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Evidence on the Improvement of the Thermal Comfort Index and Habitability in Bioclimatic Spaces of the Mediterranean Region

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A B S T R A C T

Climate change is a critical environmental challenge of this century, with particularly severe impacts projected for the Mediterranean region. In Spain, maximum temperatures are expected to increase by more than 2°C by the end of the century, with more frequent and longer-lasting heatwaves. Urban adaptation strategies such as bioclimatic architecture and integrating vegetation into built structures are effective tools to moderate microclimates and create climate shelters. However, a gap in empirical research connecting these tools in hot semi-arid Mediterranean contexts remains. This study addresses this gap by examining the impact of bioclimatic design on thermal comfort through fieldwork conducted at two distinct locations in the province of Málaga: Coín (rural) and Teatinos (urban). The research hypothesizes that spaces where the five fundamental pillars of bioclimatic design (urban planning, architecture, vegetation, landscaping, and materials) are well integrated tend to exhibit better thermal comfort. To test this, a Thermal Comfort Index (THI) was employed, adapted to the specific climatic conditions of the study areas, allowing a more accurate environmental performance assessment in each setting. Bioclimatic urban strategies, architectural configurations, vegetative elements, and material choices were analyzed in situ, revealing that the most thermally comfortable areas are aligned with a strong synergistic presence of all five pillars. The results support the notion that a thoughtful convergence of these principles mitigates heat stress and enhances spatial habitability in Mediterranean climates. This research contributes to current discussions on climate-resilient design by offering empirical evidence from two real-life case studies under urban and rural contexts.

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1. Introduction

Climate change is one of the most pressing environmental challenges of the 21st century, with particularly severe impacts projected for the Mediterranean region. Climate models consistently indicate that southern Europe will experience more intense warming than other areas of this continent (AEMET, 2024). In Spain, for instance, maximum temperatures are expected to increase by an average of 2.3 °C by the end of the century. This trend is already observable, as average maximum summer temperatures have risen by 1.4 °C in recent decades, while the frequency and duration of heatwaves have intensified significantly (Junta de Andalucía, 2022; AEMET, 2024).

In this context, urban areas in southern Spain, particularly the Málaga Metropolitan Area and Costa del Sol (AMACOS), illustrated in Fig. 1, face specific risks linked to the Urban Heat Island (UHI) effect. This phenomenon, amplified by dense construction and limited green infrastructure, can raise local temperatures by up to 4 °C compared to surrounding rural zones, exacerbating heat-related health risks and deepening socio-spatial inequalities.

To cope with these ever-increasing concerns, urban adaptation strategies have arisen as potential solutions; however, these should consider passive, low-energy design principles to be successful (Ramírez-Cuastuza & Alarcón-Rodríguez, 2024). Hence, bioclimatic architecture, and more specifically, the integration of vegetation into built structures through pergolas, green roofs, and facades, have emerged as effective tools to moderate microclimates and create climate shelters (Cano Giraldo, 2024). However, a gap in empirical research that connects UHI theory with the actual thermal performance of such vegetated elements in hot semi-arid Mediterranean contexts remains. Accordingly, the aim of this study is to address this gap by evaluating how the traditional bioclimatic structures, e.g., pergolas and grapevine arbors, among others, perform under extreme heat conditions. The analysis focuses on two contrasting, yet climatically similar sites: 1) the urban Teatinos University Campus in Málaga, and 2) the rural Todobarro estate in Coín. Both sites fall within the thermo-Mediterranean bioclimatic zone and share a dry to semi-arid ombroclimate; nonetheless, they differ in urban density, materiality, and vegetation cover.

