

COMPARATIVE THERMAL EVALUATION OF A VEGETATIVE SHADING STRUCTURE AND A SYNTHETIC SHADE NET IN PARRAL, CHILE

EVALUACIÓN TÉRMICA COMPARATIVA DE UNA ESTRUCTURA DE SOMBREADO VEGETAL Y UNA MALLA DE SOMBREADO ARTIFICIAL EN PARRAL, CHILE

AVALIAÇÃO TÉRMICA COMPARATIVA DE UMA ESTRUTURA DE SOMBREAMENTO VEGETAL E DE UMA TELA DE SOMBREAMENTO ARTIFICIAL EM PARRAL, CHILE

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ABSTRACT

This study comparatively evaluates the thermal performance of a grapevine pergola and a shade net as conditioning strategies for intermediate outdoor spaces in a temperate climate. An in situ experiment was conducted in Parral, Chile, using environmental measurements collected over a 14-day summer period as part of an exploratory approach. Air temperature, relative humidity, wind speed, and globe temperature were recorded, and mean radiant temperature and the Universal Thermal Climate Index (UTCI) were calculated for the period between 11 am and 4 pm. The results indicate the grapevine pergola performed better, with a lower UTCI and mean radiant temperature values than those recorded under the shade net. The greatest difference between the two conditions was observed for the second parameter, with daily variations ranging from 2.6 to 4.3 °C. It is concluded that the grapevine pergola constitutes a more effective passive strategy for improving outdoor thermal comfort.

Keywords

overheating, grapevine pergola, outdoor thermal comfort, transitional spaces

RESUMEN

Este estudio evalúa comparativamente el comportamiento térmico de un parrón y una malla de sombreado como estrategias de acondicionamiento de espacios exteriores intermedios en clima templado. Se desarrolló un experimento in situ en la ciudad de Parral, Chile, mediante mediciones ambientales durante 14 días de verano, con un enfoque exploratorio. A partir del registro de temperatura del aire, humedad relativa, velocidad del viento y temperatura de globo, se calcularon la temperatura radiante media y el índice UTCI entre las 11:00 y las 16:00 h. Los resultados evidencian un mejor desempeño del parrón, con valores menores de UTCI y de temperatura radiante media que los de la malla. La mayor diferencia entre ambas condiciones se observó en este último parámetro, con variaciones diarias de 2,6 a 4,3 °C. Se concluye que el parrón constituye una estrategia pasiva más efectiva para mejorar el confort térmico exterior.

Palabras clave

sobrecalentamiento, parrón, confort térmico exterior, espacios intermedios

RESUMO

Este estudo avalia comparativamente o comportamento térmico de um pergolado com parreira e de uma tela de sombreamento como estratégias de condicionamento de espaços exteriores intermediários em clima temperado. Desenvolveu-se um experimento in situ na cidade de Parral, Chile, com medições ambientais ao longo de 14 dias de verão, adotando-se uma abordagem exploratória. A partir do registro da temperatura do ar, da umidade relativa, da velocidade do vento e da temperatura de globo, calcularam-se a temperatura radiante média e o índice UTCI entre 11h e 16h. Os resultados evidenciam um melhor desempenho do pergolado com parreira, com valores mais baixos de UTCI e de temperatura radiante média em comparação à tela. A maior diferença entre as duas condições foi observada neste último parâmetro, com variações diárias de 2,6 a 4,3 °C. Conclui-se que o pergolado com parreira constitui uma estratégia passiva mais eficaz para melhorar o conforto térmico exterior.

Palavras-chave

Superaquecimento, pergolado com parreira, conforto térmico exterior, espaços intermediários



Figure 1. Two examples of grapevine pergolas and their deciduous behavior. Source: Prepared by the authors.

INTRODUCTION

The environmental conditioning of outdoor spaces is a growing challenge amid climate change and the intensification of the urban heat island (Intergovernmental Panel on Climate Change [IPCC], 2023). In cities and regions with temperate climates, rising temperatures and increased solar radiation have worsened thermal comfort in outdoor spaces, affecting their inhabitability and everyday use (Liu et al., 2025; Wang et al., 2023). In this scenario, passive climate mitigation strategies, particularly those based on vegetation, have become relevant as sustainable alternatives to energy-intensive technological solutions (Gherri, 2023).

In this sense, the literature has extensively addressed the role of green infrastructure across different scales, from urban trees to plant-based construction systems (Bowler et al., 2010). On the latter, it has been shown that the incorporation of vegetation in enclosures can significantly reduce the mean radiant temperature in outdoor environments (Perini & Magliocco, 2014) and the surface temperature of walls exposed to direct solar radiation, depending on variables such as leaf density and vegetation cover (Nasr et al., 2024).

For cooling outdoor spaces, in addition to incorporating vegetation on walls, facades, or roofs, there are vegetative shades, built with horizontal structures that control solar radiation using climbing species, typically seen on pergolas. In these cases, vegetation acts as an effective climate mediator through two main mechanisms: reducing incident solar radiation via shading and evaporative cooling associated with evapotranspiration (Salonen et al., 2022; Wu et al., 2024). These processes reduce both surface and air temperatures, improving thermal comfort in outdoor spaces and mitigating the urban heat island effect.

