons of the year.

Table 4
Percentage of hours of thermal comfort according to EN 16798.

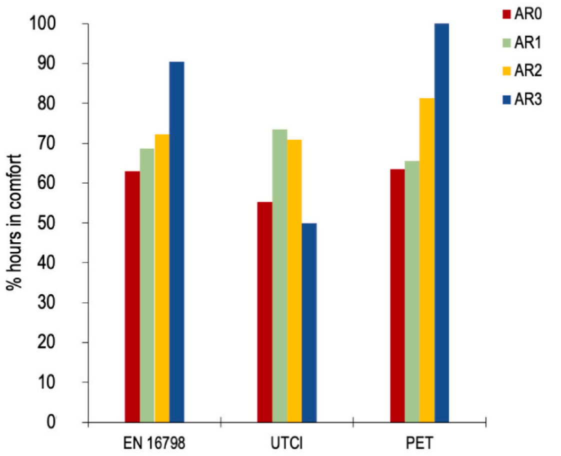
AR Range	% Comfort	% Comfort – occupancy period	% Cold Discomfort	% Hot Discomfort
0–1	**62.9**	**75.3**	24.7	12.4
1–2	**68.6**	**74.7**	25.3	6.1
2–3	**72.3**	**80.7**	18.7	9.0
> 3	**90.5**	**91.0**	8.9	0.6

Table 5
Percentage of hours of thermal comfort according to UTCI.

AR Range	% Comfort	% Comfort OP	% Cold Discomfort	% Hot Discomfort
0–1	**55.2**	**63.6**	0	44.8
1–2	**73.4**	**81.7**	0	26.6
2–3	**70.8**	**79.2**	0	29.2
> 3	**50.0**	**58.4**	0	50.0

Table 6
Percentage of hours of thermal comfort according to PET.

AR Range	% Comfort	% Comfort OP	% Cold Discomfort	% Hot Discomfort
0–1	**63.5**	**71.9**	0	36.5
1–2	**65.6**	**73.9**	0	34.4
2–3	**81.3**	**89.7**	0	18.8
> 3	**100.0**	**100**	0	0.0



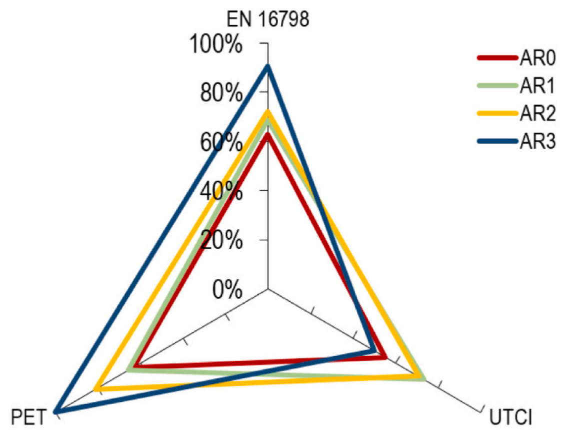


Fig. 9. Adaptive thermal comfort in courtyards according to geometry.

4. Conclusions

The need to provide cooler spaces in cities during extreme temperatures is a complex assessment today. Courtyards have provided a buffer against high temperatures since vernacular architecture, but current comfort standards continue to ignore these spaces. Building energy codes ensure good conditions for building occupants including thermal comfort, indoor air quality, and daylight indoors. Moreover, courtyards act as an additional room in Mediterranean buildings and should be considered. This study, employs both indoor standards and outdoor indices to calculate and understand the thermal comfort of transitional spaces (courtyards). It has also demonstrated the capacity of courtyards as comfortable spaces, along with the influence of their geometry on their thermal tempering potential. As these are confined spaces but in direct contact with the outside, comfort has been analysed by combining indoor comfort standards such as EN 16798 and the two most widely used outdoor comfort indices, UTCI and PET.

The values obtained show that, in general terms, courtyards can be considered habitable rooms due to their thermal comfort conditions during most hours of the day in a period of extreme heat. The influence of its geometry is important since when the AR is higher than 3, the courtyard reaches comfort 90–100% of the hours of the day and approximately 70–80% when the AR is higher than 2. In the case of the most common geometries in Mediterranean cities, with AR 1–2, >65% of the hours of the day the courtyards are within the limits of comfort.

This research has demonstrated the capacity of courtyards as a bioclimatic strategy in cities, considering it as another living space in cities affected by increasingly frequent heat waves. The main conclusions of the research are highlighted in the bulleted list:

- The TG between the courtyards and the outdoor environment varies depending on the geometry and the climatic zone between 3 °C and 13 °C.

- Thermal comfort standards for indoor spaces and outdoor comfort indices are used to analyse the thermal comfort in semi-outdoor spaces such as courtyards.
- The influence of the geometry of the courtyards on the comfort of these spaces is relevant.
- Courtyards with AR 0–1 are comfortable >60% of the hours of the day. The percentage of hours in thermal comfort increases to 65% when AR 1–2, and 70% when AR 2–3.
- Courtyards with a high AR > 3, exceed 90% of the hours of the day in thermal comfort according to the most adaptive models used EN 16798 and PET.

The novelty of the research has been to establish a first approach to the use of EN 16798 and PET in semi-outdoor spaces, as well as to demonstrate the influence that the geometry of these semi-outdoor spaces has on how comfortable they can become. Future lines of research may determine suitable comfort indices for semi-outdoor or transitional spaces, to be integrated into new updates of international standards.

Authorship statement

Authorship contributions Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames).

Conception and design of study: Eduardo Diz-Mellado; Marialena Nikolopoulou; Carlos Rivera-Gómez and Carmen Galán-Marín.

Acquisition of data: Eduardo Diz-Mellado; and Victoria Patricia López-Cabeza.

Analysis and/or interpretation of data: Eduardo Diz-Mellado; Victoria Patricia López-Cabeza; Carlos Rivera-Gómez and Carmen Galán-Marín.

Drafting the manuscript: Eduardo Diz-Mellado; Marialena Nikolopoulou; Carlos Rivera-Gómez and Carmen Galán-Marín.

Revising the manuscript critically for important intellectual content: Marialena Nikolopoulou; Carlos Rivera-Gómez and Carmen Galán-Marín.

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.

Data availability

Data will be made available on request.

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