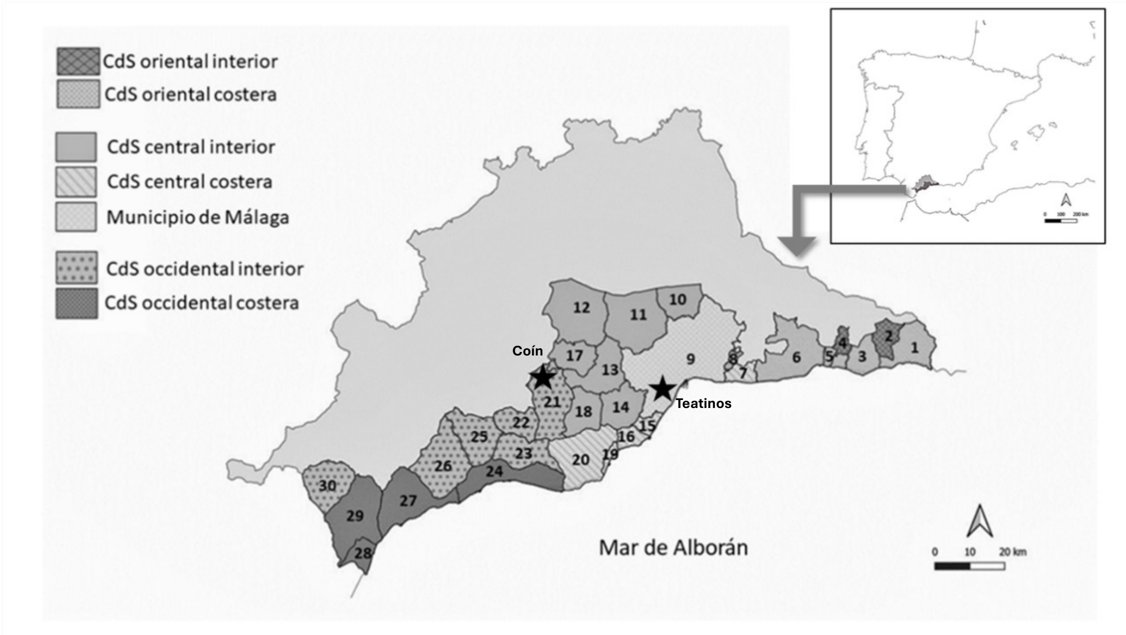

Figure 1. Map of the Metropolitan Area of Malaga and Costa del Sol (AMACOS). The stars indicate the study locations within this area (1. Nerja, 2. Frigiliana, 3. Torrox, 4. Sayalonga, 5. Algarrobo, 6. Vélez-Málaga, 7. Rincón de la Victoria, 8. Totalán, 9. Málaga ( ), 10. Casabermeja, 11. Almogía, 12. Álora, 13. Cártama, 14. Alhaurín de la Torre, 15. Torremolinos, 16. Benalmádena, 17. Pizarra, 18. Alhaurín el Grande, 19. Fuengirola, 20. Mijas, 21. Coín ( ), 22. Monda, 23. Ojén, 24. Marbella, 25. Istán, 26. Benahavis, 27. Estepona, 28. Manilva, 29. Casares, and 30. Gaucin). Source: elaborated by the authors

Unlike studies that rely solely on air temperature or broad comfort indices, this research employs an adapted Thermal Comfort Index (THI), tailored to Mediterranean climatic conditions. Since traditional THI models were developed in temperate or tropical regions, they may not reflect thermal perceptions in semi-arid climates accurately. By adjusting the THI accordingly, this study aims to better capture *in situ* the human experience of heat.

The central hypothesis is that an effective combination of the five foundational pillars of bioclimatic design, i.e., urban planning, architecture, vegetation, landscaping, and materials, can significantly improve thermal comfort, even under extreme heat conditions (Rodríguez Escandell, 2024). The findings aim to contribute not only to theoretical debates on urban adaptation but also to provide reliable input to elaborate practical guidelines for designing effective climate shelters in vulnerable regions.

In the Mediterranean region, with projected extreme climates and where both study areas are located, there is an urgent need to develop bioclimatic spaces that integrate architecture, urban planning, landscape design, vegetation, and thermoregulatory materials (Pesqueira et al. 2018). Within this framework, the concept of climate refuges has gained traction, promoted by multidisciplinary teams who define them as spaces that offer thermal comfort to people and biodiversity during extreme temperature events (Guerrero Serrano et al., 2024; Morelli et al., 2016). These refuges are grounded in passive design strategies that reduce reliance on artificial thermal control systems. Hence, this study contributes to this growing body of knowledge by calculating the Thermal Comfort Index, commonly referred to as the Temperature-Humidity Index (THI) (Equation 1), in various urban and rural environments using *in situ* measurements, to evaluate the effectiveness of passive design solutions. The results highlight how the convergence of vegetation and architecture, particularly in pergolas with well-selected plant species, i.e., with vernacular solutions, can lead to significantly more comfortable and resilient spaces. These findings reinforce the potential of nature-based solutions to enhance climate adaptation at the local scale (Morelli et al., 2016).

In this context, vegetated architectural systems emerge not only as aesthetically or culturally valuable but also as vital tools for improving thermal comfort and environmental health in urban areas. Their importance is further emphasized by future climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC, 2014), that has projected increasingly frequent and intense heat events for the Mediterranean region in the coming years. Representative Concentration Pathways (RCPs) or trajectories describe future greenhouse gas concentrations (not emissions) and have been formally adopted by the IPCC (IPCC, 2023). This study adopts two of these pathways; RCP8.5 (high emissions) and RCP4.5 (intermediate mitigation), to assess how key variables affecting thermal comfort, such as maximum/minimum temperature, hot days and nights, heatwave duration, and precipitation, are expected to evolve in the years 2024, 2025, 2045, and 2095 (Amblar et al., 2017; Rodríguez-Camino, 2013). Data from the AdapteCCa Climate Change Scenario Viewer (AdapteCCa 2023) provide a robust base for projecting future climatic stress.

Accordingly, this study aims to evaluate the effectiveness of vegetated architectural systems, such as pergolas and vine arbors, as passive climate adaptation strategies in urban and rural settings within the Mediterranean region. By calculating the Thermal Comfort Index (THI) under real-life conditions, the research assesses how the integration of vegetation, architectural shading, and permeable materials can enhance thermal comfort during periods of extreme heat (Motalbán-Pozas, 2025). The study also incorporates future climate projections based on RCP8.5 and RCP4.5 scenarios to examine how critical variables, such as temperature, humidity, and heatwave duration, may evolve by the years 2024, 2025, 2045, and 2095. This research approach contributes to the growing field of nature-based solutions by demonstrating the potential of bioclimatic design to create resilient and low-energy climate refuges that promote environmental health and human well-being in the face of intensifying climate stress.