Recent evidence agrees that the shade generated by vegetation tends to offer a better thermal performance than artificial devices, both in reducing temperature and improving outdoor thermal comfort

(Kusaka, Asano & Kimura, 2022). In contrast, there is less systematization of knowledge regarding traditional devices that, in local contexts, have fulfilled similar roles in environmental conditioning. In this context, the grapevine pergola—a vegetation-based structure associated with grape cultivation—is a characteristic element of vernacular architecture in temperate climates, particularly in Mediterranean regions and Chile's central valley. The grapevine pergola can provide habitable intermediate spaces by generating shade and favorable microclimates. Its use has been documented in rural and domestic practices in the country, where it is part of everyday life (Aravena Alvarado, 2015).

From an environmental perspective, its trait as a deciduous species (Figure 1) enables efficient seasonal adaptation, providing shade in summer and allowing solar radiation to enter in winter, as in other deciduous species (Zhang et al., 2022). From the physical point of view, the grapevine pergola acts as a thermal regulation system that combines shading and evapotranspiration. Despite its presence in both rural and urban environments, the grapevine pergola has been progressively replaced by solutions with rapid, economical implementation, such as high-density polyethylene shading meshes. These provide immediate control of solar radiation and generate cooling effects that enhance thermal comfort (Lopez-Cabeza et al., 2022; Zhao et al., 2024).

This replacement of an ancestral solution by an artificial element is not solely a matter of technical criteria, but also part of broader standardization dynamics driven by public policies and the market, which tend to displace vernacular strategies. Similar phenomena have been documented in other contexts, where the incorporation of industrialized solutions has contributed to the homogenization of vernacular built environments (Arias Tapiero, Ortega & Vasconcelos, 2025). Consequently, a progressive loss of the relevance of identity is observed in the configuration of outdoor spaces, particularly in rural areas (Figure 2).



Figure 2. People in front of a grapevine pergola and mesh shading system. Source: Prepared by the Authors.

Although there is a consolidated body of research on the role of vegetation as a climate mediator, recent research on the thermal performance of vegetation has mainly concentrated on contemporary systems, such as walls (Jim, 2015; Zheng et al., 2025), facades (MacIvor & Margolis, 2015) and green roofs (From Christ et al., 2025), so a specific gap is identified in the study of plant shadders as environmental conditioning devices. In this context, this study aims to analyze the effect of the grapevine pergola on the thermal behavior of outdoor spaces, as a representative case of vegetative shading, and compare it with a contemporary solution based on shading mesh, to evaluate its effects on micro-meteorological conditions and its potential as an environmental conditioning strategy.

METHODOLOGY

STUDY SITE

The study was conducted in the city of Parral, located in Chile's central valley (36°08' S, 71°49' W), an area characterized by a temperate climate with Mediterranean influence (Csb), according to the Köppen-Geiger classification. This climate has hot,

dry summers with high solar radiation and large daily temperature ranges, and colder, wetter winters.

These conditions allow evaluating the performance of shading strategies in scenarios representative of everyday life in south-central Chile, particularly in contexts with high summer sun exposure. According to the historical records of the nearest weather station, average maximum air temperatures during the warm months reach 28.1 °C in December, 30.6 °C in January, 30.0 °C in February, and 26.5 °C in March. Specifically for this last month, in which the measurements were made, the absolute maximum temperatures recorded range from 31.4 °C to 34.3 °C (Servicios Climáticos, 2026).

EXPERIMENTAL DESIGN

The design adopts an exploratory experimental approach, based on in situ measurements, to analyze the thermal behavior of a pre-existing plant shading system (grapevine pergola) compared with a localized surface covered with high-density polyethylene shading mesh (mesh). The study was conducted in a single intervened space, in which a limited mesh surface (1.0 × 1.2 m) was introduced, allowing localized micro-meteorological variations within the same environment. This approach considers operational constraints specific to the case study and is proposed as an exploratory strategy to identify initial comparative trends (Figure 3).

