

Experimental evaluation of the shade effectiveness of vertical green systems

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Abstract

A natural strategy for improving buildings' microclimate is using vertical vegetation systems. Such systems produce shade on the walls, minimizing the temperature increase on the adjacent surface and heat gain in the building. At the same time, they help to restore vegetation that has been eliminated by urban occupation. This research evaluated the thermal contribution of vertical vegetation systems as a shading element for buildings in bioclimatic zone 2. Three already-built environments with similar characteristics and solar orientation were selected, with the only variation being the shading system on one of the walls. In the first building, a living wall was installed; in the second, a green façade; and in the third did not undergo any intervention. The following environmental variables were measured: indoor air temperature, interior and exterior surface temperature, globe temperature, and relative humidity to assess the effect of the shading provided by each system during the fall (April 21-26) and winter (July 14-21) periods of 2022. The results prove the benefit of vertical vegetation systems as a strategy for reducing the interior temperature of the building. During the fall, measurements taken with exterior sensors on the walls revealed significant differences in maximum temperatures: the control wall exceeded the temperature of the living by 18.5°C and the green façade by 13.3°C. During periods of lower temperatures, both in autumn and winter, the vertical vegetation system's insulating effect did not affect the rooms' indoor temperatures; the two systems and the control wall behaved similarly.

Keywords: living walls. green facades. subtropical climate.

Avaliação experimental da eficácia de sombreamento de sistemas de vegetação vertical

Resumo

Uma estratégia natural para melhorar o microclima das edificações é a utilização de sistemas de vegetação verticais. Tais sistemas produzem sombra nas paredes, minimizando o aumento da temperatura na superfície adjacente e o ganho de calor no edifício. Simultaneamente, ajudam a restaurar a vegetação eliminada pela ocupação urbana. Esta pesquisa avaliou a contribuição térmica dos sistemas de vegetação verticais como elemento de sombreamento para edificações na zona bioclimática 2. Foram selecionados três ambientes já construídos, com características e orientação solar semelhantes, tendo como única variação o sistema de sombreamento de uma das paredes. Na primeira edificação foi instalada uma parede viva; na segunda, uma fachada verde; e a terceira não sofreu intervenção. Para avaliar o efeito do sombreamento proporcionado por cada sistema durante os períodos de outono (21 a 26 de abril) e inverno (14 a 21 de julho) de 2022 foram medidas as seguintes variáveis ambientais: temperatura do ar interno, temperatura superficial interna e externa, temperatura de globo e umidade relativa do ar. Os resultados obtidos comprovam o benefício dos sistemas de vegetação vertical como estratégia para redução da temperatura interna da edificação. Durante o outono, as medições realizadas com sensores externos nas paredes revelaram diferenças expressivas nas temperaturas máximas: a parede controle excedeu a temperatura da parede viva em 18,5°C e da fachada verde em 13,3°C. Nos períodos de temperaturas mais baixas, tanto no outono quanto no inverno, o efeito isolante do sistema de vegetação vertical não impactou negativamente as temperaturas internas dos ambientes, os dois sistemas e a parede controle apresentaram um comportamento semelhante.

Palavras-chave: Paredes Vivas. Fachadas verdes. Clima subtropical.

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1. Introduction

Urban sprawl replaces areas with vegetation covered by extensively paved surfaces, which contributes significantly to rising temperatures in cities. This phenomenon is called a "heat island" (Tian et al., 2021). In addition, urban growth implies the construction of buildings that often resort to mechanical systems to ensure thermal comfort indoors (Mirrahimi et al., 2016).

Using mechanical systems increases electricity costs, Brazil's primary energy source (Geraldi et al., 2022). Although there is a large availability of energy generation methods in the country that are considered clean or do not cause significant environmental impacts, investments are needed to supply them, which implies the allocation of resources that could be invested in more socially sensitive areas, such as education, health, and safety.

In this context, several studies have evaluated natural thermal conditioning strategies to reduce energy consumption in buildings, replacing mechanical equipment. Among these strategies, the use of vegetation as a shading component has been studied as a way of reducing the incidence of direct solar radiation on buildings (Châfer; Coma and Cabeza, 2021; Cosola; Olivieri and Ruiz-García, 2022; Cruciol-Barbosa; Fontes and Azambuja, 2023; Pérez et al., 2017; Vox; Blanco and Schettini, 2018). In addition to the thermal benefits, the use of vegetation integrates the natural environment with the built environment, provides benefits to the health and well-being of the population (Wang et al., 2019; Yeom; Kim; Hong, 2021), helps to retain pollutants and improves air quality (Su et al., 2011), preserves biodiversity, favoring fauna and flora (Giuliano; Accamando and Mcadams, 2004). These factors provide advantages for buildings and the urban microclimate, making them a natural strategy for reducing energy expenditure on air conditioning and mitigating environmental impacts in densely populated urban centers.

Vegetation shading systems can be applied to buildings' roofs or vertical fences. Notably, green roofs offer benefits for reducing interior temperatures (Nguyen et al., 2022). However, vertical fences in buildings with many floors have a larger available area than roofs, maximizing the potential for reducing heat islands as they are closer to the pedestrian level (Susca et al., 2022; Pérez et al., 2011).

Vertical vegetation systems are classified as green façades (extensive) and living walls (intensive), depending on the construction techniques and characteristics. The green façade is characterized by the use of climbing plants that are rooted directly in the ground or on supports. Living walls involve the cultivation of vegetation in more complex structures, such as pots fixed to the walls of the building, containing a substrate for the development of the plants, or using a hydroponic system (Scherer, Alves, and Redin, 2018).

Despite the evidence of the benefits provided by vegetation shading as a passive method for saving energy in buildings, its energy efficiency is dynamic, varying according to the climate and season. Therefore, it is necessary to observe some characteristics before implementing it, as they can influence its thermal behavior, such as the typology of the system used to implement the vegetation (Châfer; Coma and Cabeza, 2021; Wang et al., 2019; Ottelé et al., 2011), the characteristics of the plant species (Dahanayake; Chow and Hou, 2017), the density and leaf area index (Pérez et al., 2011), the orientation and dimensions of the façade (Pérez et al., 2014; Jim, 2015), the season and the climate (Dahanayake; Chow and Hou, 2017; Bianco, et al., 2017; Refati, 2020; Djedji; Belarbi; Bozonnet, 2017). Inadequate use of this system can not only fail to benefit the sustainability of the building but can also disrupt the site.

Research has been conducted in different climatic contexts to investigate the impact of vertical vegetation systems on the temperature of buildings, especially during the summer. These studies cover climates such as the Mediterranean (Pérez et al., 2017; Pérez et al., 2011; Pérez et al., 2022; Convertino et al., 2022; Bano and Dervishi, 2021; Perini, et al., 2017; Perini and Rosasco, 2013; Blanco; Schettini and Vox, 2019; Coma et al., 2017; Olivieri; Olivieri and Neila, 2014), temperate (Hoelscher et al., 2016), tropical (Sunakorn and Yimprayoon, 2011; Galagoda; Jayasinghe and Halwatura, 2018; Cruciol-Barbosa; Fontes and Azambuja, 2023; Yin et al., 2017), oceanic (Djedjig; Belarbi and Bozonnet, 2017) and continental (Bianco et al., 2017; Du et al., 2020).

However, studies analyzing the behavior of the vertical vegetation system in winter conditions are limited. Some research indicates that using this system brings benefits even at lower temperatures. A simulation study carried out in the city of Tirana, Albania, in a Mediterranean climate, found that the use of green façades resulted in an average increase of 1 to 2 °C in the average radiant temperature of the environment during the coldest hours (Bano and Dervishi, 2021). In Italy, the application of green façades led to an increase of 3.5 °C during the lowest temperature hours at night, while during the hottest hours of the day, there was a reduction of 8.3 °C in the temperature of the room protected by the shade of the vertical vegetation system (Convertino et al., 2022).

In the city of Turin, Italy, which has a continental climate, research revealed that the use of living walls (using felt as a support) brought about a 3 °C increase in the temperature of the exterior surface of the wall during the lowest temperature hours, as well as 8 °C reduction in temperature during the hottest hours of the day (Bianco et al., 2017). The increase in temperature at cooler times was also observed in a study of green façades in the UK, a temperate climate (Cameron; Taylor and Emmett, 2015). Concerning the European oceanic climate, a study was carried out in La Rochelle, a city in France, involving the implementation of living walls. This study revealed an increase of 5 °C in temperatures during the coldest hours while a reduction of 5 °C during the hottest hours (Djedjig; Belarbi and Bozonnet, 2017).

However, research results for subtropical climates are contradictory. Experimental research in Hunan, China, showed that the environment protected by the green façade system had exterior surface temperatures 3 °C higher than an unprotected wall during the coldest hours in winter (Qingwei et al., 2019). However, studies conducted by living wall simulation in Hong Kong suggest that the passive energy benefits of the vertical vegetation system can be disadvantageous during winter periods, depending on weather conditions and the intensity of solar radiation (Dahanayake; Chow and Hou, 2017). In South Brazil, a study with green façades showed indoor temperatures 4 °C lower than room temperatures without the vegetation system (Refati, 2020).

Given the results discussed above, further studies are clearly needed to understand the behavior of vertical vegetation systems in the face of seasonal variations, specifically in the context of the Cfa climate (humid subtropical with hot summers), according to the Köppen-Geiger classification (Peel; Finlayson and McMahon, 2007). In particular, research during the winter period is necessary, given the scarcity of research and the contradiction in the few results found (Susca et al., 2022).