2. Materials and Methods

2.1. Study Area

Two locations were strategically selected to compare the effectiveness of bioclimatic solutions across contrasting environmental and architectural contexts: 1) the Teatinos observation area, and 2) the Coín observation area. The first is the urban Teatinos University Campus, situated in a densely urbanized environment in Málaga, affected by the Urban Heat Island (UHI) effect and characterized by having contemporary and innovative architectural approaches. The second is a private estate in Coín, the Todobarro farm, representing a rural setting with vernacular and ancestral architecture rooted in a passive climate adaptation strategy. The two locations have a straight-line distance from each other of 26 kilometers, allowing for climatic comparability while enabling the assessment of how bioclimatic design strategies perform under different degrees of urbanization and built typologies. This contrast provides insight into the relative effectiveness of modern versus traditional bioclimatic architecture in enhancing thermal comfort and resilience to heat stress. Details on each location are found as follows.

2.1.1. Teatinos Observation Area (urban)

In this area, six sampling points strategically distributed were selected according to their solar exposure, vegetation cover, surface materials, and their potential to enhance environmental comfort (Table 1, Fig. 2). To measure air temperature and relative humidity, a Psychrometer with IR *5020-0896* (Wertheim am Main, Germany) was used, equipped with an infrared thermocouple input, humidity sensor, and laser sighting system. To validate the temperature data, a Testo 856s thermal imaging camera (Titisee-Neustadt, Germany), was employed.

This device allows for non-contact temperature measurement by converting energy signals into a thermogram, namely, a thermal image representing the infrared energy emitted, transmitted, or reflected by the surface of an object (Weller et al., 1996; Lee et al., 1998). Both devices were calibrated according to the procedures specified in the manufacturers' technical datasheets to ensure the accuracy and reliability of the measurements registered during the study, in compliance with the recommended standards for each instrument.

Table 1. Sample Points Selected in the Teatinos Observation Area (urban).

Sample Point	Altitude (m a.s.l.)	Vegetation Cover	Construction System	Maintenance	Description
Spaces that lack elements that mitigate direct solar radiation (without shade or water)					
PM.01 – Dirt Area	44	5%	No	Seasonal pruning	*Open space without vegetation cover or buildings.*
PM.02 – Asphalt Area	49	0%	No	Seasonal pruning	*Hard and dark surface, highly exposed to the sun.*
Spaces with vegetation					
PM.03 – Pergola with Wisteria (vine)	51	30% wisteria in winter / 100% in summer	Pergola	No	*A structure covered with climbing plants that provides filtered shade.*
PM.04 – Interior Courtyard	52	25%	Courtyard	No	*Enclosed or semi-open space with plant shade and moderate thermal characteristics.*
PM.05 - Pavilion E4	49	15%	Pavilion	No	*Architectural element that combines structural shade with a vegetated environment.*
Space that combines traditional materials and the presence of water with vegetation					
PM.06 – Botanical Garden	46	25%	Pergola	No	*Integrates elements of mud, a sheet of water, and vegetation, optimizing environmental comfort.*

Figure 2. Location of sampling points (SP) in the Teatinos Observation Area (urban). Source: elaborated by the authors

Sampling was conducted from April 21 to June 25, 2024 (Fig. 3). During this period, data were collected on three randomly selected days per week during three time slots. To ensure capturing the most thermally significant periods of the day, measurements were taken in the morning (9:30 to 10:30), at around noon (13:30 to 14:30), and in the evening (18:30 to 21:30).