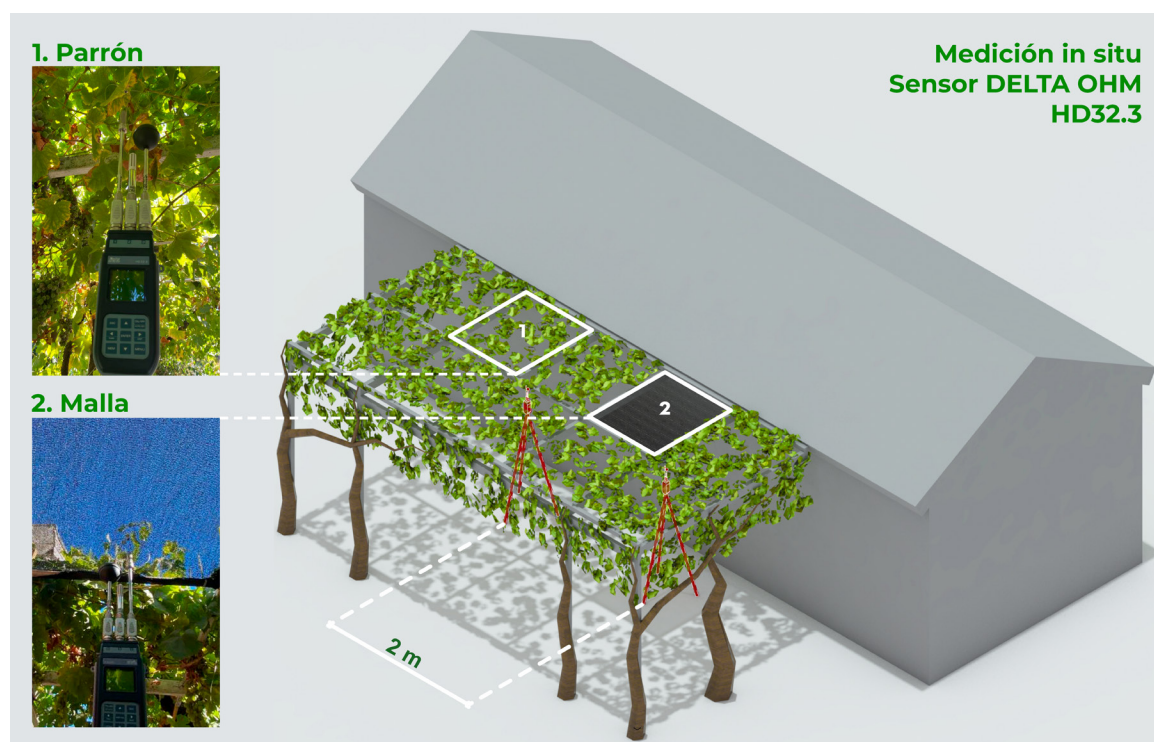


Figure 3. Layout of shading strategies studied. Source: Prepared by the Authors.

Measurements were taken at specific positions under both conditions to capture variations in thermal behavior on a micro-meteorological scale. In particular, the globe temperature was recorded beneath the mesh, approximately 75 cm from the shading surface and 1.55 m above ground level, representative of the exposure height of the human body in a standing position (Zhao et al., 2024). Data loggers and sensors were used, positioned at the center of the shading systems studied, 2 meters apart.

The measurement campaign was conducted over a continuous 14-day period during the summer season. This duration allows for the recording of daily thermal cycles and reduces the influence of specific meteorological events, improving the representativeness of the data, in line with methodological recommendations for environmental field studies (Arias-Jimenez et al., 2026; Guerrero-Blond et al., 2017; Umishio et al., 2024).

The measurements were taken by sensors installed in the study space, with a 10-minute recording interval during each 24-hour period. In similar research, the analysis time window has been restricted to capture the critical peaks of thermal stress and avoid distortions caused by low solar altitude (Elgheznawy & Eltarabily, 2021; Lee et al., 2018; Zhao et al., 2024). In accordance with this criterion, a sunlight study was run using a georeferenced digital replica of the experimental site in Archicad to identify the period

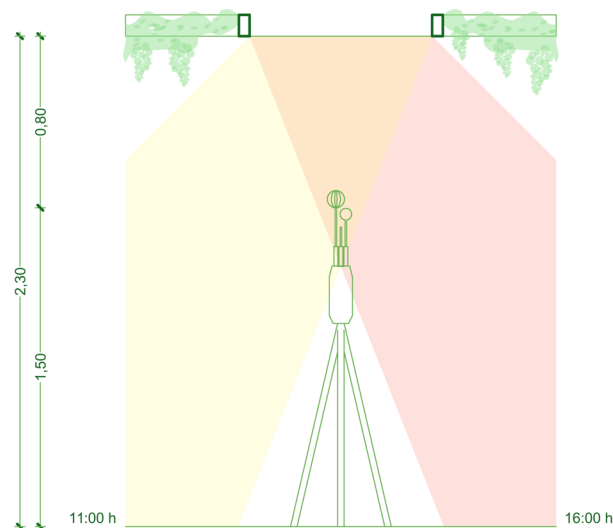


Figure 4. Period of incident solar radiation on the sensor.
Source: Prepared by the Authors.

of greatest solar exposure over the analyzed area. Based on this procedure, the interval from 11 am to 4 pm was defined as the study window (Figure 4). This made it possible to evaluate the shading performance under consistent sunlight conditions and concentrate the analysis on the hours of greatest thermal demand. In this way, the sensors recorded the variables of the outdoor thermal environment necessary for thermal evaluation of the space in the shade (Table 1 and Table 2).

Variable	Unit
t_a	Air temperature (°C)
t_g	Globe temperature (°C)
v_a	Wind speed (m/s)
RH	Relative humidity (%)

Table 1. Measured meteorological variables. Source: Prepared by the Authors.

Component / Probe	Type of Sensor	Operating Range	Accuracy / Tolerance Class	Resolution
Base Unit (HD32,3)	Processor with SICRAM inputs	T: -5 to 50 °C RH: 0 to 90%	±1 digit at 20 °C	N/A
Globe thermometer	Pt100 (Ø = 50 mm / 150 mm)	-10 to 100 °C	Class 1/3 DIN	0.1 °C
Combined Thermohygrometer	Pt100 (T) Capacitive (RH)	T: -40 to 80 °C RH: 0 to 100%	T: Class 1/3 DIN RH: ±1,5% (0-90%) / ±2% (90-100%) at 15-35 °C	T: 0.1 °C RH: 0.1%
Omnidirectional Anemometer	Hot wire (NTC 10 kΩ)	v: 0.1 to 5 m/s T: 0 to 80 °C	±0.2 m/s (0.1 to 1 m/s) ±0.3 m/s (1 to 5 m/s)	0.01 m/s

Table 2. Technical specifications and operating ranges of the DELTA OHM HD32,3 microclimatic monitoring system. Source: Prepared by the Authors.

