

Thermo-energetic simulations. Protocol for modelling traditional green facades in cities in arid areas

Simulaciones termoenergéticas. Protocolo para el modelado de fachadas verdes tradicionales en ciudades de zonas áridas

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Abstract

Today's cities face the challenge of adopting technologies that promote sustainable urbanization in order to mitigate urban warming and be resilient to the effects of climate change. This research aims to characterize the optothermal properties of Traditional Green Façades (TGF) during the summer season, and develop a simplified modelling protocol in EnergyPlusTM. To this end, a trial was conducted in the Mendoza Metropolitan Area under controlled conditions with the perennial climbing species called Pandorea jasminoides (white bignonia). Experimentally, it was determined that a reduction of 7.1°C in the indoor air temperature of a space behind a wall with TGF compared with that recorded in a similar space behind a conventional brick wall. To represent this model in the simulation, a shadow surface -Shadow Surface E+- and an additional material in the envelope representing the mass characteristics of the TGF are implemented. Unlike the methodologies adopted by other authors, this study not only provides a model in EnergyPlusTM that considers the physical and mass properties of the foliage of the climbing plant that makes up the TGF, but also allows this method to be systematically applied to characterize various plant species to develop a database for application in different contexts and building types.

Keywords: Traditional green facades; thermal model; bioclimatic architecture; sustainable construction; arid zones.

Resumen

Las ciudades actuales se enfrentan al desafío de adoptar tecnologías que promuevan la urbanización sostenible con el fin de mitigar el calentamiento urbano y ser resilientes a los efectos del cambio climático. Esta investigación tiene como objetivo caracterizar las propiedades optotérmicas de las Fachadas Verdes Tradicionales (FVT) durante la temporada de verano y desarrollar un protocolo de modelización simplificado en EnergyPlusTM. Para ello, se llevó a cabo un ensayo en el área metropolitana de Mendoza en condiciones controladas con la especie trepadora perenne llamada pandorea jasminoides (Bignonia Blanca). Experimentalmente, se determinó una reducción de 7,1 °C en la temperatura del aire interior de un espacio detrás de una pared de ladrillo con FVT respecto a la registrada en un espacio similar detrás de una pared sin cobertura. Para representar este modelo en la simulación, se implementan una superficie de sombra (Shadow Surface E+) y un material adicional en la envolvente que representa las características de masa de la FVT. A diferencia de las metodologías adoptadas por otros autores, este estudio no solo proporciona un modelo en EnergyPlusTM que considera las propiedades físicas y de masa del follaje de la planta trepadora que compone el FVT, sino que también permite aplicar este método de forma sistemática para caracterizar diversas especies vegetales con el fin de desarrollar una base de datos para su aplicación en diferentes contextos y tipos de edificios.

Keywords: Fachadas verdes tradicionales; modelo térmico; arquitectura bioclimática; construcción sostenible; zonas áridas.

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1. Introduction

It is estimated that approximately 80% of the total Latin American population resides in urban areas. The phenomenon of population concentration in these regions of the planet renders them more susceptible to the repercussions of global warming. This, in turn, serves to amplify the risk associated with extreme weather events, such as heat waves. (OLADE, 2021; IPCC 2022). In this context, it becomes necessary to move towards the construction of air-clean and cool cities, restoring the balance between the natural environment and the built habitat, and mitigating carbon emissions. To this end, technologies that promote sustainable urbanization and restore degraded ecosystems must be adopted.

The integration and expansion of urban greenery is an effective strategy to increase resilience to climate change in cities (Gill, Handley, Ennos, & Pauleit, 2007). Moreover, the incorporation of ecotechniques (strategies that seek a harmonious relationship with the environment) provides social and economic benefits to communities (Caballero Montes, Ríos Ventura, & Alavéz Ramírez, 2024). Green infrastructures are shown to be versatile elements within urban architecture and represent the essence of new trends in the field of architecture and urban planning, especially eco-architecture (González & González, 2019). Their incorporation brings energy-environmental benefits, mitigates the urban warming and urban heat island effect, and increases public space comfort. Moreover, at the building scale, it reduces energy consumption for interior space conditioning. However, the city consolidation phenomenon has limited the potential for traditional green structures – parks, squares, alignment trees – giving rise to new forms of vegetation adapted to the building envelopes: Green Roofs and Walls.

Within the new vegetated technologies, Vertical Greening Systems (VGS) are grouped into two general categories: Living Wall (LW) and Green Façades (GF). Within the LWs, the Traditional Green Façades (TGFs) are composed of climbing plants that develop directly on the wall of the building with no space in between. LW systems are extensive due to their economical and simple construction methods and their low impact on the existing building. The thermal effects produced by LW typologies are shading and evapotranspiration cooling, the former having the greatest relevance regarding urban heat island mitigation potential and building energy savings (Pérez, Coma, Sol, & Cabeza, 2017; Pérez Gallardo et al., 2018). This is particularly important in arid or semi-arid climates, given the incidence of effective solar radiation on exposed surfaces and the high air temperatures in summer.

Different experimental and theoretical methodologies have been used to analyse the VGS impact on energy saving in buildings. Among the theoretical methods, EnergyPlus™ is the most commonly used simulation software, while TRANSYS and SOLENE are used depending on the VGS impact assessment scale. Regarding the magnitude of savings in energy consumption due to the use of LW with these software tools, Zhang, Zhang, & Meng, (2022) show values ranging between 6.6 % and 15.8 % for test boxes in West orientation, with mass envelope, insulation on the rest of the faces, and thermostat set to 26 °C in a humid temperate climate (Csa). Karimi, Farrokhzad, Roshan, & Aghdasi (2022) find an energy saving of 26% for an educational building in which all exposed facades are protected with TGF in a humid temperate climate (Csa). Djedjig, Bozonnet, & Belarbi (2015) report savings between 37.3% and 50.6% for a three-story educational building with the East and West facades protected with TGF in oceanic (Cfb) and warm semi-arid (Bsh) climates.

In relation to its implementation, Alexandri & Jones (2008) determine that the maximum summer solar radiation on the vertical planes facing East and West is 1.65 times greater than that received in the north and south planes in the case of Athens, Greece, whose latitude (32° N) is comparable to the case study -city of Mendoza (32° S). For this reason, international literature recommends protecting these orientations.

The Mendoza Metropolitan Area (MMA) is located in the center-west of Argentina (32.5° South Latitude, 68.5° West Longitude). Its climate is arid desert -BWh, Köppen-Geiger climate classification- with hot summers and cold winters (average temperatures in January range from 26-31°C, and July with averages of 8-14°C.), and high values for daily and seasonal thermal amplitude. It has high levels of solar irradiance (1840 MJ/m²) -mainly in the east and west-facing planes-, low wind speeds, and scarce rainfall (average 250mm/year). The annual potential evapotranspiration (ET) is 782mm, which indicates a water deficit of 532mm. As a result, the magnitude of its Heat Island reaches 10 °C, leading to a 20% increase in the demand for auxiliary cooling energy (Correa, Ruiz, Canton, & Lesino, 2012). Furthermore, multiple studies indicate that in the South American region, where the MMA is located, the frequency and intensity of heat waves have increased significantly in recent decades (Ramarao, M. V. S et al, 2024; Suli, S et al, 2023). In a similar vein, the IPCC report (2022) anticipates an escalation in extreme heat events, a phenomenon that has already become evident in 2023 and 2024, thus designating 2024 as the warmest year recorded to date.