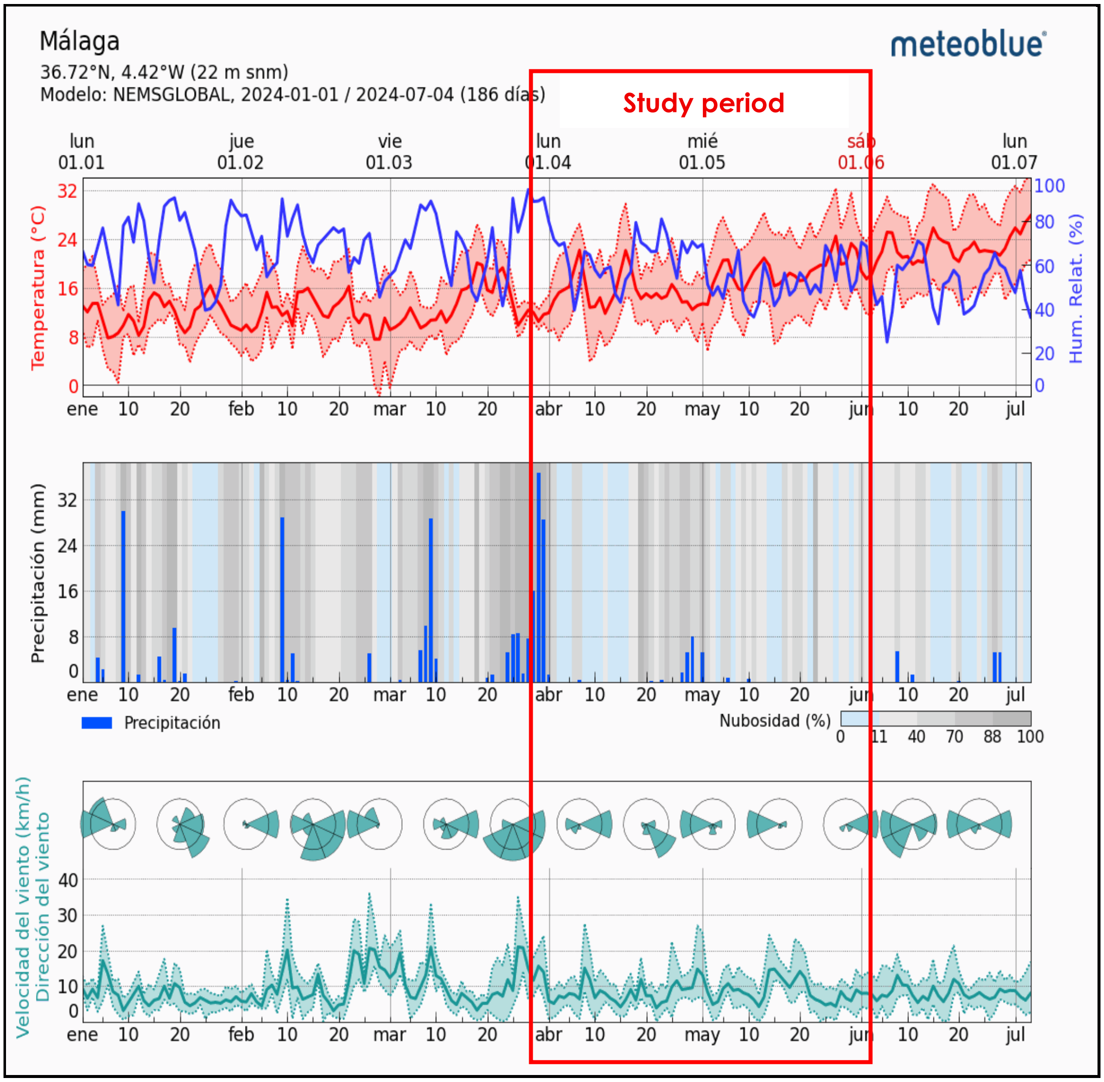

Figure 3. Climatic conditions during the study period in the Teatinos observation area (urban). Top graph: Temperature °(C) in the left x-axis, and relative humidity (%) in the right x-axis, center graph: precipitation (mm) and cloudiness (%), and bottom graph: Wind speed (km/h) and direction. Red rectangle indicates the study period. Source: elaborated by the authors based on data from AEMET (2024)

2.1.2. Coín Observation Area (rural)

The todobarro farm, located in the region of Valle del Guadalhorce, Coín (see Fig. 4), covers a 1-ha area and exhibits a high degree of environmental heterogeneity. Devoted initially to intensive olive monoculture, some of the areas are currently undergoing a renaturalization process, while others are used for diverse organically managed crops. The topography of the area features steep slopes converging into a narrow valley with a southwest–northeast orientation, through which a nearly permanent stream flows. The variation in slope exposure (sunlit vs. shaded), the vertical gradient in relative humidity from the streambed to the upper slopes, and a diverse plant mosaic contribute to a high topo-climatic diversity within this experimental landscape. Sampling points were selected based on the presence of vegetation, surface water, and architectural structures (Fig. 4, Table 2).

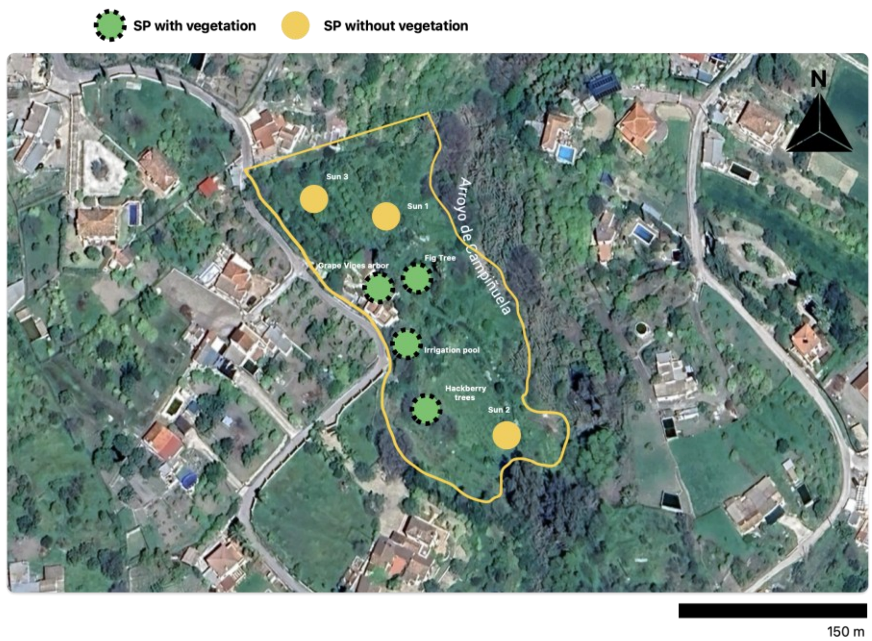

Figure 4. Location of the sampling points (SP) in the Coín Observation Area (rural). Source: elaborated by the authors.

Table 2. Selection of Sample Points in the Coín observation area. Source: elaborated by the authors.