To evaluate the outdoor thermal conditions, two complementary indicators were established. The mean radiant temperature (T_r) was used as a physical variable to characterize the radiative load of the environment on the human body, accounting for solar, reflected, and long-wave radiation emitted by surrounding surfaces. In outdoor spaces, this variable is especially relevant for analyzing the physical-radiative performance of shading systems and their influence on the thermal perception of the environment (López-Cabeza et al., 2022; Mihalakakou & Romeos, 2026). The Universal Thermal Climate Index [UTCI] (COST European Cooperation in Scientific and Technical Research, 2026) was also used as a biometeorological index of external thermal stress, which expresses an equivalent temperature derived from a thermophysiological model that integrates air temperature, relative humidity, wind speed, and thermal radiation to represent the human physiological response to the environment (Błażejczyk et al., 2013; Bröde et al., 2012). Its use is relevant to comparative studies of outdoor comfort under sunny, built-shade, and vegetative-shading conditions (Watanabe et al., 2014). Thus, the t_r allowed comparing the radiative performance of the shading system, while the UTCI allowed evaluating its effects on thermal comfort conditions at the pedestrian scale.

CALCULATION OF MEAN RADIANT TEMPERATURE

The mean radiant temperature (T_r) is calculated by the sensor from the measured parameters: globe temperature (T_g), air temperature (t_a), and wind speed (v_a); the following formulas were used, as established in the standard ISO 7226:2025.

When the air speed is less than 0.2 m/s, (Equation 1).

$$t_r = \left[(t_g + 273)^4 + \frac{0.25 \times 10^8}{\varepsilon_g} \left(\frac{t_g - t_a}{D} \right)^{1/4} \times (t_g - t_a) \right]^{1/4} - 273 \quad (\text{Equation 1})$$

When the air speed is greater than or equal to 0.2 m/s, (Equation 2).

$$t_r = \left[(t_g + 273)^4 + \frac{1.1 \times 10^8 \times v_a^{0.6}}{\varepsilon_g \times D^{0.4}} (t_g - t_a) \right]^{1/4} - 273 \quad (\text{Equation 2})$$

Where D = diameter of the globe thermometer; $\varepsilon_g = 0.95$, the presumed emissivity of the globe thermometer; t_g = globe temperature; t_a = air temperature; and v_a = air speed.

Measurement condition	Convection regime (ISO 7726)	Average combined uncertainty (u_c) [°C]	Minimum uncertainty ($u_{c\max}$) [°C]	Maximum uncertainty ($u_{c\max}$) [°C]
t_r mesh	Natural	± 0.155	± 0.077	± 0.179
	Forced	± 0.747	± 0.105	± 2.215
t_r grapevine pergola	Natural	± 0.146	± 0.082	± 0.167
	Forced	± 0.516	± 0.105	± 1.198

Table 3. Comparative analysis of the uncertainty of the calculation of t_r . Source: Prepared by the Authors

CALCULATION OF THE UTCI INDEX

The UTCI index, defined as a multivariate function of air temperature, mean radiant temperature, air velocity, and water vapor pressure, is defined by (Equation 3):

$$UTCI = f(t_a, t_r, v_a, P) \quad (\text{Equation 3})$$

Where t_a is the air temperature, t_r is the mean radiant temperature, v_a is the air speed, and P is the water vapor pressure (hPa). The values of t_a and RH were obtained directly by the Delta OHM HD32.3 sensor, while P was calculated by means of (Equation 4):

$$P = \left(\frac{HR}{100}\right) \times 0,6108 \times \exp\left(\frac{(17,27 \times t_a)}{(t_a + 237,3)}\right) \quad (\text{Equation 4})$$

Where P is expressed in hectopascals, (Equation 5):

$$hP = \frac{P}{100} \quad (\text{Equation 5})$$

As far as the v_a is concerned, although the classic formulation of the UTCI uses the wind speed referred to 10 m high (Bröde et al., 2012), in this study, the speed measured in situ at 1.55 m above ground level was used, since the evaluation was carried out on a pedestrian scale under the shading systems. Recent studies indicate that the standard wind treatment may not adequately represent the airflow in the urban pedestrian layer and that the meteorological variables used in its calculation should originate from that same scale of human exposure (Read et al., 2025). The UTCI values were calculated using a computational implementation available on the UTCI-COST Action 730 web platform, based on the formulation proposed by Bröde et al. (2012).

DATA VALIDATION AND ANALYSIS

The quantification of the combined uncertainty margin for t_r and the UTCI was performed in accordance with international guidelines (Bureau International

des Poids et Mesures [BIPM], 2008). The standard uncertainties of each input variable were determined from the maximum allowable errors specified in the manufacturer's technical datasheets (Table 2), assuming a rectangular probability distribution.

Because the equations of t_r from the norm ISO 7726:2025 and the UTCI polynomial are complex and non-linear formulas, the error propagation was solved as a coupled system. This approach links the UTCI directly to the instrument's primary readings, avoiding duplication of variance when evaluating the intermediate variables. The sensitivity coefficients for each parameter were numerically approximated, point by point, for the 478 observations in the database using the central finite-difference method. Finally, the total combined uncertainty was obtained by the quadrature total of the weighted individual errors.