In this context, this experimental study aims to investigate the thermal influence of implementing a vertical vegetation system in environments with comparable characteristics during the fall and winter seasons in a city located in southern Brazil, with a subtropical climate (Cfa), in bioclimatic zone 2 according to ABNT NBR 15220 (ABNT, 2005). In order to achieve this objective, the thermal effects of installing a living wall and a green façade were evaluated by analyzing the air temperature, globe temperature, and interior and exterior surface temperature (wall) of the rooms compared to a room without the vegetation system, which served as a control. This research will contribute to understanding the thermal performance of vertical vegetation systems, providing additional data and information on their effectiveness in subtropical climate regions during the fall and winter.

2. Research Methods

The experiment was set up on the premises of the Federal Technological University of Paraná, Francisco Beltrão Campus (UTFPR/FB), in the southwestern region of Paraná, with the following geographical coordinates: Latitude 26°04'52"S and Longitude 53°03'18"O.

The site is located at an altitude of 650 meters above sea level. According to the Köppen climate classification, the location is classified as Cfa climate, subtropical and humid with hot summers, recording an average annual temperature of 19.3 °C and average annual rainfall of 2030 mm (Instituto Agrônômico do Paraná, 2022).

Table 1 illustrates the bioclimatic conditions in the Francisco Beltrão municipality, describing the temperature and rainfall variations over forty-six years (1974 - 2020). This data shows that even in

the coldest months of the year, there are high absolute maximum temperatures, with records of 30.0°C in July 1994 and 34.0°C in August 1999.

In addition, it is important to highlight a relevant characteristic of the region in which the study is located: the high daily temperature range. During the fall and winter seasons, it is possible to observe that the difference between the average maximum and average minimum daily temperatures reaches approximately 12.0 °C. These records indicate that there are significant changes in temperature throughout the season.

Table 1 - Historical series of the 46 years with records of the maximum and minimum climatic variables during the period (1974/2020)

Month	Absolute minimum	Average minimum	Air temperature (°C)			Relative humidity average (%)	Total precipitation (mm)
			Average highs	Absolute maximum	Average compensated*		
JAN	8,0	18,5	30,2	36,4	23,6	75	190,2
FEB	8,7	18,3	29,9	37,6	23,2	76	173,3
MAR	3,4	17,0	29,2	37,4	22,2	76	145,0
APR	1,0	14,2	26,2	33,8	19,3	77	163,4
MAY	-0,2	10,9	22,3	31,9	15,7	81	193,7
JUN	-4,2	9,5	20,8	31,0	14,2	81	163,7
JUL	-5,0	9,0	21,2	30,0	14,2	77	129,2
AUG	-2,4	10,2	23,4	34,0	16,0	71	110,5
SEP	-0,4	12,1	24,7	36,6	17,7	70	157,6
OCT	3,3	14,7	26,9	37,2	20,2	71	250,7
NOV	4,8	15,9	28,4	38,3	21,7	69	178,9
DEC	8,6	17,1	29,7	38,2	23,1	72	173,5
YEAR	-5,0	14,0	26,1	38,3	19,3	75	2030

* Compensated average temperature: takes into account factors such as wind and humidity to reflect the real thermal sensation

Source: Adapted from Paraná Rural Development Institute (2023).

2.1. The vertical vegetation system

The experiment was carried out in three rooms. The difference between the locations consisted of adopting a vertical vegetation system on the façades of two rooms. More specifically, a living wall was installed in the room called "PV," while a green façade was applied in the room called "FV." For comparison purposes, a control room without shading elements was monitored and named "CC" (Figure 1). Each site consists of a single-story building comprising laboratories and teachers' offices. The experiment was carried out in the teachers' offices. It should be noted that the façades used in the experiment face north-northwest. This means they receive solar incidence during the fall, from 9 a.m. until sunset, and during the winter, from sunrise until sunset. The buildings are not interfered with by shadows from other constructions.

Air temperature and globe temperature data were collected before implementing the vertical vegetation system to assess the similarity between the test room. The analysis revealed non-significant differences. The most significant variation in air temperature recorded was 0.6° C between the "PV" and "FV" environments, with lower temperatures observed in the PV environment. These results prove the feasibility of using these rooms for comparative studies.

Information on atmospheric weather conditions was obtained from the records of the automatic weather station installed on the UTFPR campus, shown in Figure 1.

The floor plans of these rooms have equal dimensions and orientation in the building. The rooms are 2.80m wide and 2.80m long, with a total area of 7.84 m² and a ceiling height of 2.65m.

The living wall (Figure 2, on the left) was installed on 02/24/2022. It consists of rectangular pots (500x150x200mm) made of laminated recycled cardboard sheets, 8 mm thick, fixed to the wall with metal screws and filled with substrate (50% humus and 50% soil) enriched with 100 grams of organic fertilizer from chicken bedding. Using laminated recycled cardboard for the pots is unprecedented in living wall projects and aims to reduce the project's environmental impact. The fertilizer was maintained every 30 days, with each pot receiving a dose of 1 liter of liquid rabbit manure effluent. Irrigation was carried out manually using a hose connected to a faucet near the experiment. After

planting, during the first fifteen days, 1 liter of water was applied to each pot every two days. After this initial period, the plants were watered only twice a week until the end of the experiment.

Figure 1 - Aerial view of the study location showing the living wall (LW), green façade (GF) and control room (CC) panels



Source: The authors.

Figure 2 – Vertical vegetation systems on the planting day: living wall in the photo on the left (02/24/2022) and green facade (11/26/2021) in the center and on the right



Source: the authors.

On the green facade (Figure 2, in the center and to the right), the climbing plant was planted on 11/26/2021. The species used in the experiment were acquired from a nursery in the same city where the experiment was controlled. These plants were approximately 100 cm tall at the time of acquisition. The beds were opened with a depth and width of 30 cm, with a spacing of 95 cm between the seedlings. In total, seven seedlings were planted in the structure. This distance was chosen to allow for a quick closure of the vegetation. In this location, there is a concrete passage box. In addition to the seven climbing plants during the autumn campaign, two more pots were placed above this box. However, in the winter campaign, the plants were collected for protection due to the complete loss of leaves of these plants in pots and the incidence of frosts that could damage them. The beds were filled with a mixture of 50% local soil, 50% humus, and 100 grams of organic fertilizer from poultry bedding. To ensure suitable soil for the development of the vines. Moreover, monthly, before irrigation or during rainy periods, each plant received a dose of 1 liter of liquid rabbit manure effluent as fertilization.

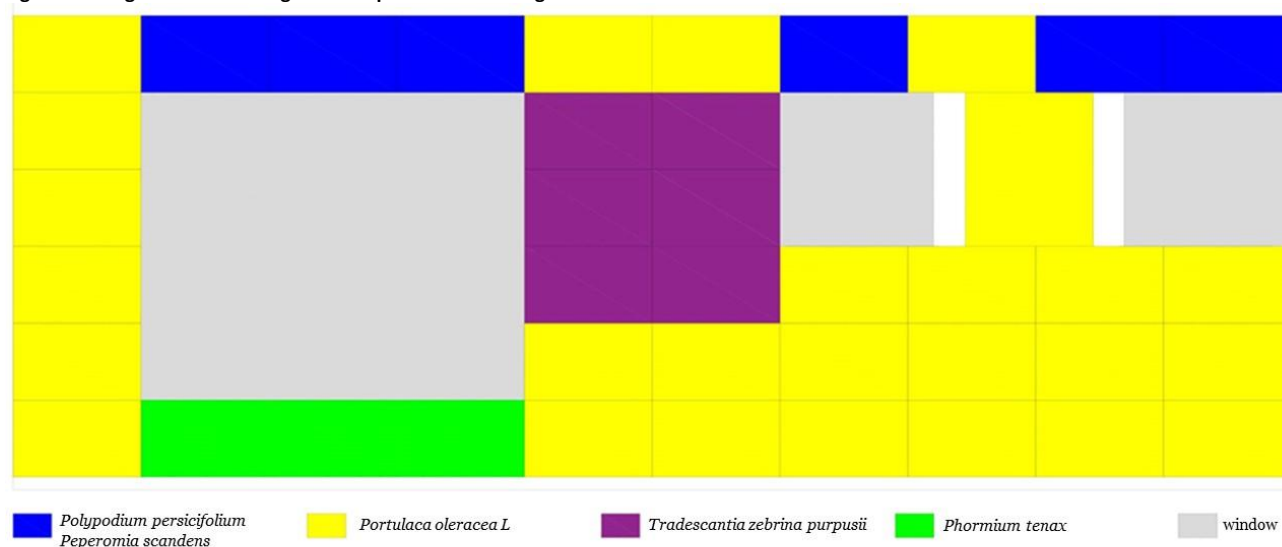
Irrigation was conducted manually using a hose connected to a faucet near the experiment. After planting, during the first fifteen days, 10 liters of water were applied to each plant daily, divided into two periods: early in the morning and late in the afternoon. After this initial period, the plants were watered only once daily, with 5 liters of water per plant. The watering frequency was reduced to every two days in the second month. From the third month onwards, irrigation was natural, supplied exclusively by rainwater on days when precipitation occurred.

For the support and growth of the climbing plants, a structure made of welded steel mesh, measuring 6.00m x 2.40m (with a spacing of 15x15cm), was used, fixed in an inclined position on the facade, secured by metal hooks on the eaves. The lower part is fixed with clamps directly to the ground.