Sample Point	Altitude (m a.s.l.)	Vegetation Cover	Construction System	Maintenance	Description
Spaces with plant shade					
CO.01 – Grapevine arbor	175.4	30% in winter / 100% in summer (vine)	Trellis	Seasonal pruning	Trellis: A structure covered with climbing plants that provides filtered shade.
CO.02 – Irrigation pool	176.1	Coverage: 25% in winter / 100% in summer (hackberry trees)	Pool	Seasonal pruning	Open-air irrigation pool surrounded by hackberry trees
Spaces with vegetation					
CO.03 – Fig tree	169.32	20% / 100%	No	No	Area with a fig tree
CO.04 – Hackberry trees	175.15	25% / 100%	No	No	Area with hackberry trees
Spaces that lack elements that mitigate direct solar radiation (without shade or water)					
CO.05 – Sun1	169.1	15%	No	No	Vacant area: Open space without vegetation cover or buildings.
CO.06 – Sun2	168.98	10%	No	No	Vacant area: Open space without vegetation cover or buildings.
CO.07 – Sun3	171.13	5%	No	No	Vacant area: Open space without vegetation cover or buildings.

Sampling was conducted during April 2023, specifically on days 13, 14, 18, 19, 21, 24, and 25. As illustrated in Fig. 5, the prevailing wind during these days was the Levant wind, which is an easterly wind that blows westwards with frequent gusts exceeding 25 km/h, resulting in mostly clear skies. A light, non-significant precipitation event occurred on April 23. Throughout the sampling period, temperature and relative humidity remained within the normal range for the location. Measurements were taken around noon, from 10:00 to 13:30, to register the maximum thermal stress period.

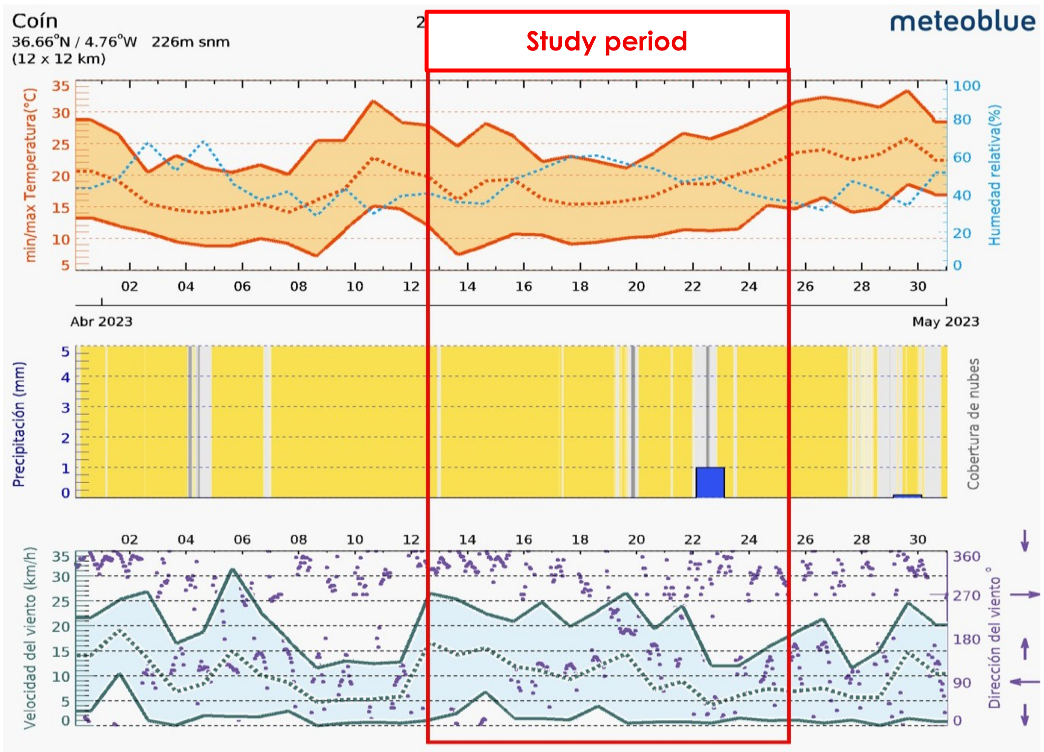

Figure 5. Climatic conditions during the study period in the Coín Observation Area. Top graph: minimum/maximum temperatures °(C) in the left x-axis, and relative humidity (%) in the right x-axis, center graph: precipitation (mm) and cloud cover (%), and bottom graph: Wind speed (km/h) in the left x-axis and direction in the right x-axis. Red rectangle indicates the study period. Source: elaborated by the authors based on data from AEMET (2024)

To measure air temperature and relative humidity, a Psychrometer with IR 5020-0896 (Wertheim am Main, Germany) was used. This device includes an infrared thermocouple input, a humidity sensor, and a laser aiming system. The sampling protocol involved visiting all preselected measurement points on each scheduled sampling day, following a fixed itinerary, and completing the route in the shortest time possible to ensure consistency across readings. The device was calibrated following the protocol specified in the manufacturer's technical datasheet to measure air temperature and relative humidity. Calibration ensures the precision and reliability of the measurements obtained during the study, following the recommended standards for the instrument.

2.2. Calculation of the Temperature-Humidity Index (THI) as a Measure of Climatic Comfort

According to Jendritzky (1991), climatic comfort is defined as the relationship between the local climate and the sensory perception the population has concerning that particular climate. This perception is subjective and can vary depending on individual factors such as gender, diet, age, or health status. Nevertheless, understanding how people perceive climate is essential for the design and planning of urban environments (Ferrelli & Piccolo, 2017).