Regarding the measurements, since they were carried out in the same environment and under simultaneous conditions, the data were analyzed as paired time series, which allows direct comparison of the values recorded at each instant. Firstly, a descriptive analysis of the measured variables was conducted, considering the average and maximum values and their hourly evolution within the study period (11 am to 4 pm), to identify thermal behavior patterns under high solar radiation exposure. Secondly, variations between paired measurements over time were evaluated using paired comparisons, which allow the identification of systematic variations associated with vegetation-based and artificial shading. Finally, differences between the t_r values recorded and the UTCI index values were analyzed, due to their relevance in the characterization of outdoor thermal comfort.

MARGIN OF UNCERTAINTY

Based on the metrological analysis of coupled propagation (BIPM, 2008) applied to the 478 observations of each measurement condition, the final standard combined uncertainty (u_c) [°C] for

Measurement condition	Average combined uncertainty (c) [°C]	Minimum uncertainty (uc max) [°C]	Maximum uncertainty (ucmax) [°C]	Final expanded uncertainty (U) 95% Confidence [°C]
UTCI mesh	± 0,115	± 0,284	± 0,412	± 0,230
UTCI grapevine pergola	± 0,137	± 0,089	± 0,076	± 0,274

Table 4. Comparative analysis of the uncertainty in UTCI calculations. Source: Prepared by the Authors.

the results of t_r and of the UTCI can be reviewed in Table 3 and Table 4. The analysis of the margin of error shows that the accuracy of t_r depends on the chosen method. The natural convection model (calm air) is highly stable, with an average error of ± 0.150 °C, while the forced convection model (with wind) raises the average error to between ± 0.516 °C and ± 0.747 °C due to the wind sensor. The latter method becomes unstable in absolute calm (less than 0.1 m/s), the point error being triggered at ± 2.215 °C. Despite this, the UTCI maintains an average error of less than ± 0.137 °C and a definitive total error of less than ± 0.274 °C (with 95% confidence). This stability occurs because the system compensates for errors internally: the direct cooling of the wind on the human body is opposed by the indirect effect on the globe thermometer, which balances the sensor's deviations in the final result. This supports the instrumental relevance and the calculation procedure for the comparative analysis developed within the study's exploratory scope.

RESULTS AND DISCUSSION

INITIAL METEOROLOGICAL DATA

During the monitoring period (March 01-14, 2024), the meteorological conditions recorded between 11 am and 4 pm show relatively stable behavior, with limited variation between days and consistent differences between the two measurement conditions (Table 5). The t_a under the mesh has daily average values ranging from 22.6 °C to 28.3 °C, while under the grapevine pergola, it varies from 21.1 °C to 26.5 °C. On all recorded days, the air temperature under the grapevine pergola is lower than that under the mesh, with differences ranging from approximately 1.3 °C to 2.0 °C. The differences between the two conditions were consistently maintained throughout the period, with higher values in the mesh condition.

Regarding the RH, the values recorded under the shading mesh are between 31.2% and 46.8%, while under the grapevine pergola, they range between

Day	ta (°C) mesh	tg (°C) mesh	va (m/s) mesh	HR (%) mesh	ta (°C) grapevine pergola	tg (°C) grapevine pergola	va (m/s) grapevine pergola	HR (%) grapevine pergola
01-03-2024	28,2	30,4	0,3	32,3	26,5	27,7	0,3	36,5
02-03-2024	26,5	28,3	0,4	31,2	25,0	26,1	0,4	34,8
03-03-2024	24,5	26,7	0,3	33,7	22,9	24,2	0,3	37,8
04-03-2024	26,2	28,4	0,2	35,0	24,5	25,8	0,2	38,8
05-03-2024	28,3	30,3	0,3	35,0	26,5	27,6	0,3	39,1
06-03-2024	26,8	28,9	0,2	42,8	25,3	26,5	0,2	47,2
07-03-2024	23,6	25,3	0,3	38,3	22,3	23,3	0,3	41,4
08-03-2024	24,1	25,8	0,3	38,9	22,9	23,8	0,3	42,0
09-03-2024	25,3	27,1	0,3	35,3	23,8	24,9	0,3	39,5
10-03-2024	22,6	24,2	0,2	46,8	21,1	22,1	0,2	51,1
11-03-2024	25,7	27,5	0,3	37,3	24,1	25,1	0,3	41,2
12-03-2024	26,2	27,7	0,3	40,5	24,7	25,6	0,3	44,0
13-03-2024	24,1	26,0	0,3	41,6	22,2	23,4	0,3	46,8
14-03-2024	25,0	26,6	0,4	36,2	23,2	24,3	0,4	40,7

Table 5. Average day values for each variable recorded. Source: Prepared by the Authors.