2.2. Selection of plants

The potential for reducing solar transmission is influenced by the plant species' characteristics, especially by the shape and amount of leaf layer. More diminutive and thicker leaves can produce more consistent effects due to their larger evapotranspiration surface area (Hoelscher et al., 2016). To implement the living wall system, we selected plant species that strictly fill the space, require low maintenance, and are adapted to the local climate and direct sunlight exposure. Such species include *Portulaca oleracea* L (eleven-o'clock), *Peperomia scandens* (Peperomia), *Phormium tenax* (Flax), *Tradescantia zebrina purpusii* (Purple Heart), and *Polypodium persicifolium* (Fern). Figure 3 illustrates the distribution of the plants on the facade. This arrangement was carried out strategically to ensure that the taller plants, such as *Phormium tenax*, *Peperomia scandens*, and *Polypodium persicifolium*, were positioned below and above the windows, providing a larger shading area. The other species (*Portulaca oleracea* L and *Tradescantia zebrina purpusii*) were distributed mainly considering the aesthetics of the arrangement.

Figure 3 – Diagram of the arrangement of plants on the living wall



Source: The authors.

Wisteria floribunda (wisteria), a fast-growing deciduous climber, was chosen for the green facade system. This species is considered suitable due to its ability to provide shade and adapt to the subtropical climate, which experiences winters with frost occurrences.

2.3. Data monitoring

After planting the vegetation, two monitoring campaigns were conducted to evaluate the environment's thermal behavior during the autumn (April 21 to 26) and winter (July 14 to 27) of 2022. In these measurements, the data on indoor and outdoor air temperature, outdoor relative humidity, globe temperature, and exterior and interior surface temperature of the facade were simultaneously collected in the three offices. This collection occurred every 15 minutes in an automated manner, using previously calibrated equipment.

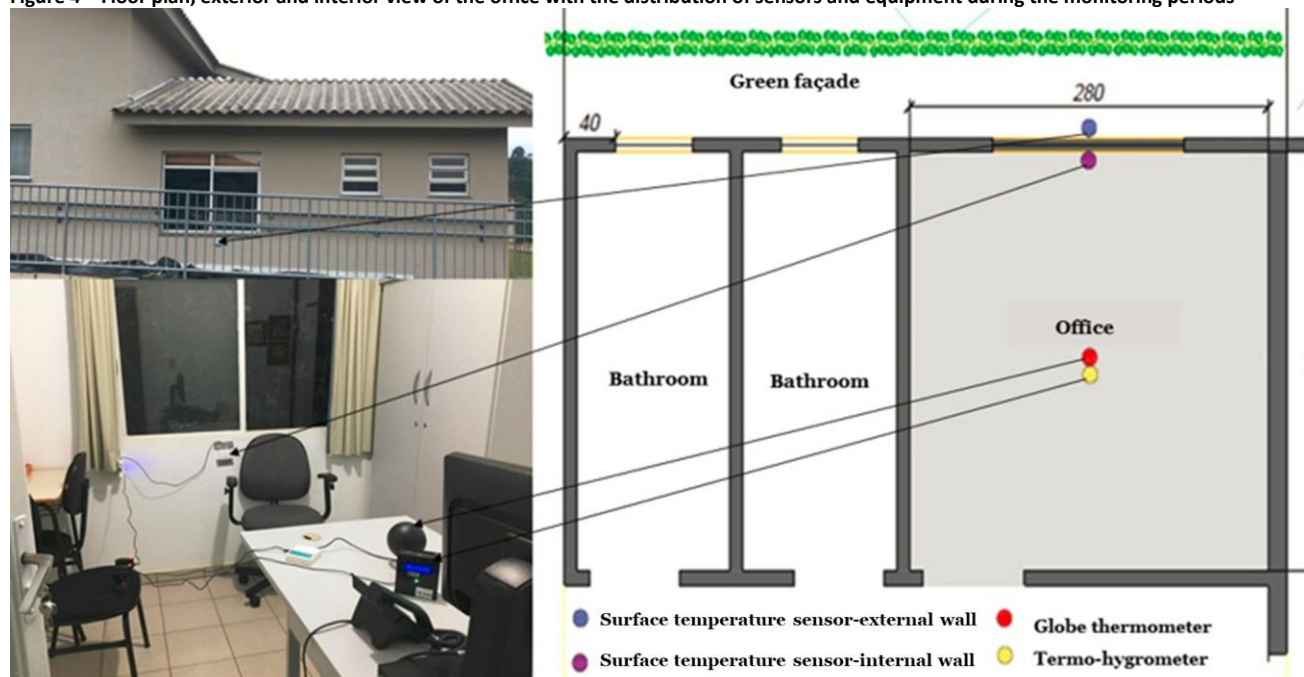
For the measurement of air temperature and relative humidity, a thermo-hygrometer equipped with the HDC1080 sensor was used, with the following measurement precisions: for the relative humidity of the air, $\pm 2\%$ within an operating range of 0% to 100%; regarding the air temperature, $\pm 0.2^\circ \text{C}$, covering an operating range from -40°C to 125°C .

The globe temperature was evaluated using a globe thermometer equipped with the DS18B20 sensor. This sensor operates in a range of -55°C to $+125^\circ \text{C}$ and has an accuracy of $\pm 0.5^\circ \text{C}$.

The data on outdoor air temperature and relative humidity from both campaigns were obtained from the automatic weather station installed in Francisco Beltrão at the Federal Technological University of Paraná, with data available at (<https://www.e-clima.fb.utfpr.edu.br>).

During the measurements, the test rooms were maintained with doors closed, curtains opened, and no access to people. The data loggers were positioned as illustrated in Figure 4. The globe thermometer and the thermo-hygrometer were positioned in the center of each room at a height of 75 cm during autumn and 110 cm during winter. This variation in height was made to avoid direct sunlight on the globe. The surface temperature sensors were centrally placed below the window, at the same height, on both sides of the wall, inside and outside, so that the obtained values reflect the midpoint of the facade. In the living wall system, the pot in that position was mounted with a space of about 1 cm from the wall to facilitate the sensor insertion during measurements.

Figure 4 – Floor plan, exterior and interior view of the office with the distribution of sensors and equipment during the monitoring periods



Source: the authors.

2.4. Data analysis

Environmental variables were monitored to understand the impact of shading in environments protected by vertical vegetation systems, and the results were analyzed in two stages. In the first stage, the variations in the walls' interior and exterior surface temperatures were compared. In the second stage, the operative temperatures and comfort limits were identified to compare the thermal performance in each observed environment (PV, FV, and CC).

2.4.1. Operating temperature

The operative temperature of each measurement period was determined according to the ISO 7726 (2001) standard. The hourly mean radiant temperature ($\bar{t}_r$) was calculated according to Equation 1.

$$\text{Eq.1 } \bar{t}_r = \left[(tg + 273)^4 + \frac{0,25 \times 10^8}{\varepsilon_g} \left(\left| \frac{tg - ta}{D} \right| \right)^{\frac{1}{4}} x (tg - ta) \right]^{\frac{1}{4}} - 273$$

Were, $\bar{t}_r$ is mean radiant temperature (°C); t_a is air temperature (°C); t_g is globe temperature (°C); ε_g is emissivity of the globe, dimensionless; and D is diameter of the globe, (m).

Equation 2 was then applied to calculate the operative temperature.

$$\text{Eq.2 } t_o = At_a + (1 - A)\bar{t}_r$$

Were, t_o is operative temperature (°C); A is air speed < 0.2 (0.5); t_a is air temperature (°C); t_r is mean radiant temperature (°C).

2.5. Acceptable limit

To establish the acceptable limits for comfort within the operative temperature range for each measurement period, the daily average of the outdoor air temperature over the last ten days ($t_{(pma(out))}$) was calculated for each measurement campaign. Based on this data, the limits of operative temperature for thermal comfort for each period were determined according to the alternative method for thermal comfort analysis in naturally ventilated environments, described in equations 3 and 4 of Standard 55 (ASHRAE, 2013).

(Eq. 3) Upper limit 80% = $0.31 \cdot t_{(pma(out))} + 21.3$

(Eq. 4) Lower limit 80% = $0.31 \cdot t_{(pma(out))} + 14.3$

Applying these equations, the upper limit calculated for the autumn period was 26.8 ° C, and for the winter, the limit was 26.1 ° C. As for the lower limits, the obtained values were 19.8 ° C for autumn and 18.8 ° C for winter.

3. Results and discussion

The initial data collection occurred in the autumn, between April 21 and 25, 2022. In that period, the maximum global solar radiation observed on the horizontal plane was 786 W/m², with an average of 399 W/m². The air temperature ranged between 12.0 ° C (minimum) and 29.5 ° C (maximum). The days with maximum relative humidity were April 21 and 22, reaching 96%, while the minimum relative humidity was 69%. This variation can be attributed to clouds and rain occurrence on those two days. Starting from the 23rd, the sky remained sunny and cloudless until the end of the measurement, with relative humidity ranging from 54% to 94%.

During the winter campaign period (07/14 to 07/22), sunny conditions and low cloud cover in the sky prevailed. The global solar radiation did not exceed a maximum value of 714 W/m². During this period, the minimum air temperature reached 1.5 ° C at 6:45 AM (07/18), while the maximum was 27.3 ° C at 2:15 PM (07/22). The relative humidity of the air ranged between 40% and 96%. Notably, the annual minimum temperature occurred at the location on 07/30, outside the measurement period, with a recorded temperature of 1.1 ° C at 6:45 AM.