In relation to their building features, the city of Mendoza has a predominant mass type and locally produced construction system made up of baked brick partitions and a reinforced concrete structure without insulation. The massive spread of this non-conservative system shows the need

to improve the urban-building efficiency of the city to achieve better living conditions within public spaces and to reduce energy consumption in summer. This will enable a progressive decarbonization of the national energy matrix and its transition to clean energies based on nature-based solutions, without resorting to insulating materials intensive in fossil fuel consumption and GHG emissions. In this sense, TGF technologies have a positive impact on both indoor and outdoor thermal performance.

In this context, the present research aims to characterize the optical and thermal properties that represent the summer-season behavior of the TGF to be incorporated in simulation software (EnergyPlus™). As a result, the impact of its implementation on both energy consumption and the thermal behavior of different building typologies will be established.

2. Development

The structure of this work comprises two stages: the first is to determine the optical and thermal properties that represent the behavior of a type of TGF through the simulation and adjustment of an experimental test under controlled conditions. This test consists of simultaneously monitoring the temperature in two test boxes, one with a bare wall and the other with a vegetated wall. Through a combined behaviour adjustment of both boxes, it is possible to extract the vegetation contribution to the TGF typology. The characterization of the optical and thermal properties of this technology will allow its incorporation into the EnergyPlus™ simulation software to evaluate the impact of alternative implementation methods in different building typologies. Moreover, the most efficient combinations in terms of rational use of resources, building energy savings, and impact on the urban environment will be identified.

2.1 Determination of the optical and thermal properties that characterize TGFs

This first stage aims to determine the optical and thermal characteristics of the TGF using the climbing species that reported the best thermal and vegetative performance (thickness and coverage) in a controlled trial carried out in the dry-desert climate of the Metropolitan Area of Mendoza -Bwk-, during the summer of 2022. TGF -add species- were applied in West facing walls, considered the most unfavorable orientation. A detailed description of the selection process can be found in Suárez, Cantón, & Correa (2023). This orientation has greater sun exposure than the North façade in summer, which combines with the higher outside air temperature due to the heat accumulated by the thermal inertia of the city. Perennial species are tested to obtain the greatest potential for annual thermo-energetic building performance. TGF has positive effects in winter due to the energy conservation effect associated with the reduction of heat losses produced by the insulating effect of the green façade, and in summer as a result of the decrease in solar gain produced by the shading effect in the envelope.

The experimental test monitors two prism-type test boxes, each consisting of a 1.3m wide, 2.3m high, 0.17m thick west-facing mass wall that supports the TGF. This wall is made of baked brick and framed in a reinforced concrete structure. Attached to the wall is a 0.18 m thick air chamber, fully insulated by 0.05 m of high-density expanded polystyrene. One of the test boxes has an TGF cover which is attached directly to the wall by means of a metal support device and the other is uncovered to function as a witness wall (See Figure 1). The dimensions of the test boxes are in keeping with similar experimental models carried out in the international literature (Vox, Blanco, & Schettini, 2018) (Ruiz-Valero, Faxas-Guzmán, Arranz, Flores-Sasso, & Céspedes, 2022).

The configuration of the experiment includes the unvegetated control wall -CW- and the vegetated wall covered by TGF using the species White Bignonia (Pandorea Jasminoides) -VW-. The monitored variables included outdoor temperature, humidity, and solar radiation; temperature and humidity inside the air chamber, and the exterior and interior surface temperature of the wall. Data were recorded every 15 minutes using various sensors (Figure 2), which were previously calibrated to guarantee the reliability of the data. These sensors included thermistor types: -HOBO Onset, UX100-003, U30 USB Weather Station-, all placed at a height of 1.30 m (air chamber) and 1.60 m (outer space).

In summer, the application of Traditional Green Façades shows greater efficiency for energy saving in buildings as the shading effect increases (Pérez et al., 2017). For this reason, a four-day analysis period that represents the expected summer temperature and solar radiation was considered (See Table 1). These days correspond to 15-18 February 2022 (See Figure 3).



Figure 1. Experiment consisting of two test boxes.

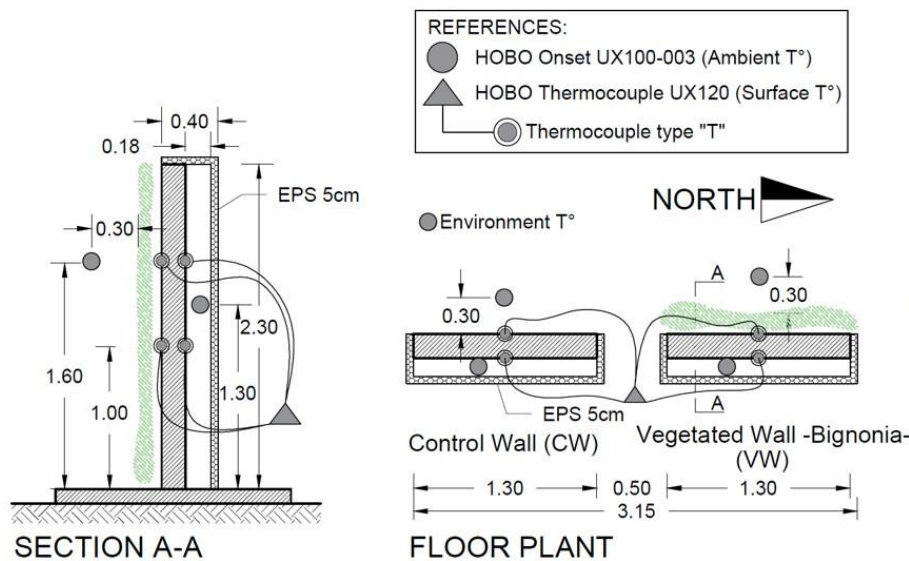


Figure 2. Test Configuration and Sensor Placement.