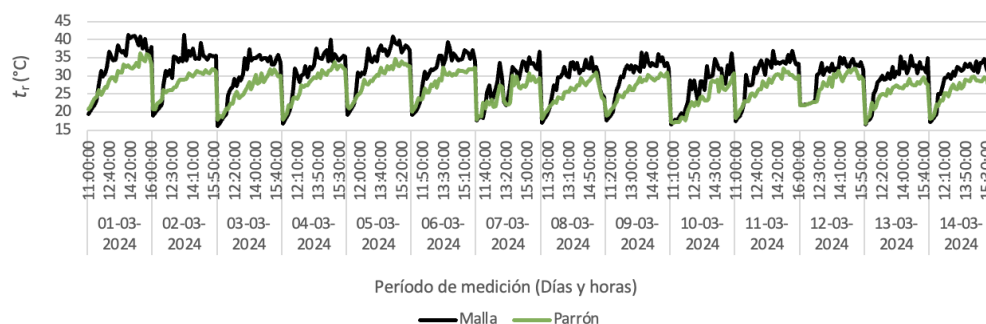


Figure 5. t_r throughout the analyzed measurement period. Source: Prepared by the Authors.

Day	Mesh	Grapevine Pergola	Difference Mesh - Grapevine Pergola
01-03-2024	34.0	29.8	4.2
02-03-2024	32.3	28.1	4.2
03-03-2024	30.2	26.1	4.1
04-03-2024	31.2	27.9	3.3
05-03-2024	33.6	29.3	4.3
06-03-2024	32.0	28.3	3.7
07-03-2024	28.0	25.1	2.9
08-03-2024	28.6	25.3	3.3
09-03-2024	30.4	26.7	3.7
10-03-2024	26.6	23.4	3.1
11-03-2024	30.6	26.9	3.8
12-03-2024	30.0	27.4	2.6
13-03-2024	29.4	25.5	3.9
14-03-2024	29.7	26.2	3.5

Table 6. Daily average t_r (°C) values of the analyzed schedule. Source: Prepared by the Authors.

34.8% and 51.1%. In all cases, relative humidity is higher under the grapevine pergola, with differences ranging from approximately 3% to 5%. v_a presents low and practically constant values in both conditions, between 0.2 and 0.4 m/s, with no appreciable differences between the measurement points due to the proximity of the sensors in both cases.

On the other hand, the t_g ranges from 24.2 °C to 30.4 °C under the shading mesh and from 22.1 °C to 27.7 °C under the grapevine pergola. The differences between the two conditions were consistently maintained throughout the period, with higher values under the mesh. Overall, the recorded meteorological conditions indicate higher temperatures and lower RH under the shading mesh, whereas the grapevine pergola shows lower temperatures and higher RH, with similar wind speeds in both configurations.

AVERAGE RADIANT TEMPERATURE BEHAVIOR

During the analysis period, t_r has constant differences between the two evaluated conditions. The maximum temperature was reached on 01-03-2024 at 2:10 pm, with 41.3 °C under the mesh, while the space under the grapevine pergola was 33 °C, a difference of 8.3 °C. Meanwhile, the maximum temperature under the grapevine pergola was recorded one hour later, at 3:10 pm, at 36.2 °C, while the mesh recorded 40.8 °C, a difference of 4.6 °C (Figure 5). On the other hand, the maximum average daily value under the mesh reaches 34 °C, while under the grapevine pergola it is 29.8 °C, resulting in a difference of 4.2 °C, both observed on 01-03-2024. Consistently lower values are presented under the grapevine pergola throughout the period (Table 6).

Measurement time	Mesh	Grapevine Pergola	Difference Mesh - Grapevine Pergola
11:00:00	18.0	19.0	-1.0
11:30:00	20.2	21.8	-1.6
12:00:00	27.8	23.5	4.3
12:30:00	30.1	25.3	4.8
13:00:00	31.3	26.6	4.7
13:30:00	33.5	27.8	5.7
14:00:00	33.8	29.1	4.7
14:30:00	34.7	29.8	4.9
15:00:00	34.3	30.3	4.0
15:30:00	34.6	30.7	3.9
16:00:00	33.8	29.8	3.9

Table 7. t_r (°C) values every 30 minutes on an average day. Source: Prepared by the Authors.

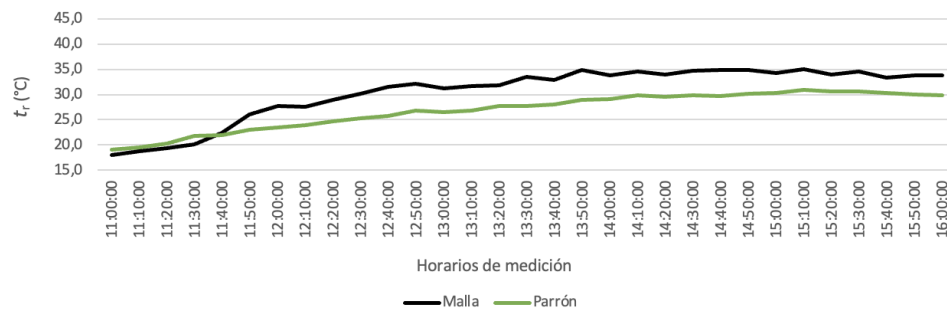


Figure 6. Behavior of t_r on an average day. Source: Prepared by the authors.