3.1. Development of plants

The development of the vegetation during the measurement periods can be observed in Figure 5. The autumn collection corresponded to 150 days after planting *Wisteria floribunda* (wisteria) seedlings on the green facade and 60 days after planting and installing the living wall.

It is possible to notice that in the green facade (Figure 5, top right), the plants had not yet fully closed their leaves in the autumn campaign. In winter (Figure 5, bottom right), the number of leaves is reduced due to the deciduous characteristics of the *Wisteria floribunda* plant (wisteria). However, the

plants on the living wall (Figure 5, top left and bottom left) showed a higher closure density, filling the entire wall extent in both campaigns.

Figure 5 – Exterior view of vertical vegetation systems with plant development: living wall and green facade



Source: The authors.

3.2. Surface temperature of the walls

Figures 6,7,8 and 9 (autumn) and 10,11,12 and 13 (winter) represent the profiles of interior and exterior surface temperatures recorded during the monitoring period. Generally, the shade provided by the living wall system (PV) and the green facade system (FV) significantly reduces thermal amplitude. This reduction is evidenced by the smoothness of the walls protected by the vertical vegetation system's temperature variation curves compared to the control room's wall (CC).

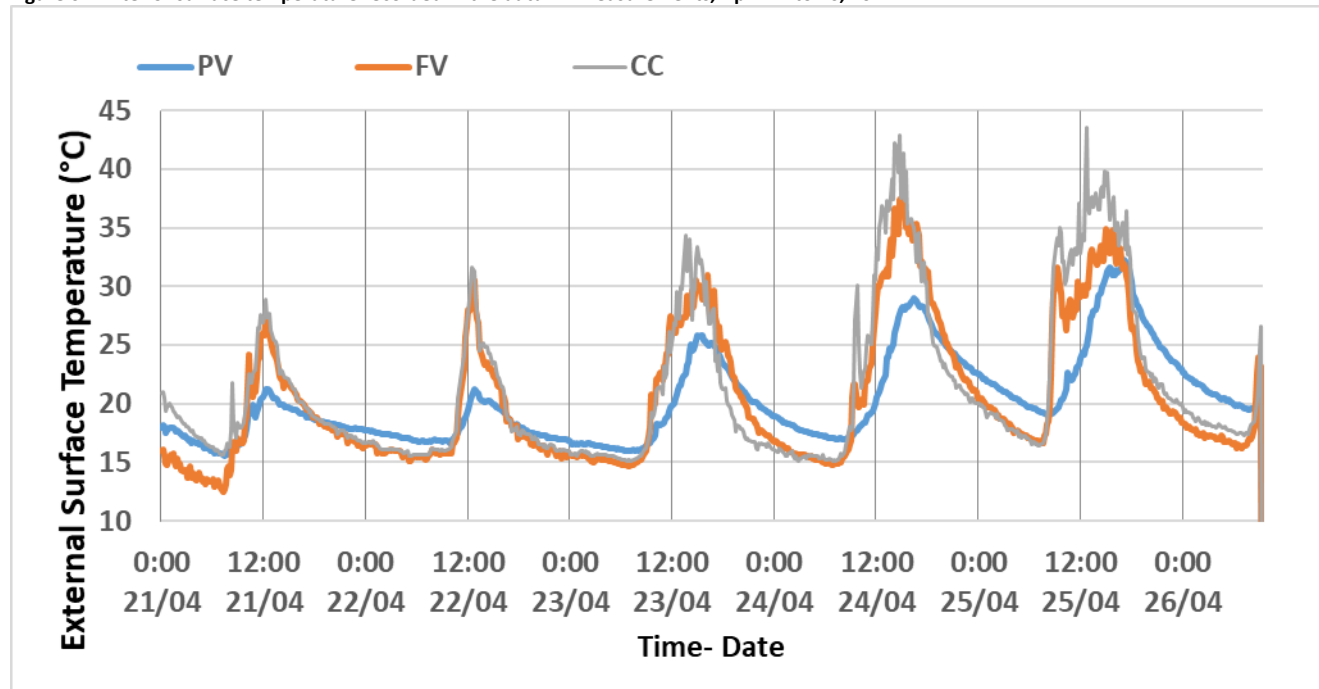
In autumn (Figures 6,7,8 and 9), it is notable that the temperatures on the surfaces protected by the living wall (PV) are lower than those in the control room (CC) during the hours of highest temperatures, usually in the afternoon. However, in the early hours of the day, the exterior surface temperatures of the living wall (PV) have a slight increase compared to the environment with the green facade (FV) and the control room (CC). However, the temperatures of the interior surfaces (Figure 8) of the three environments at these times are similar and, at times, overlap. Regarding the green facade system, it should be mentioned that the plants were still in the early stages of development during this measurement period, which resulted in temperature readings close to the observed in the control room at both periods (CC).

It is important to highlight that there is a difference between the first two days of monitoring and the last days. On April 21 and 22, cloudy skies with occasional rain showers were recorded, resulting in lower temperatures. As a result, the temperature curves in the three rooms remained close, with a maximum difference of 4.2 °C on the 21st between the room with a living wall (PV) and the control room (CC), with higher temperatures in this room.

On the other hand, in the last few days (from April 23 to April 26), temperatures increased, and the difference between the curves became more pronounced in the afternoon, with lower values observed for the living wall system (PV). This trend is particularly evident on April 24, as illustrated in Figures 7 and 9.

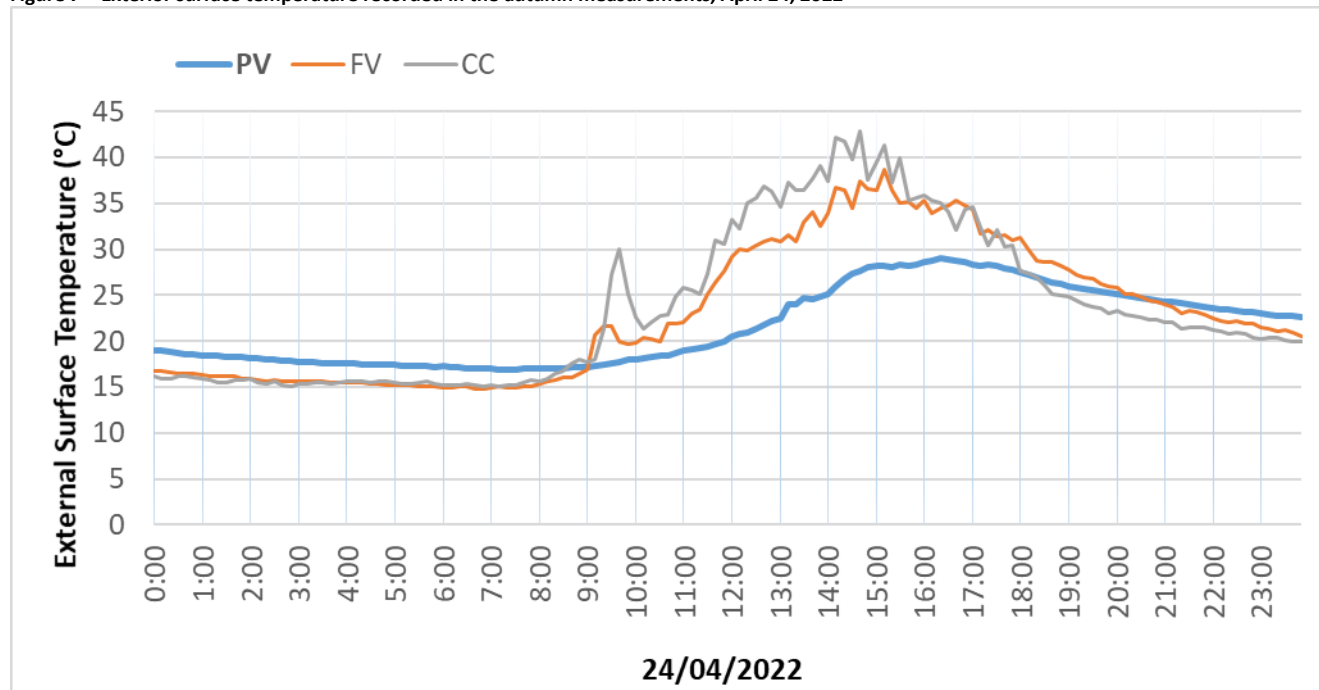
These results demonstrate that incorporating the living wall system layers in the facade played an important role as a mechanism for thermal insulation and heat storage. This reflected the living wall system's ability to reduce temperature fluctuations in the indoor environment. Despite receiving less radiation, the room with the living wall maintained its temperatures close to the control room (CC) during lower temperatures. These data corroborate the research of Perini et al. (2017).