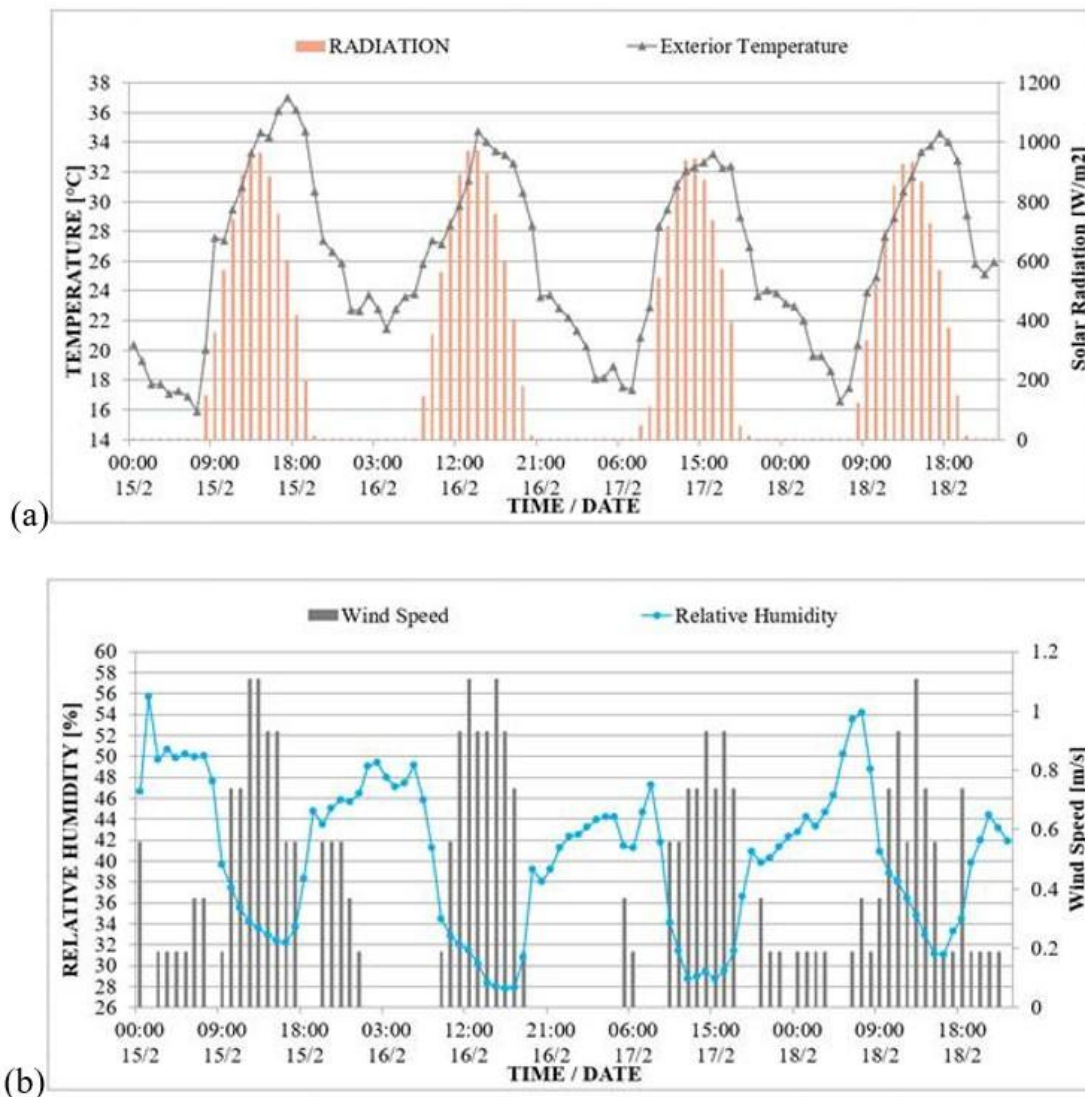


Figure 3. Climate data, radiation, air temperature (a); relative humidity and wind speed (b).

Table 1. Climatic characteristics of the period analysed.

	Maximum temperature	Minimum temperature	Temperature Minimum average	Temperature maxim average	Amplitude thermal average
Period: 15/02 – 18/02	37.0	15.9	17.8	34.9	26.4

Thickness and coverage were considered to characterize the vegetation cover. Thickness was measured at eight equidistant points, and the data were averaged in order to determine a representative growth value regarding the TGF species (See Figure 4). Vegetation cover was estimated by taking photographic images during the measurement period at a time of minimum solar radiation incidence, to avoid image distortions. The images were processed using MultiSpec software to determine the proportion between voids and fills, representing the degree of coverage of the TGF species.

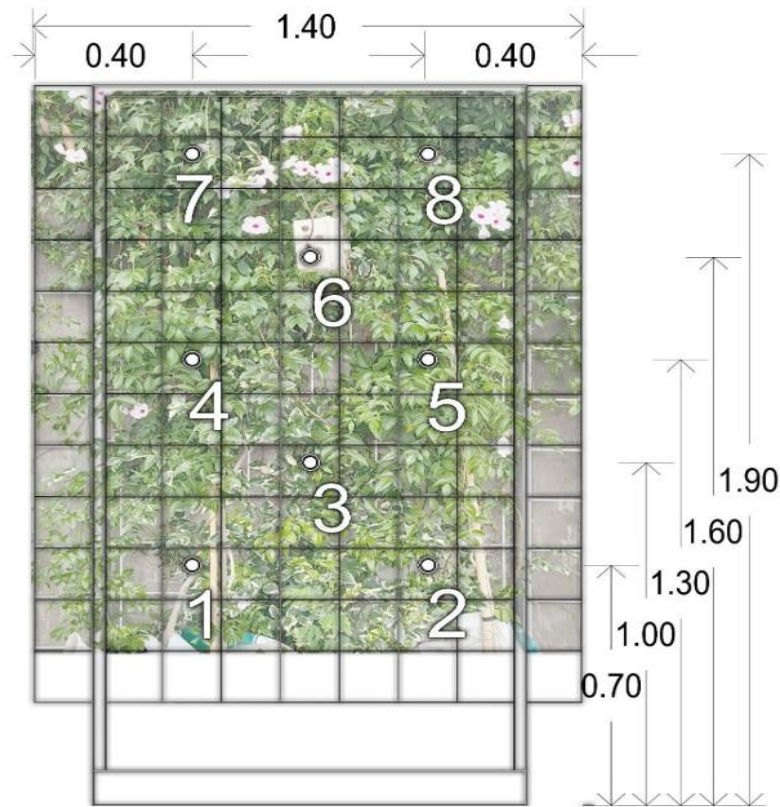


Figure 4. Vegetation thickness measurement points.

During the monitored period, the VW climbing plant shows a coverage value of 88.0% and an average thickness value of 0.27 m, measured as previously described. Both variables show a homogeneous distribution of these values, as shown in Figure 5.

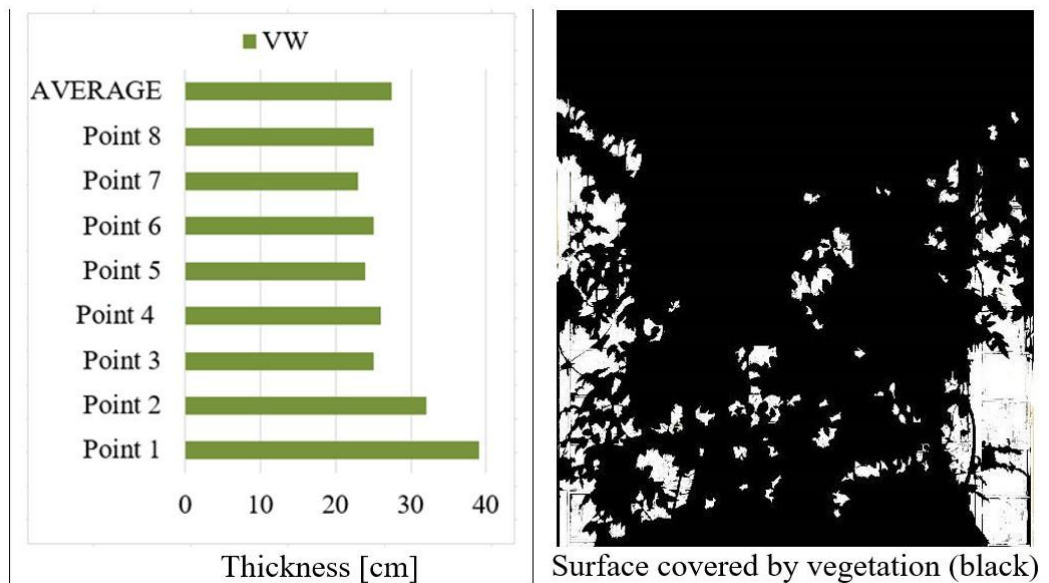


Figure 5. VW vegetation thickness and coverage.