To quantify climatic comfort, the index proposed by Thom (1959) was used. This index is commonly referred to as the Temperature-Humidity Index (THI) and must be adjusted to reflect both local climatic conditions and the optimal metabolic conditions of the species under study (Espín-Sánchez & Olcina, 2025; De Oliveira et al., 2006). For this purpose, the original formula was adapted to incorporate variables representing the ecological optimum for humans (García, 2003), resulting in the following expression (Eq. 1):

$$THI = T - (0.55 * (1 - 0.01 * RH) * (T - 14.5)) \quad (1)$$

Where *T* represents the mean air temperature in °C, and *RH* is the relative humidity. Index results interpretation follows the classification shown in Table 3, which is based on the optimal climatic ranges for humans.

Using the data obtained from both stations, a Basic Data Matrix (BDM) was created, and the THI (Equation 1) was calculated for all sampling points. For statistical processing, the PAST software (Hammer et al., 2001) was employed to perform a Principal Component Analysis (PCA) and a clustering analysis, to identify groupings among the sampling points and to evaluate how the variables contributed to these groupings. Furthermore, three isopleth maps were generated using spatial autocorrelation gridding (kriging method) to visualize THI values. Fig. 6 illustrates the local THI deviation, the average temperature difference (DIF T), and the average relative humidity difference (DIF RH) between the sampling points and the reference meteorological station.

Table 3. Thermal sensation according to the Temperature-Humidity Index (THI) value. Source: elaborated by the authors based on the optimal climatic ranges for humans.

Thermal Sensation	THI Range (°C)
Refreshing	9–15
Pleasant	15–21
Warm	21–27
Hot	27–30
Extreme Heat	>30

3. Results and Discussion

It is important to acknowledge that this study is seasonally and temporally limited, as the thermal comfort data were collected during specific months of the year and at different times of the day. These constraints inevitably introduce a degree of sampling bias, restricting the generalizability of the findings across all seasons and climatic variations.

However, despite these seasonal and temporal limitations, the conclusions drawn from both locations, i.e., Teatinos University Campus (urban) and Todobarro farm (rural), are remarkably consistent. This convergence suggests a robust correlation between the integration of vegetation and architectural design and improved thermal comfort, regardless of the specific urban or rural context. The consistency of these outcomes highlights the validity of the initial hypothesis. Nevertheless, expanding the study to include additional sampling locations, a broader range of microclimates, and year-round data collection would not only mitigate current limitations but would significantly strengthen the empirical foundation of the findings. Such an expanded approach would enhance the reliability and applicability of the results, providing a stronger basis to classify vegetated spaces as effective climate refuges across diverse environments.

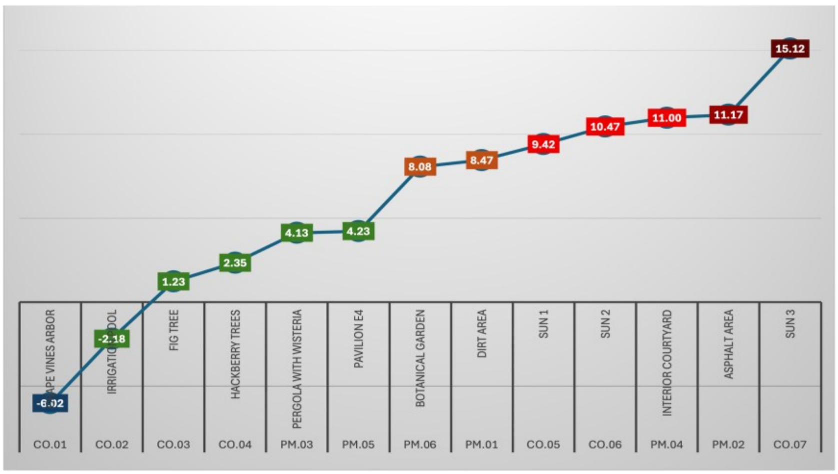

Figure 6. Deviation of the local Temperature-Humidity Index (THI) values of each sampling point concerning their respective reference location: Malaga (PM), and Coín (CO). Five categories are identified: Refreshing (9-15; blue); Pleasant (15-21; green); Warm (21-27, ochre); Hot (27-30; red); Extreme Heat (>30; maroon). Source: elaborated by the authors

a. Teatinos Observation Area (urban)

As illustrated in Figs 6 and 7, the Teatinos University Campus in 2024 reveals a pronounced spatial differentiation in thermal behavior driven by solar exposure and surface characteristics. At the maximum thermal stress period, solar radiation strikes the surface of the Earth at a nearly perpendicular angle, intensifying heat absorption, particularly in unshaded zones. This effect is especially evident in the "Dirt Area" and the "Asphalt Area," which exhibit the highest recorded surface temperatures due to their lack of vegetation or structural cover and high thermal inertia.