Figure 6 – Exterior surface temperature recorded in the autumn measurements, April 21 to 26, 2022



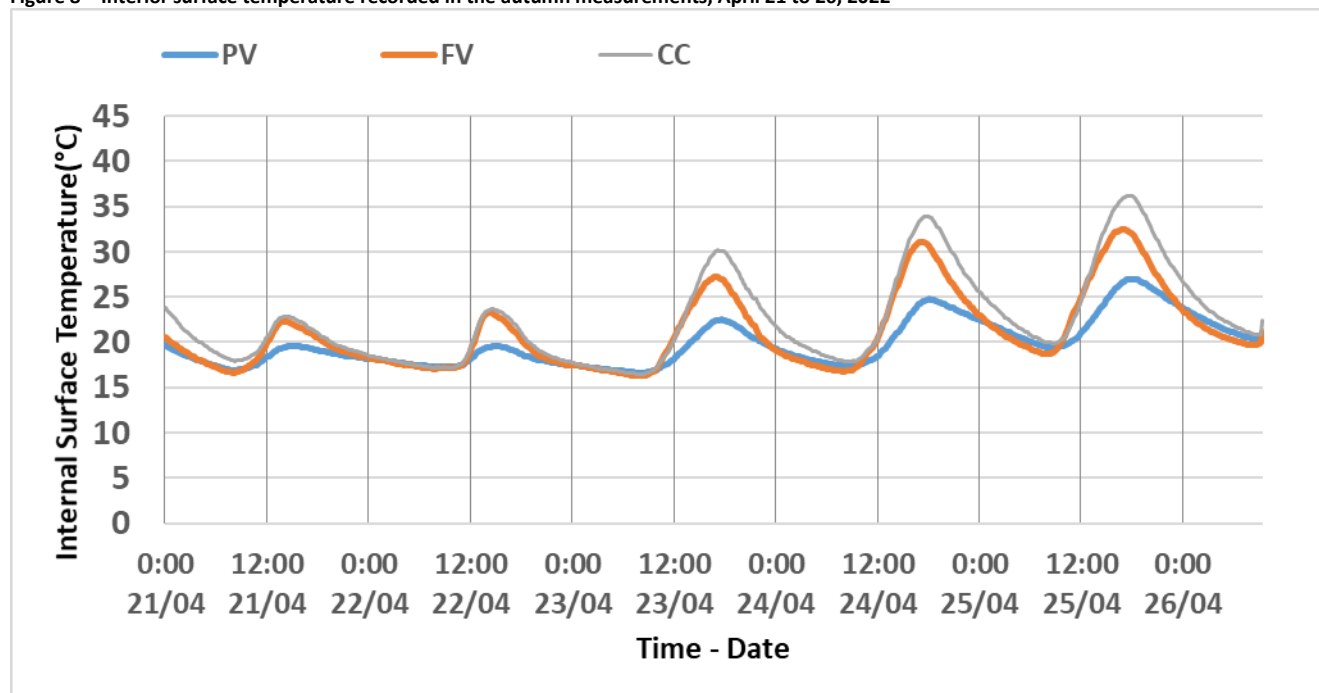
Source: The authors.

Figure 7 – Exterior surface temperature recorded in the autumn measurements, April 24, 2022



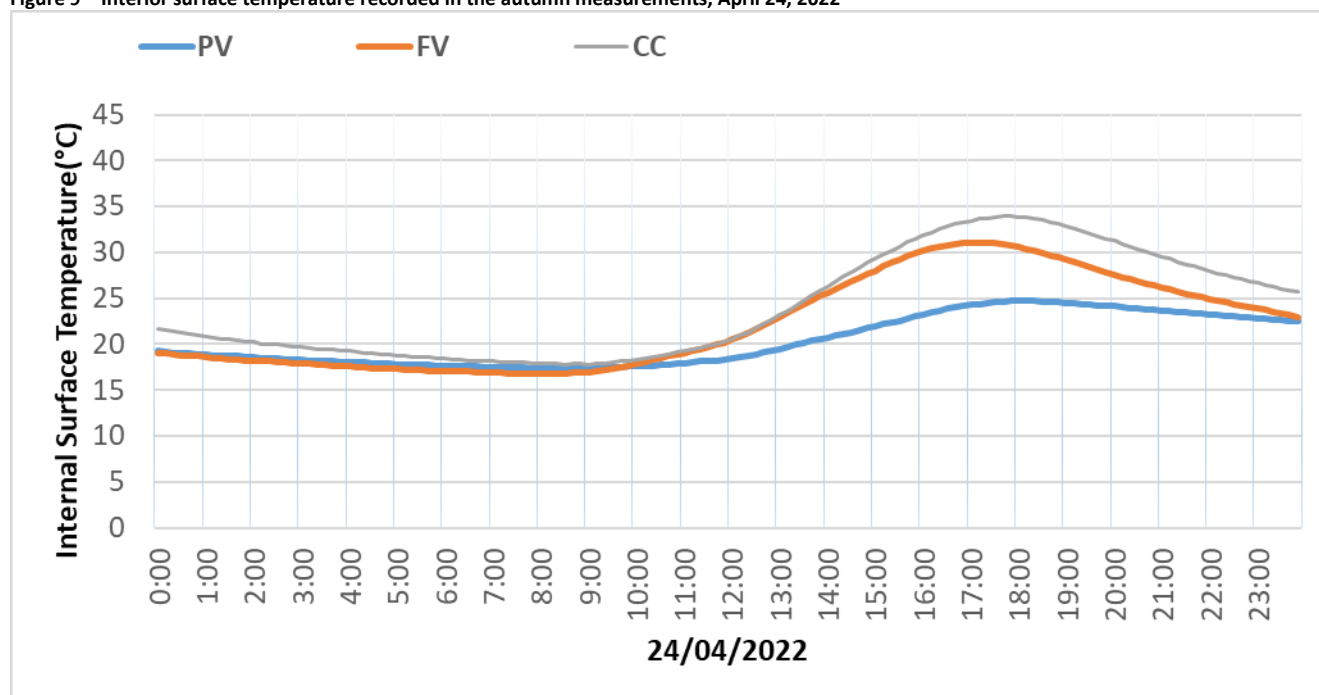
Source: The authors.

Figure 8 – Interior surface temperature recorded in the autumn measurements, April 21 to 26, 2022



Source: The authors.

Figure 9 – Interior surface temperature recorded in the autumn measurements, April 24, 2022



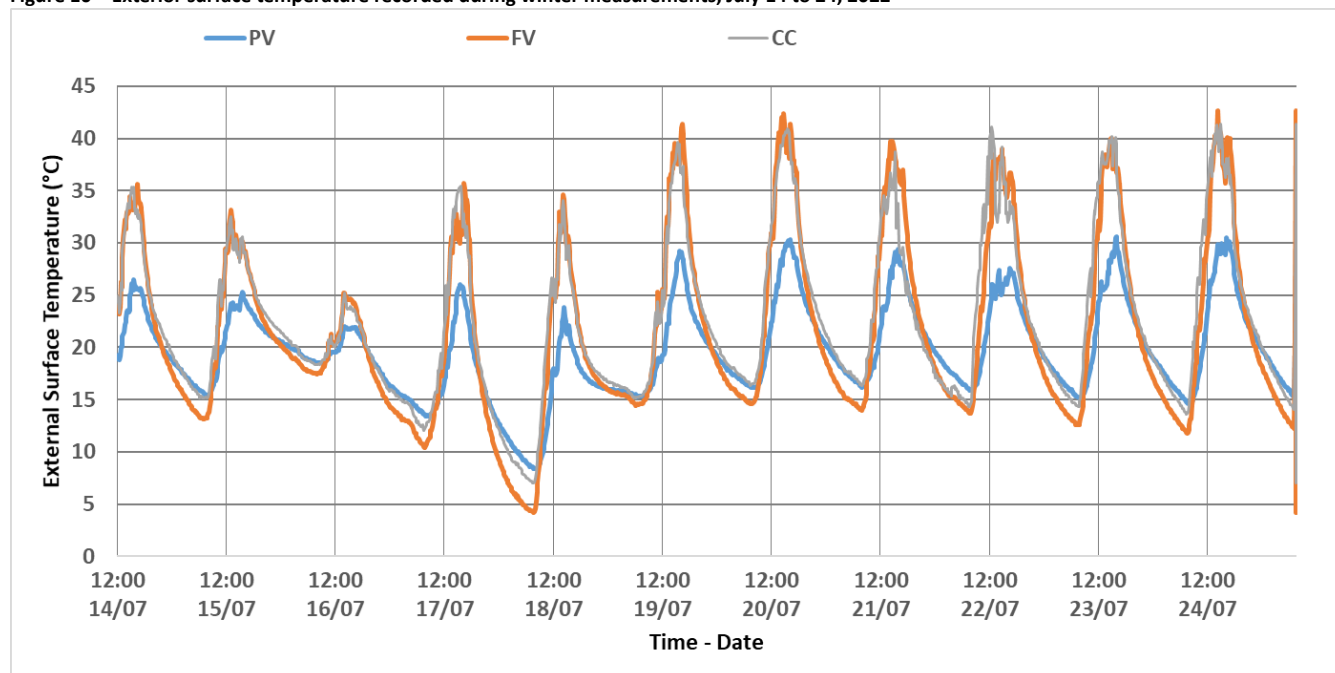
Source: The authors.

The temperatures recorded by the sensors installed on the surfaces of the facades over ten days of winter are represented in Figures 10 e 11 (exterior) and 12 e 13 (interior). During this period, there were sunny days with clear skies. It can be observed that the highest temperatures were recorded on the exterior surfaces of the control room (41.4 °C) and the green facade (42.7 °C) on 07/20 (Figure 11). At the same time, the minimum temperatures were also recorded on the surfaces of these rooms,

being 4.2 °C for the green facade (FV) and 7.0 °C for the control room (CC) on 07/18 (Figure 10). There is considerable variation between these areas' minimum and maximum temperatures. At the same time, the exterior surface protected by the living wall (PV) showed less fluctuation between its temperatures, with a maximum of 30.6 °C and a minimum of 8.4 °C (Figure 10 e 12).