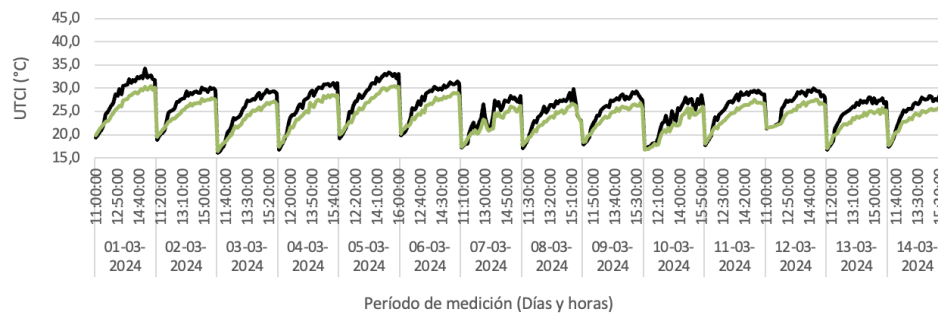


Figure 7. UTCI index over the analyzed measurement period. Source: Prepared by the authors.

The analysis of the average day (Table 7 and Figure 6) reveals clear time dependence. In the early morning intervals (11 am - 11:30 am), the t_r under the mesh is slightly lower than that recorded under the grapevine pergola (up to 1.7 °C). From 12 pm, this relationship is reversed in a sustained way: the t_r under the mesh consistently exceeds that of the grapevine pergola, with differences that scale to reach values between 4 and 5.9 °C between 1 pm and 3 pm, coinciding with the highest incidence of direct solar radiation. From 3:20

pm to 4 pm, the gap narrows, dropping to a difference between 3.9 and 3.1 °C.

UTCI INDEX BEHAVIOR

During the analysis period, the UTCI presents constant differences between the two evaluated conditions. The maximum temperature was reached on 01-03-2024, with 34.2 °C under the mesh at 3:10 pm, while the space under the grapevine pergola was at 30.3 °C,

Day	Mesh	Grapevine Pergola	Difference Mesh - Grapevine Pergola
01-03-2024	28,7	26,5	2,2
02-03-2024	26,8	25,0	1,9
03-03-2024	25,0	23,1	1,9
04-03-2024	26,7	24,6	2,1
05-03-2024	28,8	26,6	2,2
06-03-2024	27,7	25,8	1,9
07-03-2024	24,0	22,5	1,5
08-03-2024	24,6	23,0	1,6
09-03-2024	25,7	23,9	1,8
10-03-2024	23,3	21,7	1,7
11-03-2024	26,2	24,2	2,0
12-03-2024	26,7	24,9	1,8
13-03-2024	25,0	22,9	2,1
14-03-2024	25,4	23,4	1,9

Table 8. Average UTCI (°C) values of the analyzed daily times. Source: Prepared by the Authors.

Day	Mesh	Grapevine Pergola	Difference Mesh - Grapevine Pergola
11:00:00	18,1	18,4	-0,4
11:30:00	19,6	20,1	-0,5
12:00:00	23,1	21,5	1,7
12:30:00	25,0	22,8	2,2
13:00:00	26,1	23,8	2,3
13:30:00	27,4	24,8	2,6
14:00:00	28,3	25,7	2,6
14:30:00	29,1	26,3	2,7
15:00:00	29,4	26,8	2,6
15:30:00	29,4	27,1	2,4
16:00:00	28,7	26,9	1,9

Table 9. UTCI (°C) every 30 minutes on an average day. Source: Prepared by the Authors.

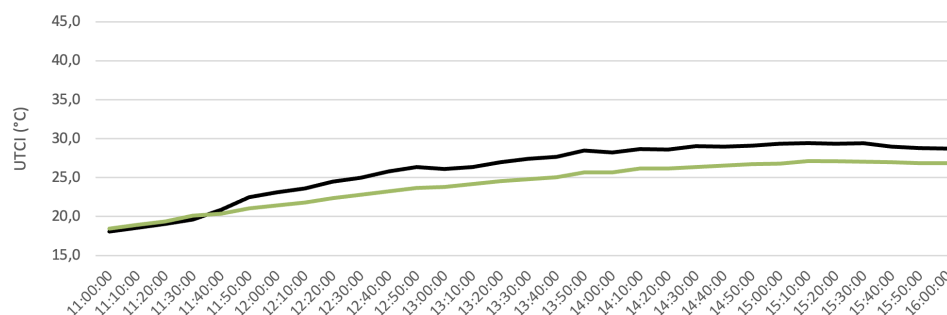


Figure 8. UTCI behavior on an average day. Source: Prepared by the Authors.

a difference of 3.9 °C. Meanwhile, the maximum reached under the grapevine pergola was recorded 30 minutes later, at 3:40 pm, at 30.5 °C, while the mesh recorded 32.8 °C, a 2.3 °C difference (Figure 7). On the other hand, the average value under the shading mesh is 26.0 °C, while under the shade is 24.1 °C. The average difference between the two conditions is 1.9 °C, with lower values consistently recorded under the grapevine pergola throughout the analyzed period.

In terms of maximum average daily values, the UTCI reaches 28.8 °C under the mesh and 26.6 °C under the grapevine pergola. The maximum observed difference between the two conditions is about 2.2 °C, observed on 05-03-2024 (Table 8).

The analysis of the average day (Table 9 and Figure 8) reveals a clear time dependence. In the first intervals of the morning (11:00 – 11:30 am), the UTCI under the mesh is slightly lower than that recorded under the grapevine pergola, by values between 0.4 and 0.5 °C. From 11:40 am onward, this relationship is reversed in a sustained way: the UTCI under the mesh consistently exceeds that of the grapevine pergola, with differences of over 2°C in 67.74% of the average records, reaching a maximum of 2.9 °C at 13:50. The gap begins to decrease from 15:50, which makes a difference of 1.9 °C.