Figure 7. Temperature and humidity index (THI) calculated on April 21 at 12:30 (noon) at the Teatinos (PM, urban) and Coín (CO, rural) Observation Areas. PM.01: Dirt Area, PM.02: Asphalt Area, PM.03: Pergola with Wisteria (vine), PM.04: Interior Courtyard, PM.05: Pavilion E4, PM.06: Botanical Garden, CO.01: Grapevine arbor, CO.02: Irrigation pool, CO.03: Fig tree, CO.04: Hackberry trees, CO.05-07: Sun1-Sun3. Source: elaborated by the authors according to Eq. 1

In contrast, areas such as the "Botanical Garden", the "Pergola with wisteria", and the "Pavilion E4" consistently maintain lower temperatures, as can also be observed in the morning isopleths. These zones demonstrate the critical role of shading and airflow in mitigating heat. "Pavilion E4" exemplifies this effect. Its roofed structure, combined with louvered side panels, provides effective protection from direct solar radiation while facilitating cross-ventilation. Similarly, the pergola benefits from the combined shading of vegetation and open architectural design, reducing radiant heat load while allowing air movement.

The mapped thermal comfort values (THI) confirm that these shaded and vegetated environments provide the most thermally comfortable conditions on campus during peak heat hours. Notably, the midday period exhibits the widest thermal differentials across the site, highlighting the spatial impact of bioclimatic interventions. Areas with greater vegetative density and architectural shading exhibit significantly moderated microclimates, characterized by lower ambient temperatures and more stable relative humidity, which are conducive to human comfort and meet the criteria to be designated as climate refuges.

b. Coín Observation Area (rural)

As illustrated in Fig. 6, the THI in the sampling points "Grapevines Arbor", "Hackberry trees", and "Irrigation pool" registered the best THI values, indicating elevated levels of thermal comfort and a more pleasant thermal sensation for humans. In this same figure, these

locations appear below the positive line, confirming that they recorded lower temperatures relative to the Coín reference meteorological station. Conversely, sampling points "Sun 1", "Sun 2", and "Sun 3" are situated in topo-climates characterized by elevated temperatures and low relative humidity, which translate into marked thermal discomfort conditions.
The superior thermal performance of "Grapevines Arbor", "Hackberry trees", and "Irrigation pool" is closely linked to the presence of vegetation, which plays a critical role in microclimatic regulation. Vegetation can block up to 90% of incoming solar radiation, absorbing and transforming it into energy for photosynthesis and evapotranspiration, significantly reducing ambient temperature beneath the canopy (Aram et al., 2020). During evapotranspiration, leaf stomata act as thermoregulatory valves, opening under high temperatures (when water is available) and releasing moisture into the air, thereby increasing relative humidity and cooling the surrounding environment (Castelán Lorenzo, 2022; Poveda Santos et al., 2021).

Among all sampling points, the "Grapevines arbor," a vegetated architectural system, emerged as the most thermally comfortable and health-supportive microenvironment. It consistently recorded the lowest temperatures and maintained optimal humidity levels throughout the day. These favorable conditions can be attributed to the presence of climbing plants and its horizontal structural orientation, maximizing shading. A pergola, thus, represents a climate refuge prototype, offering a thermally stable and human-friendly environment even under extreme weather conditions.

4. Conclusions

This study highlights that among the architectural elements analyzed, structures integrated with well-selected vegetation provide the most effective improvement in thermal comfort. Compared to other sampled spaces, such as bare soil zones and asphalt parking lots, which exhibited high thermal stress due to direct solar exposure and lack of shading, vegetated architectural models consistently showed lower temperatures and more favorable Thermal Comfort Index (THI) values (Equation 1). Notably, the results reveal that the grapevine arbor in Coín (rural area), representing a vernacular, low-impact design, outperformed the modern wisteria-covered pergola in Teatinos (urban area). This demonstrates that ancestral architectural practices and the use of traditional, climate-adapted plant species can be more effective than contemporary bioclimatic adaptations. While other systems, such as green roofs were not examined in this study, the findings support the conclusion that the strategic convergence of the five bioclimatic pillars, i.e., urban planning, architecture, vegetation, landscaping, and materials, when applied to vegetated architectural models, creates optimal microclimates that enhance thermal comfort. As such, well-designed, vegetated pergolas stand out as a low-cost, high-impact solution for mitigating urban heat and improving habitability in Mediterranean climates.

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Data availability statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

Ethics statements

Studies involving animal subjects: No animal studies were carried out in this study.
Studies involving human subjects: No human studies were carried out in this study. Inclusion of identifiable human data: No potentially identifiable human images or data are included in this study.

Conflict of Interests

The Authors declare that there are no conflicts of interest to disclose.

References

AdapteCCa (2023). AdapteCCa's climate change scenario viewer: interactive query and access to scenarios. Ministry for the Ecological Transition and the Demographic Challenge of Spain.

Agencia Estatal de Meteorología AEMET. (2024). Informe sobre el estado del clima de España 2024 https://doi.org/10.31978/666-25-002-1.2024

Amblar, M. P., Casado Calle, M. J., Pastor Saavedra, M. A., Ramos Calzado, P., & Rodríguez Camino, E. (2017). Guide to regionalised climate change scenarios for Spain based on the results of the IPCC-AR5. Aragón Correa, J. A., Hurtado-Torres, N. E., Sharma, S., & García-Morales, V. J. 2018. Strategic proactivity and firm approach to the natural environment. *Academy of Management Journal, 51*(5), 971–985. NIPO: 014-17-010-8

Aram, F., Solgi, E., Baghaee, S., García, E. H., Mosavi, A., & Band, S. S. (2020). How parks provide thermal comfort perception in the metropolitan cores; a case study in Madrid Mediterranean climatic zone. *Climate Risk Management*, *30*, 100245. https://doi.org/10.1016/j.crm.2020.100245