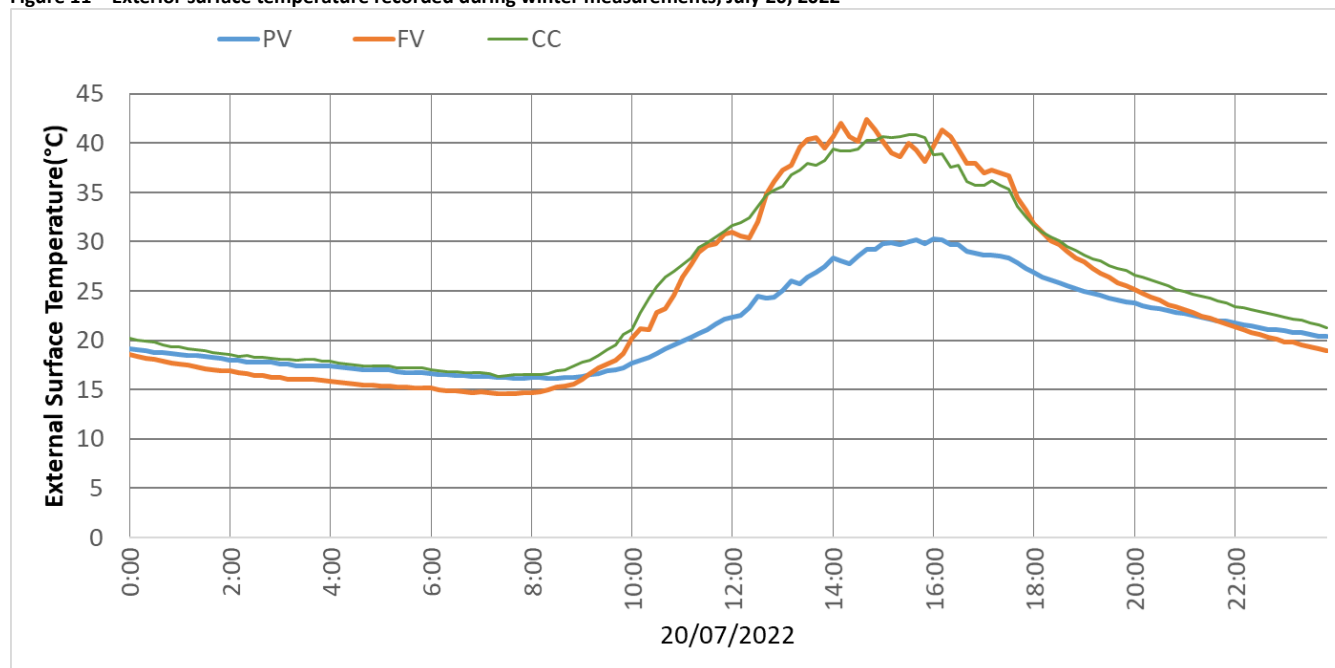
It is relevant to highlight that the green facade (FV), which features climbing plants of the species *Wisteria floribunda* (wisteria), exhibited a notable leaf drop during the winter season due to these plants' deciduous nature. The Leaf drop allowed solar radiation to reach the facade with greater intensity than the surface covered by the living wall (PV), causing the results of the green facade to be closer to those of the control wall.

Figure 10 – Exterior surface temperature recorded during winter measurements, July 14 to 24, 2022



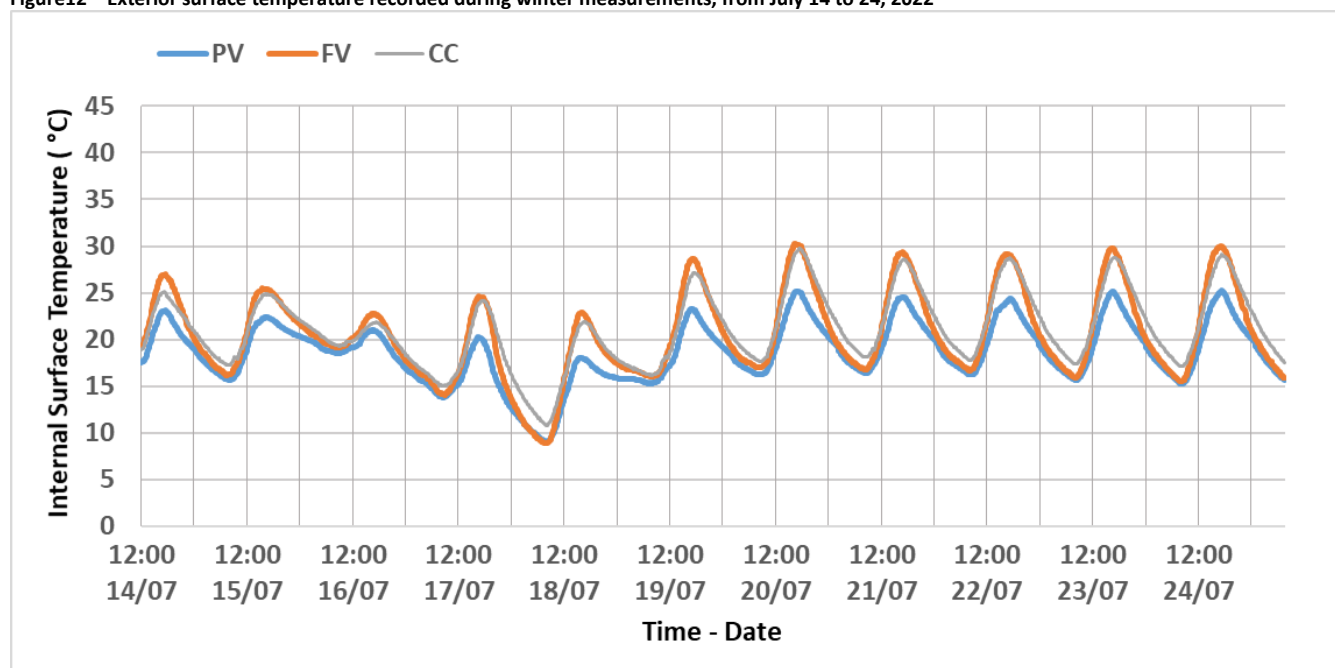
Source: The authors.

Figure 11 – Exterior surface temperature recorded during winter measurements, July 20, 2022



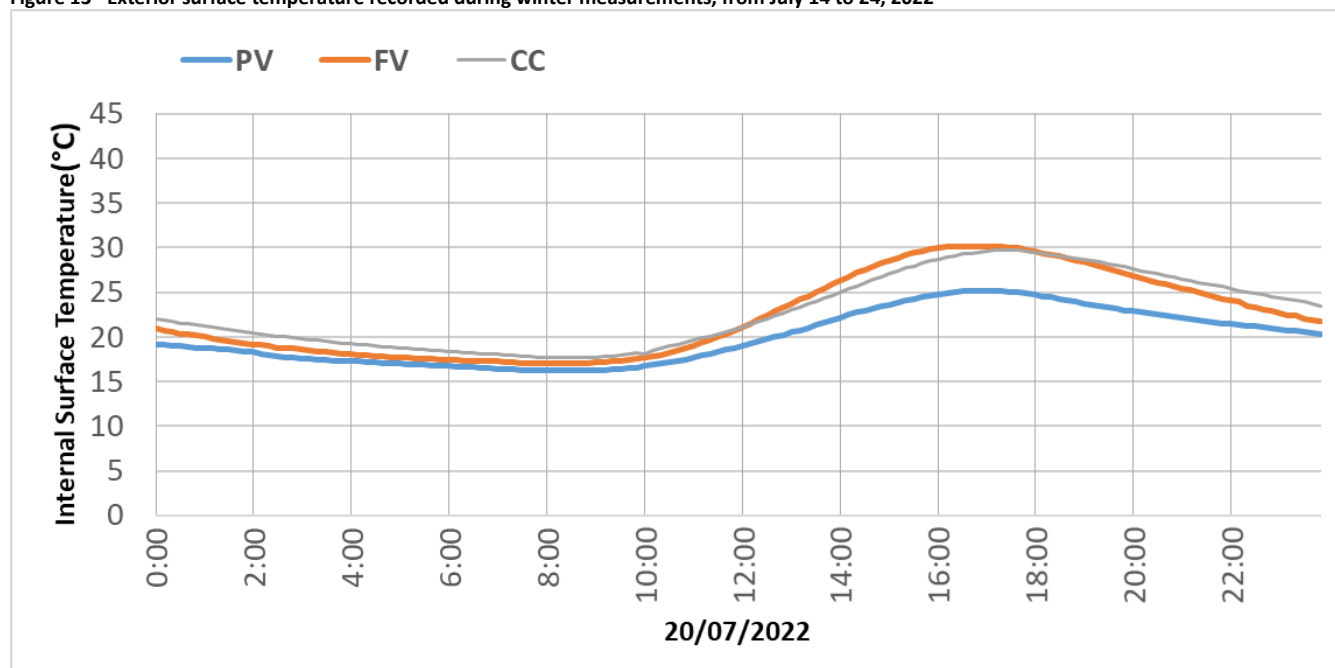
Source: The authors.

Figure12 – Exterior surface temperature recorded during winter measurements, from July 14 to 24, 2022



Source: The authors.

Figure 13– Exterior surface temperature recorded during winter measurements, from July 14 to 24, 2022



Source: The authors.