The hourly behavior of the UTCI shows an increasing trend between 11:00 am and 3:30 pm, followed by stabilization or a slight decrease toward 4:00 pm in both conditions. The differences between the grapevine pergola and the mesh are maintained throughout the hourly interval, with a relatively constant separation between the curves. The greatest differences are observed in the central section of the analyzed period, coinciding with the hours when the t_r recorded higher values, between 12:30 and 2:30 pm.

Depending on the UTCI index ranges, the values recorded under the shading mesh are mostly in the thermal stress range due to heat during the study period, reaching strong thermal stress in some cases. On the other hand, the values under the grapevine pergola are distributed between the categories “thermal stress due to heat” and “without thermal stress”, with a higher frequency of values in the latter (Figure 9).

The data collected are consistent with those indicated by Watanable et al. (2014), Kusaka et al. (2022), and Châfer et al. (2020), who agree on the high efficiency of horizontal vegetation-based covers to mitigate thermal stress on a human scale by controlling the radiative environment and evaporative cooling, which reinforces the

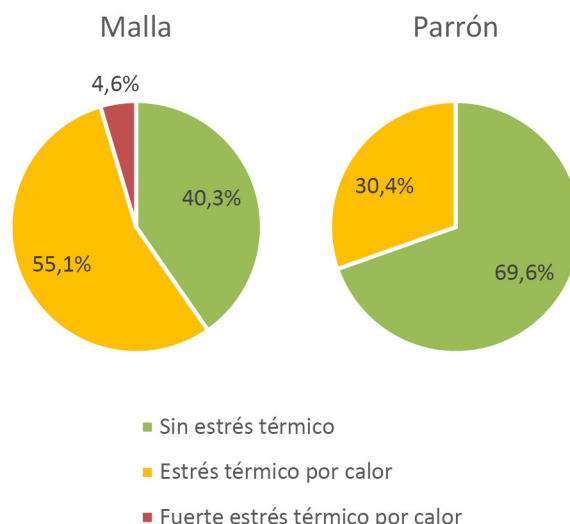


Figure 9. UTCI thermal stress frequencies. Source: Prepared by the Authors.

potential of the grapevine pergola as a passive thermal conditioning and climate adaptation strategy for intermediate spaces and backyards in temperate climates.

CONCLUSION

The results of this study show that the grapevine pergola creates an outdoor space that is thermally more favorable than the artificial shading mesh. During the analyzed period, the grapevine pergola systematically recorded lower t_a (reductions of between 1.3°C and 2.0°C) and higher RH levels (between 3% and 5% more) compared to the mesh. In terms of thermal comfort, the grapevine pergola maintained an average UTCI of 24.1 °C, compared to 26.0 °C for the mesh, representing an average reduction of 1.9 °C and maximum daily differences of up to 2.2 °C. These differences were interpreted in light of the uncertainty analysis incorporated into the study, which allowed for contextualizing the margins of error associated with instrumental measurements and the calculation of derived indicators such as the mean radiant temperature and the UTCI.

The decrease in the t_r is identified as the determining factor in improving comfort. Under the grapevine pergola, the t_r was consistently lower, with average daily differences between 2.6 °C and 4.3 °C relative to the mesh, reaching up to 5.9 °C during the hours of greatest radiative load. These findings suggest that not all shades offer the same performance: while the mesh acts as an inert system limited to solar obstruction, the grapevine pergola functions as an

active thermal regulator that combines shading with bioclimatic processes such as evapotranspiration and lower surface temperatures.

These results reinforce the potential of the grapevine pergola as a passive thermal-conditioning and climate-adaptation strategy for intermediate spaces and backyards in temperate climates. However, its implementation faces practical limitations such as growing time, the need for structural support, and the dependence on foliage density. Also, given the study's exploratory experimental approach, a methodological limitation is the proximity of the measurement points, which could lead to slight moisture transfer from the grapevine pergola to the mesh area. In addition, the mesh condition may have been partially influenced by the vegetation of the immediate environment. Therefore, the results should be understood as localized evidence for two nearby shading conditions, avoiding generalizations not supported by the experimental design.

As future lines of research, it is suggested to analyze the impact of these shaders on adjacent indoor enclosures and to evaluate how plant species variability influences the magnitude of cooling, in order to optimize their use as a tool for urban resilience at a domestic scale. Also, it should be considered that the measurements were made in March; future studies should evaluate warmer summer periods, during which the observed differences could be more pronounced, especially in the UTCI. It is also recommended to consider more physically independent shading scenarios, equivalent shading surfaces, and greater separation between measurement points to strengthen comparability between vegetation-based and inert setups.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, N.A.; Data curation, R.F.; Formal analysis, N.A.; Acquisition of financing, N.A.; Research, N.A., R.F., DC; Methodology, N.A., R.F., DC; Project management, N.A.; Resources, N.A., R.F.; Software, R.F.; Supervision, N.A.; Validation, N.A., R.F.; Visualization, R.F., D.C.; Writing - original draft, N.A., R.F., D.C.; Writing - revision and editing, N.A., D.C.

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