2.2 Simplified Opto-Thermal Model of TGF

The simulated indoor air temperature curve obtained from the EnergyPlus™ model is adjusted to the values of the monitored test boxes during the previously described period (February 15-18), representative of summer days and clear skies in the study area. This procedure is divided into two stages. The first consists of the adjustment of the vegetated masonry wall, called the witness wall -CW-, to characterize the real opto-thermal properties of the TGF support walls. Table 2 shows the properties of high-density Expanded Polystyrene -EPS- used to house the air chamber, according to Llorente-Alvarez et al. (2022). In the second stage, the properties obtained from the adjustment of the witness wall are applied to readjust the interior temperature curve of the wall with the TGF -VW- by simulation (See Figure 6).

Table 2. Properties of EPS.

EPS Properties		
Property	Unit	Value
Roughness	--	Smooth
Thickness	m	0.05
Conductivity	W/m°K	0.04
Density	kg/m ³	20
Specific heat	J/Kg°K	1700
Thermal absorption	--	0.9
Solar absorption	--	0.08
Visible absorption	--	0.7

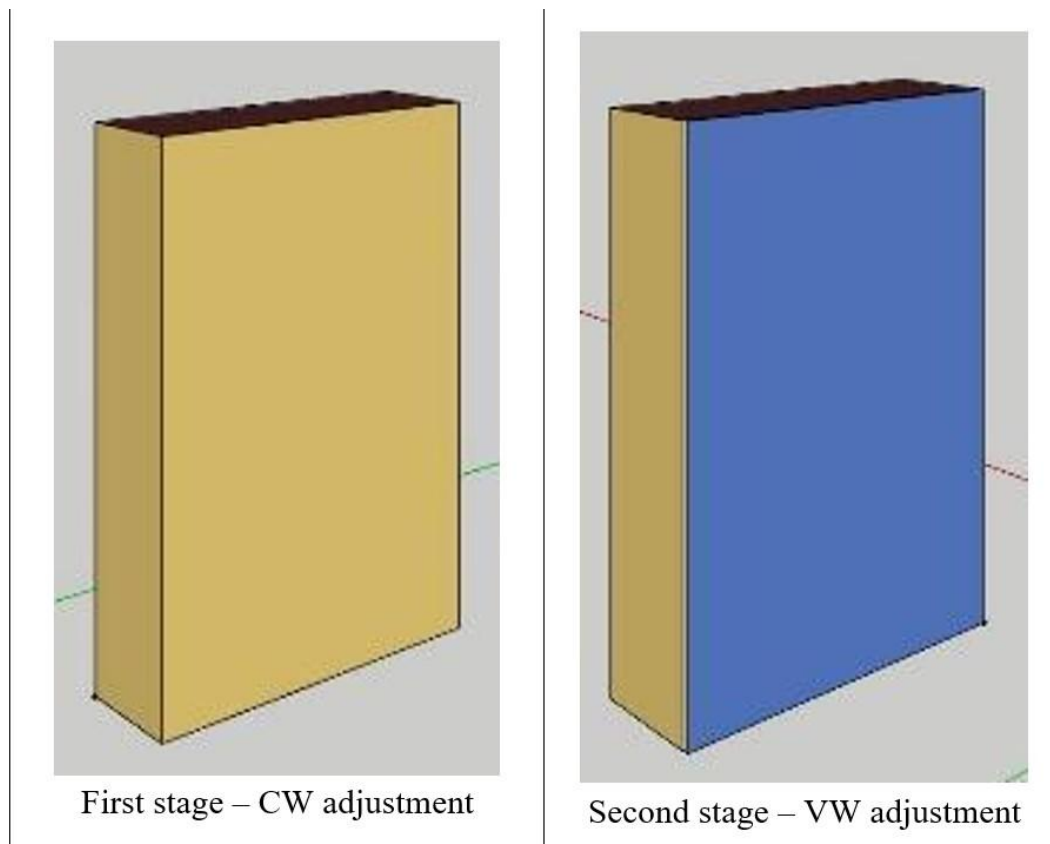


Figure 6. Test simulation model under controlled conditions.

The construction of the EnergyPlus™ opto-thermal model representing the behavior of the VW with Bignonia involves two steps: the implementation of a shadow surface and the addition of an exterior material (similar to an insulating outer layer) to the masonry wall. The first step simulates, through the variable of solar transmittance, the degree by which the foliage of the climbing species interferes with solar radiation, mainly determined by the degree of coverage. The second functions as a representative element of the average physical properties of the plant body, including variables such as roughness, conductivity, density, specific heat, thermal absorption, and solar absorption, all of which depend largely on the thickness of the foliage.

3. Results and Analysis

The results of the measurement, adjustment, and simulation of test walls under controlled conditions are organized in two stages:

- Analysis of thermal magnitudes by the application of a TGF strategy, which, under controlled test conditions, shows a high plant development in terms of thickness and coverage, in contrast to an uncovered wall.
- Determination of the optical and thermal properties representative of the TGF behavior, simulated in the EnergyPlus™ software.

3.1 Results of the analysis of thermal magnitudes by the application of the TGF strategy

Next, the analysis of the interior ambient temperature curve of the air chamber is presented, as this variable has the greatest influence on both energy consumption and interior thermal comfort in a bare wall -defined as CW- and a wall covered with TGF -VW (Bignonia). The maximum magnitude was identified to assess the impact of the TGF itself (maximum performance) based on the observation of the greatest impact during summer heating hours.

Within the monitored summer period (02/15/22 to 02/18/22), a maximum indoor ambient temperature reduction of 7.1 °C for VW, with respect to CW, is determined at 9:00 pm on February 15 (See Figure 7). The strategy consistently reduced temperatures across most hours of the four days, highlighting the benefits of the strategy on reducing energy demand to achieve comfort conditions in indoor spaces during summer days and nights.

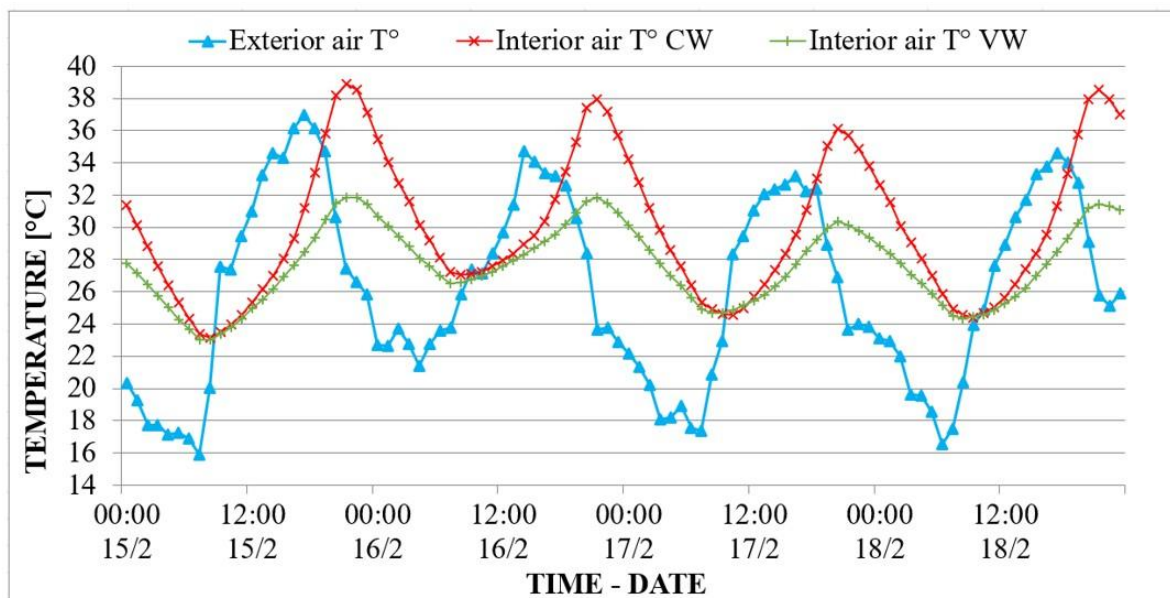


Figure 7. Comparison between simulated and measured indoor ambient temperature in CW vs. VW.