These data highlight the cooling effect provided by the vertical vegetation system and the thermal insulation effect that occurs in the room where the living wall is installed, reducing the temperature flow between the surfaces. This corroborates previous studies conducted by Bianco et al. (2017) and Qingwei et al. (2019).

The shading system's effectiveness is highest when the temperature curves of the room where the living wall (PV) is located diverge from the curve of the control room (CC), especially between 3 PM and 7 PM.

The results corroborate previous research findings, which demonstrate the effectiveness of the vertical vegetation system in providing shade to the building's walls, allowing for a natural reduction in energy consumption for air conditioning. The comparative analysis in Table 2 evaluates studies conducted with different models of the vertical vegetation system carried out during the autumn and winter periods.

Table 2 - Differences in surface temperatures of facades found in other research conducted with vertical vegetation shading models

Reference	System	Species	Local	Weather	Orientation	temperature difference (C °)		Season
						Exterior	Interior	
Bianco <i>et al.</i> (2017)	PV	<i>Lonicera nítida</i>	Italy/ Europe	Sub. Humid Continental	S	-8 °C Máx. +3°C Min.	-	Winter
Cameron; Taylor e Emmett, (2015)	FV	<i>Hedera helix</i>	United Kingdom/ UK	Temperate	-	-	3°C Máx.	Winter
Dahanayak; Chow e Hou, (2017)	PV	<i>Peperomia claviformis</i>	Hong Kong/Asia Wuhan/Asia	Subtropical humid	W	16,9 °C Máx. 18,4 °C Máx.	-	Winter
Qingwei <i>et al.</i> (2019)	FV	<i>Sedum lineare</i>	Hunan, na China/ Asia	Subtropical humid		+ 3°C Máx.	-	Winter
Convertino <i>et al.</i> (2022)	FV	<i>Pandorea jasminoides</i> , <i>Rhynchospermum jasminoides</i>	Italy/ Europe	Mediterranean	S	+ 3,5 °C Máx. dia - 8,3 °C Máx.	-	Winter
Djedjig; Belarbi e Bozonnet (2017)	PV	Various species	França/ Europa	Oceanic	W	+ 5 °C Máx. -5 dia°C Min.	-	Winter
The authors	PV	Various species	Brazil/ South America	Subtropical	NW	18,5 °C Máx.	9,3 °C Máx.	Autumn
						16,6 °C Máx.	5,6 °C Máx.	Inverno
						13,3 °C Máx.	4,4 °C Máx.	Autumn
	FV	<i>Wisteria floribunda</i> (glicínia)				9 °C Máx.	2,8 °C Máx.	Winter

Source: The authors.

Note: " - " indicates data not available or not reported in the referenced study.

In the present study, during daytime periods with higher temperatures, a decrease of 16.6 ° C was observed in the exterior surface of the wall protected by the living wall system (PV) compared to the unprotected wall (CC). These results agree with a previous study, which recorded a maximum reduction of 18.4 ° C in the exterior surface temperature of the wall protected by a living wall throughout the day (Dahanayake; Chow and Hou, 2017).

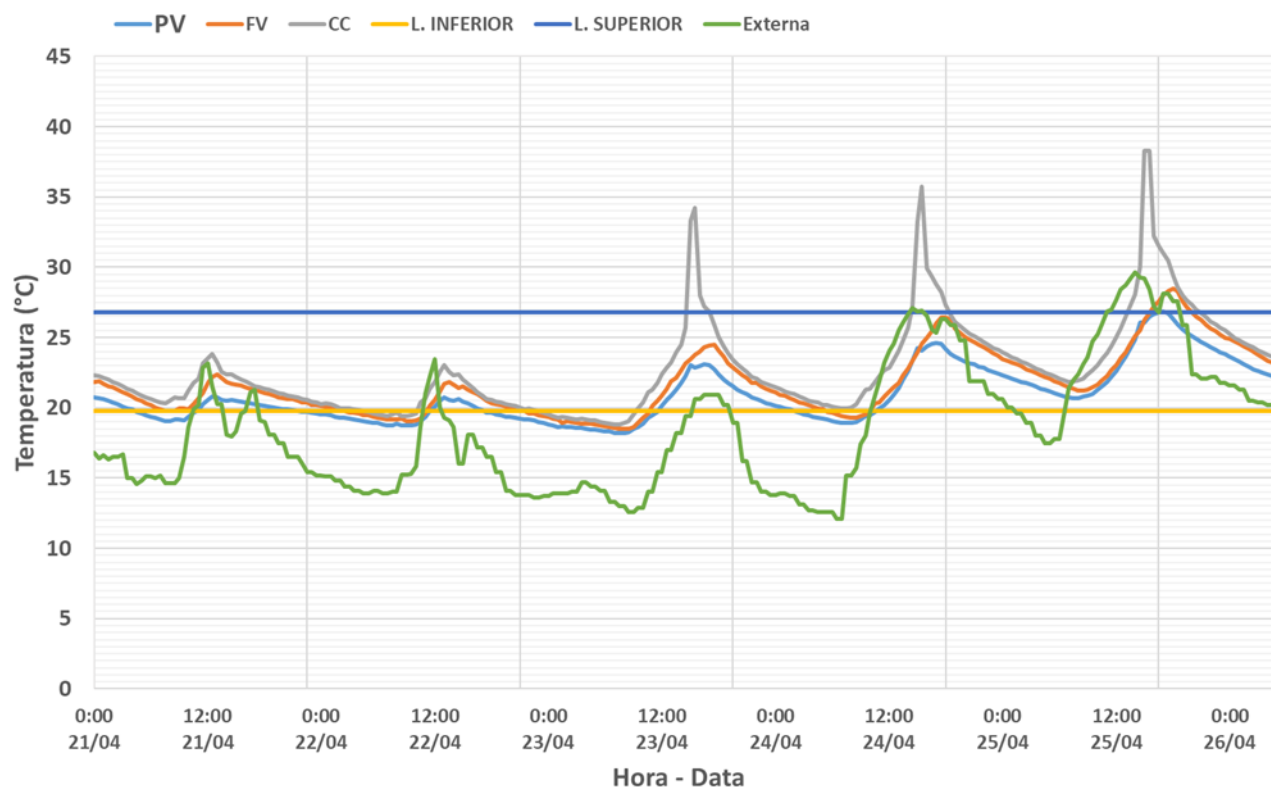
During the nighttime hours, when exterior temperatures are lower, it was observed that the living wall acted as a thermal insulator, exhibiting higher exterior surface temperatures compared to the unprotected wall. This observation was also verified in previous studies conducted by Djedjig, Belarbi, and Bozonnet (2017), and Bianco *et al.* (2017). Previous research regarding green facades conducted by Cameron, Taylor, and Emmett (2015), Qingwei *et al.* (2019), and Convertino *et al.* (2022), also confirmed this relationship.

The scarcity of leaves on the *Wisteria floribunda* (wisteria), observed on the green facade during the fall and winter campaigns, is due to the initial stage of plant development in the fall and its deciduous nature in the winter. This characteristic resulted in exterior surface temperature records of this facade being similar to those of the control room wall, exhibiting a more pronounced curve, with higher temperatures during the period of maximum solar radiation and lower temperatures at night compared to the results of the facade where the living wall is inserted.

3.3. Operating temperature

Based on the data collected on indoor air temperature and globe probe, an analysis was conducted on the variation of the indoor operative temperature of the rooms during the autumn and winter periods compared to the thermal comfort limits. Figures 14 and 15 present this variation, revealing that the operative temperature values exceeded these limits at certain measurement times, resulting in thermal discomfort.

Figure 14 – Operative temperatures in rooms with living wall (PV), green facade (GF), and control room (CC); lower and upper limits for thermal comfort, and outdoor air temperature in autumn (April 21 to 26)



Source: The authors.

The graph in Figure 14 (autumn) reveals distinct patterns directly related to weather conditions, especially the presence of clouds. On the days when the sky was cloudy (April 21 and 22), none of the rooms recorded temperatures above the upper limit of 26.8 °C. The results suggest that the presence of clouds moderated the interior heating of the room, limiting the increase in temperatures.

Even under these conditions, the vertical vegetation system had a mitigating effect on the operative temperature. On April 21, at 12:30 PM, the three rooms reached the peak of operative temperature: the control room (CC) recorded 23.8 °C, the room with the green facade (FV) 22.2 °C, while the room with the living wall (PV) reached 20.8 °C. A difference of 3.0 °C between this room's operative temperature and the control room's temperature was observed.

However, in the following days, when the sky was clear, an increase in temperatures was observed in the afternoon in autumn, causing some rooms to exceed the established upper limit. This trend was particularly evident in the control room (CC), where the temperature exceeded the upper limit by 11.5 °C at 3:30 PM on 04/25. In this room, the equipment was positioned at a height that resulted in direct sunlight on the sensor, unlike the equipment installed in the other rooms (PV and FV), which, although positioned at the same height, were not affected by sunlight due to the shade provided by the vertical vegetation systems.