Cano Giraldo, J. (2024). Architecture adapted to local climate cycles: Adaptive technologies, bioclimatic architecture, and coastal landscape. (Bachelor's thesis, School of Architecture and Design). DC: 2024-05-31T22:05:31Z

Castelán Lorenzo, M. (2022). Cooling and condensation capacity of atmospheric humidity of shade trees in coffee plantations in the Pluma Hidalgo region, Oaxaca. *Chapingo Magazine Tropical Agriculture Series*, *2*(1), 33-43. https://doi.org/10.5154/r.rchsagt.2022.03.03

Espín Sánchez, D., & Olcina, J. (2025). Evolution of climate comfort on the southeast coast of the Iberian Peninsula and its relationship with climate change. Boletín de la Asociación de Geógrafos Españoles, (104). https://doi.org/10.21138/bage.3487

Ferrelli, F., & Piccolo, M. C. (2017). Climatic comfort perception and urban planning: Assessing bioclimatic conditions in urban open spaces. *Urban Climate, 20*, 168–181. https://doi.org/10.1016/j.uclim.2017.04.002

García, F. F. (2003). Fundamentos físicos y métodos de evaluación del confort climático en los estudios de Bioclimatología humana. *VI Reunion nacional de climatologia, Asociación de Geográfos Españoles Santiago de Compostela*, 135-170. ISBN: 84-9750-142-X: DC: C-1423/2003.

Guerrero Serrano, P.M., Salvo Tierra, A.E., Cozano-Pérez, P., Macías, N., & Pereña-Ortiz, J.F. (2024). Conceptualization of Climate Comfort Areas and Their Typologies in the Mediterranean Region. DOI:10.13140/RG.2.2.24929.21601.

Hammer, O., Harper, D.A.T., Ryan, P.D. 2001. PAST: Paleontological Statistics software package for education and data analysis. Palaeontologia Electronica 4(1): 9 pp.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. ISBN: 978-92-9169-143-2

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647.

Jendritzky, G. (1991). Selected questions of topical interest in human bioclimatology. *International Journal of Biometeorology*, *35*, 139-150. https://doi.org/10.1007/BF01049060

Junta de Andalucía. (2022). *Andalusian Plan for the Prevention of the Effects of Excessive Temperatures on Health (2022)*. ISBN: 978-84-18778-48-3

Lee, F. S., Van Cura, J. E., & BeGole, E. (1998). A comparison of root surface temperatures using different obturation heat sources. *Journal of endodontics*, *24*(9), 617-620. https://doi.org/10.1016/S0099-2399(98)80123-4

Montalbán Pozas, B., Lucas Bonilla, M., Lorenzo Gallardo, J. M., & Bote Alonso, I. (2025). Understanding the Impact of Thermal Performance on Thermal Comfort in Dwellings: A Large-Sample Study With a Homogeneous User Profile. *Indoor Air*, *2025*(1), 5533639. https://doi.org/10.1155/ina/5533639

Morelli, T. L., Daly, C., Dobrowski, S. Z., Dulen, D. M., Ebersole, J. L., Jackson, S. T., ... & Beissinger, S. R. (2016). Managing climate change refugia for climate adaptation. *PloS one*, *11*(8), e0159909. https://doi.org/10.1371/journal.pone.0159909

de Oliveira, L. M., Yanagi Junior, T., Ferreira, E., Carvalho, L. G. D., & Silva, M. P. D. (2006). Bioclimatic zoning of the southeastern region of Brazil for animal and human thermal comfort. *Agricultural Engineering*, *26*, 823-831. https://doi.org/10.1590/S0100-69162006000300020

Pesqueira Calvo, C., Fernández Nieto, M. A., García Carbonero, M., & Lara Ruiz, M. (2018). *Plant architecture: material strategies*. Ediciones Asimétricas. ISBN: 978-8494917813

Poveda Santos, J. J., Díaz Martínez, B., & Rodríguez García, E. (2021). Vegetation as a climate modulator in urban spaces. *Journal of Urbanism and Sustainability, 15*(2), 44–58. https://doi.org/10.14198/ruys.2021.15.02.03

Ramírez-Cuastuza, A. G., & Alarcón-Rodríguez, O. M. (2024). Evaluation of energy demand and thermal comfort in climate change scenarios for tropical housing: the case of San Andrés and Providencia, Colombia. *AUS-Architecture/Urbanism/Sustainability*, (35), 99-107. https://doi.org/10.4206/aus.2024.n35-11

Rodríguez Camino, E. (2013). *Climate Change 2013: Physical Basis*. www.climatechange2013.org

Rodríguez Escandell, A. (2024). Evolution of bioclimatic strategies in Mediterranean buildings in the face of climate change. Bachelor's thesis, Universitat Politècnica de Catalunya, Spain. DC: 2024-07-23T09:34:54Z

Thom, E. C. (1959). The discomfort index. *Weatherwise*, *12*(2), 57-61.https://doi.org/10.1080/00431672.1959.9926960

Weller, R. N., Kimbrough, W. F., & Anderson, R. W. (1996). Root surface temperatures produced during post-space preparation. *Journal of Endodontics*, *22*(6), 304-307. https://doi.org/10.1016/S0099-2399(96)80264-0