3.2 Results of the determination of the opto-thermal properties that characterize TGFs

Subsequently, the development of a simplified model was carried out to represent the optical and thermal characteristics of the TGF with the climbing species White Bignonia (*Pandorea jasminoides*). This species showed good thermal performance (reduction of indoor ambient temperature in the test box) and vegetative performance (thickness and coverage) during February 2022 under controlled summer conditions.

Simulations were divided into two stages: adjustment of the masonry wall (control wall -CW-) and determination of optical and thermal properties to adjust the interior temperature curve of the vegetated wall with TGF -VW wall-.

Table 3 shows the properties used for the adjustment of the masonry wall in summer. The assigned properties correspond to the values found in Llorente-Alvarez et al. (2022). The climate data corresponds to the TMY Airport statistical archive -MDZ- (2003-2017), with the analyzed period modified using measurements from the Onset U30 meteorological station in the experimental area, from February 13-19, 2022, representative of warm days and clear skies. The results of the simulated indoor ambient temperature show an adjustment with an R2 of 0.98 when contrasted with the measured data (See Figure 8 and Figure 9).

Table 3. Masonry wall properties used in fitting.

Masonry wall properties		
Property	Unit	Value
Roughness	--	rough
Thickness	m	0.18
Conductivity	W/m°K	1.5
Density	kg/m3	2000
Specific heat	J/Kg°K	850.9
Thermal absorption	--	0.9
Solar absorption	--	0.85
Visible absorption	--	0.7

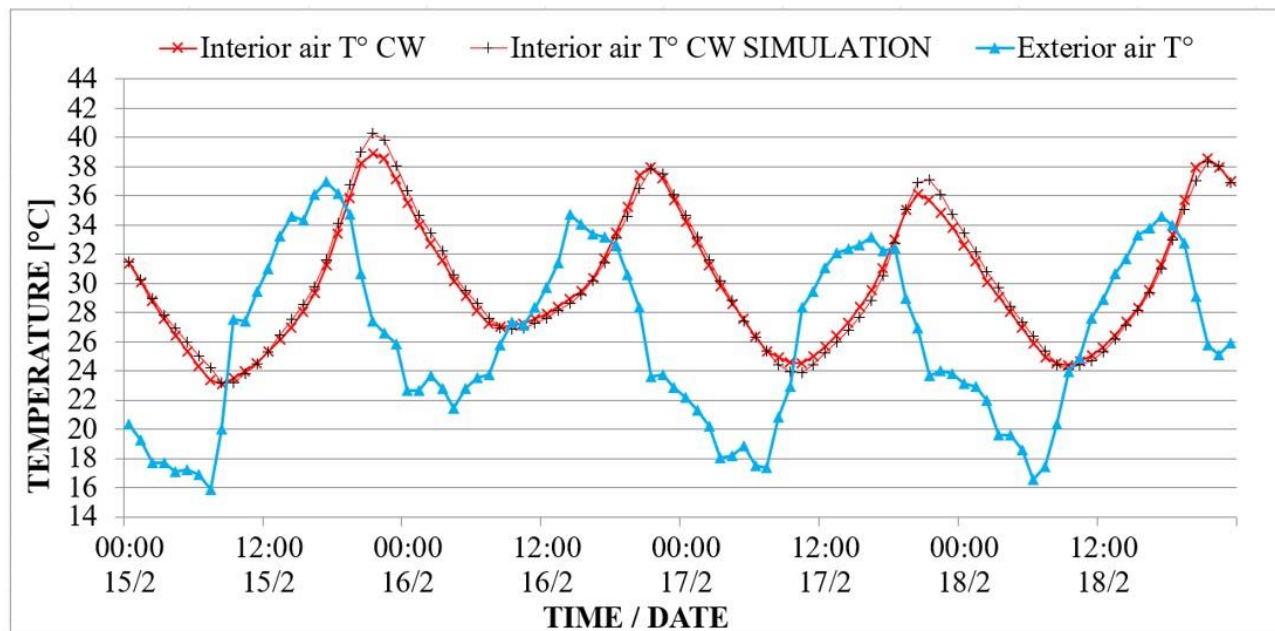


Figure 8. Comparison between simulated and measured indoor ambient temperature in Control Wall (CW).

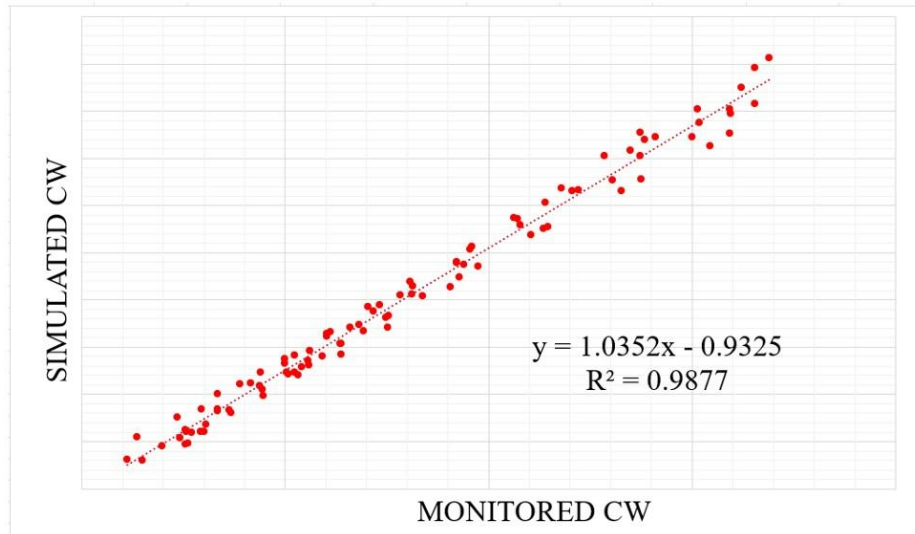


Figure 9. Indoor ambient temperature regression analysis.

The model obtained from the adjustment of the witness wall was used for the construction of the EnergyPlus™ opto-thermal model that adjusts the measurements of indoor ambient temperature in the air chamber of the wall with TGF -VW-. For this, a shadow surface is implemented -Shadow Surface- along with an additional material on the external face of the brick wall construction, whose properties are described in Table 4. The values of the variables used to construct Table 4 were tested within the ranges reported in various literature sources. (Jayalakshmy & Philip, 2010; Casto et al, 2017; Lee & Jim 2019) and adjusted according to the combination of property values that verified the best fit with the TGF wall interior temperature data measured during the experiment. The shade surface has a solar transmittance of 0.4, regulated by a Transmittance Schedule that applies this property throughout all hours of the day. The material has mass properties similar to an insulating outer layer of the masonry wall, the most relevant being: thickness 0.03m, density 1000 Kg/m², conductivity 1 W/m²K, and specific heat 2000 J/Kg²K. When contrasting the results of the simulation of the indoor ambient temperature with the measured data, an adjustment with an R² of 0.97 is shown (See Figure 10 and Figure 11).