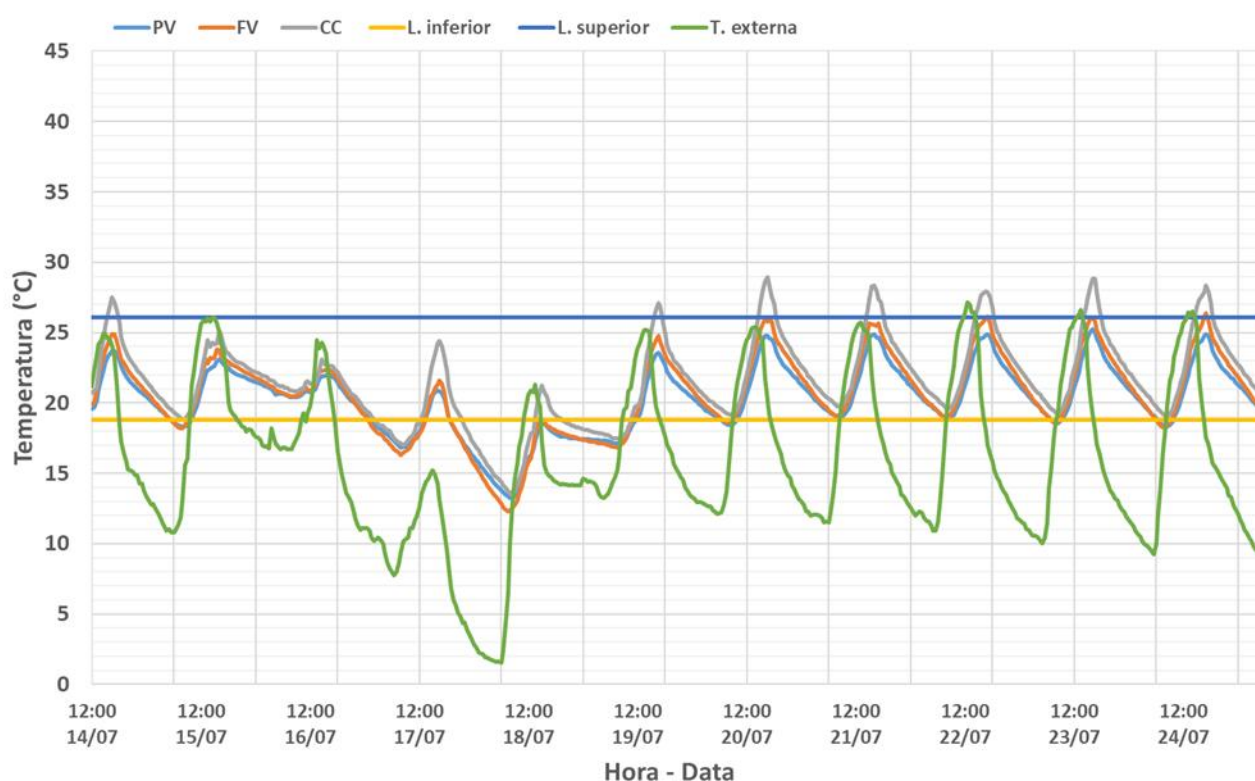
The room with the green facade system (FV) exceeded this limit only that day, with a maximum increase of 1.7 °C at 6 PM. On the other hand, the room with the living wall (LW) remained with a temperature below the upper comfort limit throughout the analyzed period. This fact illustrates the

shading effect of the vertical vegetation system. However, it is important to emphasize that, in this measurement campaign, due to direct solar incidence on the sensor, it is impossible to analyze the temperature peaks in the control room on days when the sky remains sunny.

Regarding the lower limit in autumn (Figure 14), with exceptions on the days 04/21, 04/24, and 04/25 (control room) and 04/25 (all rooms), temperature records below this value were observed in the three studied rooms. However, the values were very close to the lower limit (19.8°C). In this season, the maximum temperature difference between the lower limit and the rooms was recorded on 04/23, being 1.6°C (8:00 AM) for the living wall, 1.3°C (8:00 AM) for the green facade, and 1.0°C (7:30 AM) for the control room, with values below this limit.

Figure 15 illustrates the operative temperatures of the rooms, the lower and upper limits for thermal comfort, and the exterior air temperature throughout the winter campaign. A significant daily variation in the values of outdoor air temperature is observed. On the 22nd to the 24th days, the outdoor air temperature exceeds 26.1°C , peaking at 27.1°C on the 22nd at 12:30 PM, with a minimum recorded at 10.9°C at 5:30 AM.

Figure 15– Operative temperatures in the room with a living wall (PV), green facade (FV), and control room (CC); lower and upper limits for thermal comfort, and outdoor air temperature in winter (July 14 to 24)



Source: The authors.

The maximum operative temperature recorded during this campaign for the control room was 28.9°C at 4:30 PM on July 20, exceeding the upper limit by 2.1°C and resulting in thermal discomfort due to heat.

However, the room with the living wall did not show any records of operative temperature exceeding the upper limit on any of the measurement days. On the other hand, the room with the green facade only exceeded by 0.3°C on the 24th, at 5 PM.

The lowest exterior temperatures of the winter campaign were recorded on July 17 and 18. This condition resulted in minimum operative temperatures below the lower limit (18.8°C) in the three test rooms. On 07/18 at 6:00 AM, the exterior air temperature recorded at the campus weather station was 1.5°C .

The minimum operative temperature was recorded at 8:00 AM in the experiments. At that moment, the environment with the living wall showed 13.3 °C, the room with the green facade showed 12.3 °C and the control room recorded 13.6 °C. It is important to emphasize that there was a slight variation between the minimum operative temperatures recorded in the environments. Therefore, the vertical vegetation system did not significantly impact periods of minimum temperatures.

4. Conclusions

Based on the data obtained in the experiment, the implementation of the vertical vegetation system revealed a significant shading potential capable of mitigating the excess heat generated by the solar radiation incident on the walls. This intervention resulted in milder temperatures for the indoor environment, especially during periods of likely overheating.

Throughout the two measurement campaigns presented in this article, autumn and winter, higher exterior surface temperatures were observed in the control room during the hours of highest solar radiation. In autumn, the difference compared to the surface protected by the living wall was 18.5 °C, while in winter, it was 16.6 °C. Compared to the surface protected by the green facade, the differences were 13.3 °C in autumn and 8.3 °C in winter.

However, during the times of minimum surface temperatures, the differences decreased. The exterior surface of the environment where the green facade is installed recorded the lowest temperature, 4.3 °C. In contrast, the exterior surface of the control room showed 7.0 °C, and the exterior surface protected by the living wall showed 8.4 °C. These were the lowest temperatures recorded during the measurement period in winter.

By monitoring the interior surface temperature, it was possible to identify the impact of the vertical vegetation system on the heat flow into the interior of the building. The results revealed a clear relationship between the reduction in the temperature of the exterior surface of the wall protected by the living wall (LW) and the consequent reduction in the temperature of the interior surface of that wall. Throughout the entire measurement period, both in autumn and winter, the interior surface of the living wall exhibited lower temperatures than the control room during the hours of higher temperatures. It is important to emphasize that there was an approximation of these temperatures in the early hours of the day; however, with the increase in solar radiation, they began to diverge again in the afternoon.

It is possible to observe a minor variation between the maximum and minimum surface temperatures in environments with a vertical vegetation system compared to the control environment. This finding suggests that the system lowers temperatures during the hottest periods and helps maintain a more stable temperature throughout the day.

These results reinforce the benefits of the living wall system in reducing the exterior surface temperature and controlling the heat flow into the interior of the building. However, seasonal variations and specific times of the day can influence the thermal effects of this system, highlighting the importance of considering these aspects when implementing the vertical vegetation system in construction projects.

Regarding the results of the operative temperature calculation, in the autumn campaign, it was found that all environments recorded temperatures below the lower limit for thermal comfort, which is 19.8 °C. However, the room protected by the living wall showed the highest occurrence of hours of cold discomfort. At the same time, it was the only environment that managed to keep the interior temperatures below the upper limit of 26.8 °C, showing superior performance in reducing thermal discomfort due to heat. It is important to emphasize that, in the autumn campaign, the green facade had only been opened for five months since the vines were planted, and therefore, the vegetation had not yet reached its full development. Possibly, in future measurements with more excellent plant coverage, the results of the green facade may show a more effective shading effect.

Throughout the winter campaign, the operative temperature limits for comfort during the data collection period ranged between 18.8 °C and 26.1 °C. The three environments showed values below

the lower limit. The living wall proved more efficient this season than the green facade, as the latter recorded more hours below the lower limit. For both campaigns, the results indicate that during the hours of minimum temperatures, the operative temperatures of the three environments remained close.

However, temperatures above the upper limit were observed during the winter. More specifically, in the control environment, seven of the ten days of measurement showed temperatures above the acceptable limit. On the other hand, no occurrences of exceeding this limit were recorded during this season in the environments with the vertical vegetation system.

The results indicate that even during milder seasons, such as winter, the subtropical climate can present periods of discomfort due to heat. However, the main contribution of this research was to demonstrate that the vertical vegetation system, particularly the living wall, is effective in significantly reducing heat entry into the analyzed environments. This suggests that such systems can provide substantial benefits for thermal comfort and energy efficiency in subtropical climates during autumn and winter.

These findings highlight the importance of vertical vegetation systems as viable solutions for mitigating high temperatures and reducing reliance on artificial air conditioning in built environments. However, more comprehensive data is needed for these systems to be considered a practical alternative for lowering energy consumption. This includes the full development of *Wisteria floribunda*, adjustments in the height of indoor air temperature and globe temperature sensors, and data covering all seasons of the year. Additionally, studies involving other plant species and large-scale analyses will be essential for a more thorough evaluation of the system's overall performance.

Declaration

The authors declare the use of generative artificial intelligence, specifically Grammarly, to enhance the English grammar and vocabulary throughout the text. After using this tool/service, the authors have reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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