Table 4. Properties of the material used as TGF in the fitting.

TGF Properties		
<i>Property</i>	<i>Unit</i>	<i>Value</i>
Roughness	--	smooth
Thickness	m	0.03
Conductivity	W/m ² K	1.0
Density	kg/m ³	1000
Specific heat	J/Kg ² K	2000
Thermal absorption	--	0.9
Solar absorption	--	0.85
Visible absorption	--	0.7

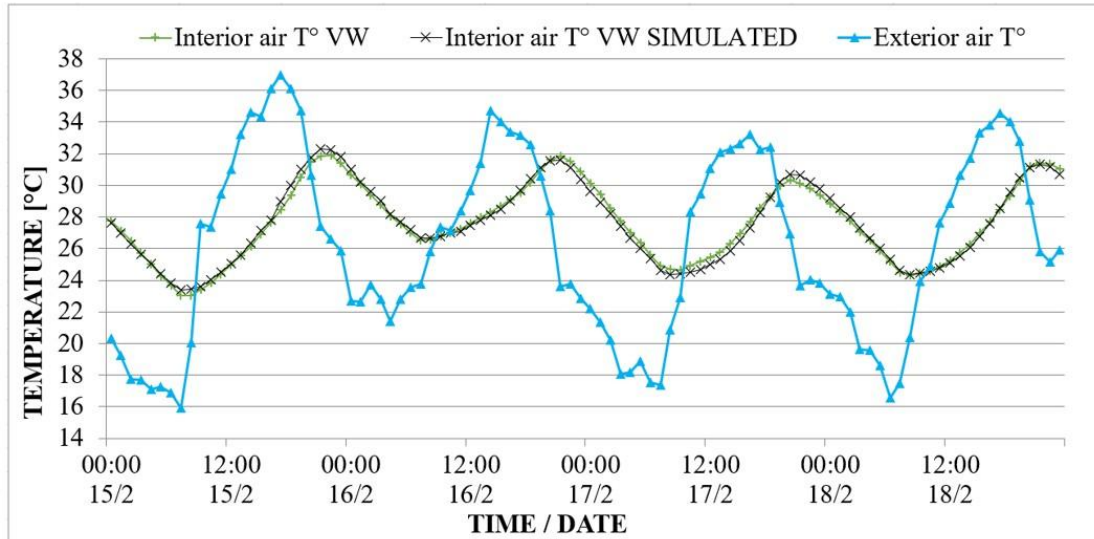


Figure 10. Comparison between simulated and measured indoor ambient temperature in Vegetated Wall (VW).

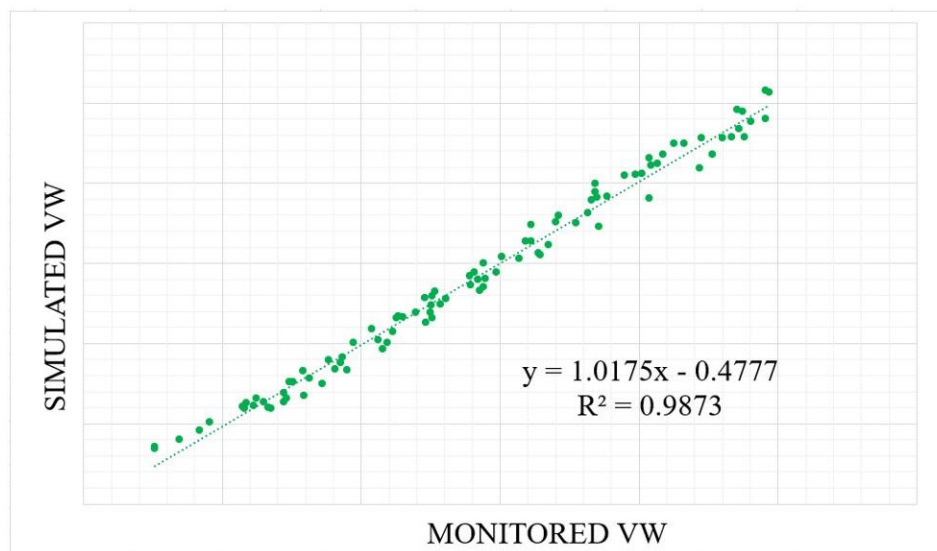


Figure 11. Indoor ambient temperature regression analysis.

3.3 Analysis of the impact of TGF on the specific humidity of the immediate environment

As previously outlined, in order to evaluate the impact of TGF on temperature and relative humidity in the immediate environment, a temperature and relative humidity sensor was placed at a distance of 30 cm from both the control wall and the wall with TGF, at an approximate height of 2 m. The sensor was encased in a perforated PVC box to protect it from precipitation and solar radiation. As demonstrated in Figure 12, the graphs illustrate the behaviour of both variables at 30 cm from both walls during the specified period.

As demonstrated in Figure 12, a marked disparity in relative humidity (RH) values is evident between the wall with TGF and the control wall on February 18 and 19 during the evaluated period. Given the established correlation between relative humidity and temperature, the specific humidity behaviour was evaluated for the cases assessed on the specified days. The hourly specific humidity value was obtained by entering the air temperature, relative humidity, and altitude for each hour using an online psychrometric calculator (<https://www.herramientasingenieria.com/onlinecalc/spa/psicrometricos/psicrometricos.html>). As illustrated in Figure 13, the behaviour of the specific humidity was monitored at a distance of 30 cm from the control wall and the wall with TGF.

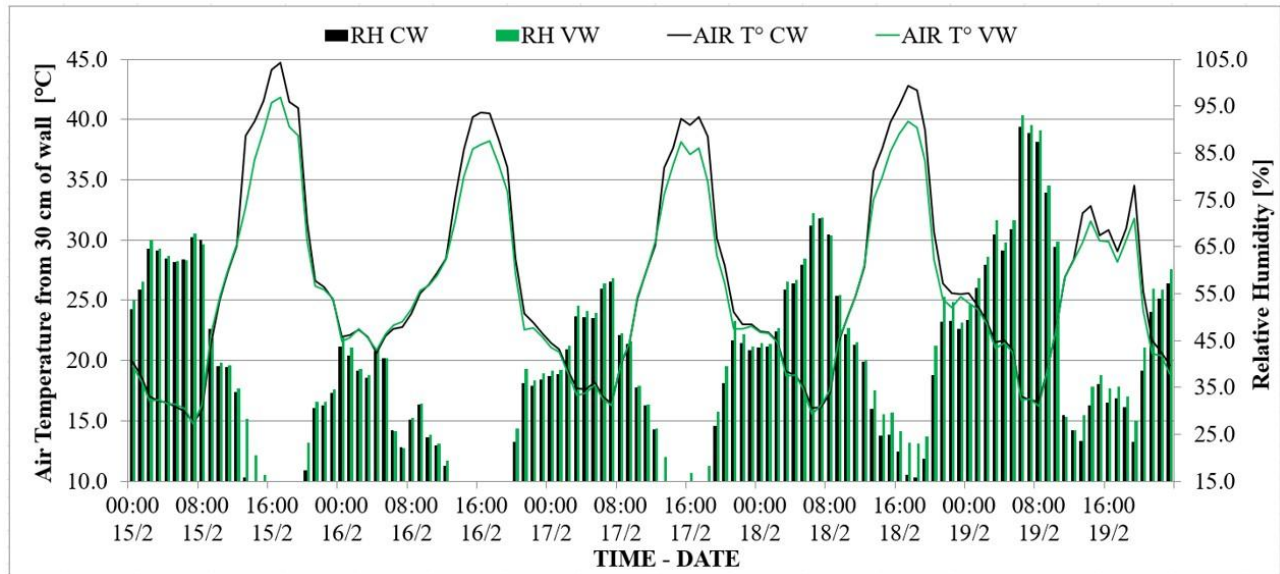


Figure 12. Air Temperature and HR at 30 cm from the wall, during the evaluated period 15/02-18/02.

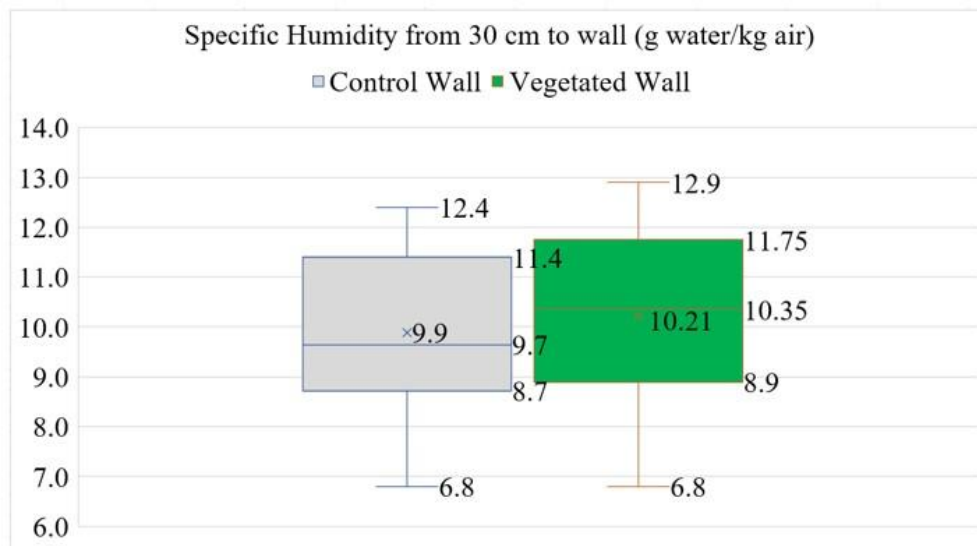


Figure 13. Specific Humidity (g water/ kg air) at 30 cm from the test wall and TGF during 18/02 to 19/02.

As demonstrated in Figure 13, the air in the vicinity of the TGF (Traditional Green Facade) consistently exhibits a higher specific humidity compared to the air surrounding the control wall. The most prevalent values recorded were 10.4 GW/kg air for the TGF and 9.7 GW/kg air for the control wall. The standard deviation was recorded as +/-1.6 gw/kg air for the TGF and +/-1.5 gw/kg air for the control wall. The maximum recorded difference in specific humidity near the evaluated walls was observed at 6:00 PM on 18 February for the wall with the TGF, reaching 2.2 gw/kg air. A further intriguing observation is that during the period under scrutiny, the specific humidity of the air in proximity to the control wall never exceeded that of the air adjacent to the TGF.

The findings, though modest in scale, indicate that the TGF exerts a role in regulating the water content of the atmosphere, a phenomenon that may be attributed to the plant's evaporation mechanisms. The magnitude of the contribution found in this experiment corresponds to conditions of full solar exposure, where the analysed environment exhibits greater solar gain, a lower roughness coefficient, and therefore greater air

circulation, and a smaller vegetated area (2 m^2). This is in contrast to the conditions that could develop in a road channel within the city under study, where the vegetated wall area would be larger and solar exposure and air circulation lower, depending on the morphology of the space. A comprehensive evaluation is imperative to ascertain the extent to which these variables influence the magnitude of the contribution to atmospheric humidity in the vicinity of the TGF. In an arid city such as the Mendoza metropolitan area, the results of this study, although preliminary, are encouraging with regard to the potential benefits that these technologies could provide in terms of urban air humidification. Consequently, future research should concentrate on further analysis of the impact of the aforementioned factors on air humidity near TGF. This objective can be accomplished through a comparative analysis of various parameters, including solar exposure, the distance from the green wall, green wall area, and wind circulation.

Sensitivity analysis is a pivotal component of examining the variability in the output due to the input factors. This approach enables the identification of input factors that exert the most significant effect on the output, as well as input parameters that demonstrate minimal or negligible impacts. Furthermore, it facilitates the analysis of how the interactions between input variables influence the output (Roka et al, 2025). In this research, a local sensitivity analysis (LSA) has been conducted for the purpose of evaluating the impact of opto-thermal properties and weather files on the adjusted degree of air temperature indoors, as simulated versus the air temperature indoors measured on the wall with a green facade. LSA is a straightforward approach that implies varying only one input parameter at a time, whilst maintaining all other parameters constant. The objective of LSA is to ascertain the influence of minor alterations in input parameters on model performance. This is achieved by systematically varying input parameters within the context of specific reference values. Due to its ease of use and minimal computational requirements, the LSA technique has been extensively employed in numerous studies pertaining to building energy modelling (Zhan et al., 2023). Dual-objective building retrofit optimization under competing priorities using an Artificial Neural Network (Journal of Building Engineering, 70, 106376). The results of the LSA are illustrated in Figures 14 and 15. Figure 14 shows the variation in transmittance of the shaded surface, thermal conductivity, density, specific heat, and solar absorptance of the foliage layer. Added, in Figure 15, the impact of the weather file is demonstrated.

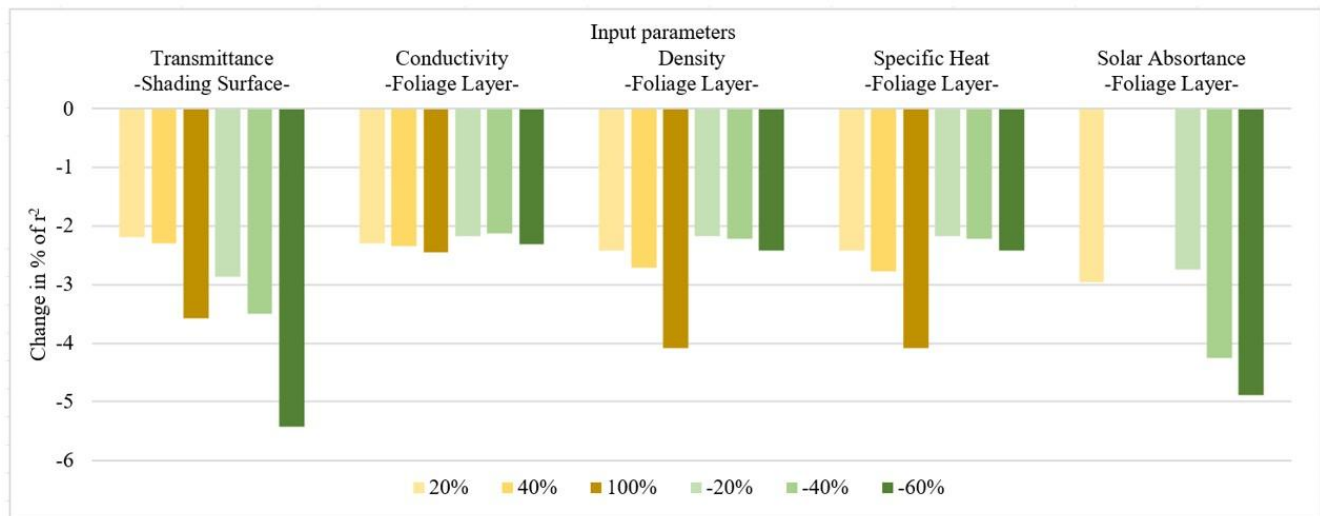


Figure 14. Sensitivity analysis of the input parameters, the shading surface, and the foliage layer.

A thorough examination of Figure 15 indicates that a variation of up to 60% in the conductivity, specific heat, and density of the layer representing the foliage has less than a 2.5% impact on the R^2 value of the fit. Conversely, the variables identified as having the greatest impact – transmittance of the shaded surface and leaf absorptance – result in a decrease in model fit of approximately 5%. However, while solar transmittance and absorptance have been shown to have an impact on the model fit, the R^2 value in the evaluated scenarios never falls below 92.5%.

In Figure 14, the impact of modifying the climate file is demonstrated. In this case, the .epw files corresponding to the 2009–2023 TMY period from the Observatorio and Plumerillo stations in Mendoza are used, as opposed to the climate file constructed with the climate data monitored during the experiment. In contrast to the opto-thermal properties, the climate file employed in the EnergyPlus model exerts a substantial influence on the model's fit. This has been shown to reduce the R^2 value by up to 30%. The findings indicate that utilising a climate file derived from in-situ climate variable monitoring is imperative for ensuring the replicability of the proposed methodology.

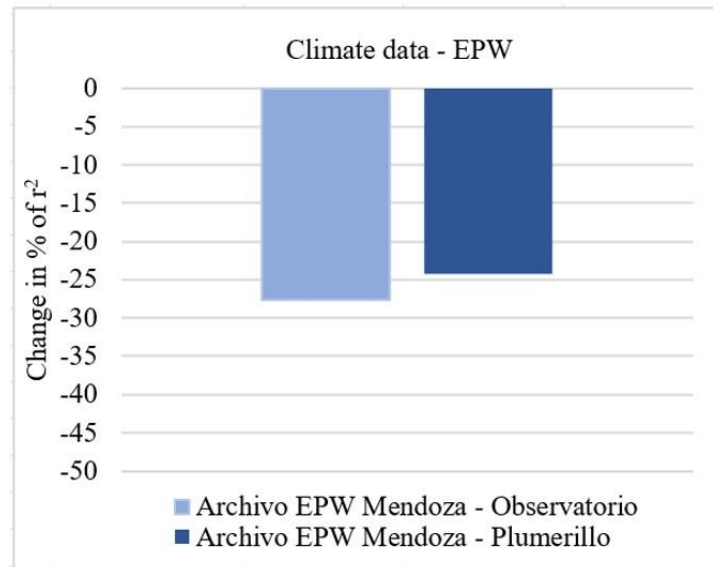


Figure 15. Indoor ambient temperature regression analysis.

4. Discussion

If we look at models analyzed in the international literature, Arengi, Perra, & Caffi (2021), for example, compare the software used for the development of computational models for the study of Green Façades, highlighting EnergyPlus™ as the most used, along with ECOTECT. Among them, only EnergyPlus™ remains open access.

Regarding models developed in EnergyPlus™ software, including the one addressed in this research, Flores Larsen, Filippín, & Lesino (2015) propose a methodology to develop a GF model attached to walls. This consists of the implementation of the envelope of a building shading object (SBO) to the construction package, in which three variables are managed: solar transmittance, solar reflectance, and visible reflectance. The first is given a constant value of 0.2, the average value established in the international literature for climbers. In addition, the wind barrier effect is considered through the calculation of a convective heat exchange coefficient, as well as the diffuse solar radiation reflected from the ground, by modifying the wall vision factor. However, the physical and mass properties present in the foliage of the climber are not considered in this model, which becomes more relevant as plant thickness increases.

Several authors have used a mathematical model of VGS for EnergyPlus™ developed by Dahanayake & Chow (2017) to simulate the thermal effect of VGS. The equations in that model are based on the heat balance principle of foliage and substrate layers, taken primarily from the EnergyPlus™ green roof module, among other validated models. According to the author, adopting a roof model for a wall will ignore differences between vertical and horizontal surfaces. More recently, García, Vera, Rouault, Gironás, & Bustamante (2022) measure and adjust an experiment using an EnergyPlus tool™. This experiment is based on the same EnergyPlus Green Roof Heat Transfer (Radiation, Convection, Evapotranspiration, and Conduction) (GRHMT) model™, adapting it to achieve a Living Wall Heat Transfer (LWHMT) model. However, the layer of foliage in the model is not thick, limiting the possibility to account for variations across type and selection of species. In addition, heat transfer dynamics is considered a one-dimensional process, following the same approach as a green roof.

In future stages, evapotranspiration will be integrated into EnergyPlus through Grasshopper, as tested by Da Rocha Hendzel et al. (2025), to distinguish between shading and evaporative cooling. This is relevant to analyse in conjunction with their 'shade + mass layer' protocol and to establish the limitations of the method.

Finally, Bano & Dervishi (2021) simulate various types of GF in a hypothetical building, while Karimi et al. (2022) experimentally simulate and adjust various GFs in EnergyPlus™. Both studies integrate the layers of the protected wall with the climbing plant as a single envelope material, considering variables such as thickness, thermal transmittance, density, conductivity, and specific heat. This prevents the separation of the

properties of the GF to apply the strategy in different situations. In this sense, the contribution of the results presented in this research becomes clear.

5. Conclusions

This work aims to determine a set of optical and thermal properties that represent the behavior of a TGF in summer and to develop a simplified opto-thermal model of TGF to be inserted into a simulation software (EnergyPlusTM). To this end, a test is monitored, simulated, and adjusted under controlled conditions with the perennial climber White Bignonia -Pandorea jasminoides.

The study experimentally demonstrates reductions in indoor ambient temperature in the air chamber, produced by the use of the strategy. Despite the effect of the scale associated with the test box, the differences reach a maximum magnitude of 7.1 °C and are evident throughout most of the monitored hours. Since this variable has the greatest impact on electricity consumption, the results show the potential impact of the strategy on energy demand to achieve comfort conditions in indoor spaces in summer, both during the day and at night.

For the simulation and adjustment of the experimental test, the variable of indoor ambient temperature in the air chamber of the wall with TGF -VW- and control -CW- is used, reaching R2 values between 0.97 and 0.98. The EnergyPlusTM opto-thermal model of the wall with adjusted TGF implements a shadow surface with a solar transmittance of 0.4 and an additional material on the external face of the brick wall construction, whose most relevant properties are: thickness 0.03m, density 1000 Kg/m², conductivity 1 W/m²K and specific heat 2000 J/Kg²K. For the solar absorption value, the value with which the witness wall was adjusted is adopted: 0.85. The results of the simulation of the indoor ambient temperature contrasted with measured values show an adjustment with an R2 of 0.97.

Unlike the methodologies used by other authors, this study provides a model in EnergyPlusTM that contemplates the physical and mass properties present in the foliage of the climber that makes up the TGF. Moreover, the model can also be extrapolated to other thermal models. These variables have a greater impact as the thickness of the plant increases. Future stages will focus on a systematic application of this method to various species in order to develop a database for its application in different contexts and building typologies in the study area.

6. Declaration of generative AI and AI-assisted technologies

In preparing this manuscript, AI-assisted technologies were not used during the preparation of this article. All content was carefully reviewed and edited by the authors, who take full responsibility for the manuscript. All outputs generated with the assistance of these technologies were carefully reviewed and edited by the authors, who take full responsibility for the content of the manuscript.

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