ENHANCING THERMAL EFFICIENCY AND COMFORT WITH GREEN FAÇADES IN AFFORDABLE HOUSINGS IN SUBTROPICAL CLIMATE

APRIMORAMENTO DA EFICIÊNCIA TÉRMICA E DO CONFORTO COM FACHADAS VERDES EM HABITAÇÕES DE INTERESSE SOCIAL EM CLIMA SUBTROPICAL

MEJORA DE LA EFICIENCIA TÉRMICA Y DEL CONFORT MEDIANTE FACHADAS VERDES EN VIVIENDAS DE INTERÉS SOCIAL EN CLIMA SUBTROPICAL

RENATA SERAFIN DE ALBERNARD, MSc. | UFSM – Universidade Federal de Santa Maria, Brasil
ELAISE GABRIEL, Dra. | UFSM – Universidade Federal de Santa Maria, Brasil
MINÉIA JOHANN SCHERER, Dra. | UFSM – Universidade Federal de Santa Maria, Brasil

ABSTRACT
The study investigates the thermal efficiency and indoor comfort of green façades in affordable housing units located in Santa Maria, southern Brazil. Over the course of one year, six housing units were monitored to evaluate summer performance, with five units incorporating green façades and one serving as a control unit without vegetation. Data collection focused on climate parameters, such as air temperature and relative humidity, recorded every 15 minutes using thermal sensors and thermographic imaging. The results reveal that the green façades significantly enhanced thermal performance by reducing surface temperatures and improving indoor thermal comfort. The maximum observed temperature difference between units with green façades and the control unit reached 12.6 Cº. The thermographic images visually validated these findings, visually confirming the cooling effect. Physiologically Equivalent Temperature (PET) analyses further demonstrated increased thermal comfort in green façade units, with the highest PET difference of 6.5 ºC recorded on February 24. The findings advocate for broader adoption of green façades in social housing in any geographic location, emphasizing their role in addressing environmental challenges, improving energy efficiency, and promoting occupant well-being in urban settings.

KEYWORDS
Physiologically Equivalent Temperature; Microclimate; Outdoor thermal comfort.

RESUMO
O estudo investiga a eficiência térmica e o conforto interno das fachadas verdes em habitações de interesse social localizadas em Santa Maria, Brasil. Ao longo de um ano, seis unidades habitacionais foram monitoradas para avaliar o desempenho durante o verão, sendo que cinco unidades incorporaram fachadas verdes e uma serviu como unidade de controle sem vegetação. A coleta de dados concentrou-se em parâmetros climáticos, como temperatura do ar e umidade relativa, registrados a cada 15 minutos por meio de sensores térmicos e imagens termográficas. Os resultados revelam que as fachadas verdes melhoraram o desempenho térmico, reduzindo as temperaturas superficiais e aprimorando o conforto térmico. A diferença máxima de temperatura observada entre as unidades com fachadas verdes e a de controle atingiu 12,6°C. As imagens termográficas validaram visualmente esses resultados, confirmando o efeito de resfriamento. As análises da Temperatura Fisiologicamente Equivalente (PET) demonstraram o aumento do conforto térmico nas unidades com fachada verde, com a maior diferença de PET registrada em 6,5°C no dia 24 de fevereiro. A pesquisa reforça a importância da adoção dessa

http://dx.doi.org/10.29183/2447-3073.MIX2025.v11.n2.93-108
ISSN: 2447-0899 (IMPRESSA) | 2447-3073 (ONLINE)

estratégia em habitações sociais para mitigar desafios ambientais, melhorar a eficiência energética e promover o bem-estar em áreas urbanas.

PALAVRAS-CHAVE

Temperatura Fisiologicamente Equivalente; Microclima; Conforto térmico.

RESUMEN

El estudio investiga la eficiencia térmica y el confort interior de las fachadas verdes en viviendas de interés social ubicadas en Santa Maria, Brasil. A lo largo de un año, se monitorearon seis unidades habitacionales para evaluar el desempeño durante el verano, de las cuales cinco incorporaron fachadas verdes y una sirvió como unidad de control sin vegetación. La recolección de datos se centró en parámetros climáticos, como la temperatura del aire y la humedad relativa, registrados cada 15 minutos mediante sensores térmicos e imágenes termográficas. Los resultados revelan que las fachadas verdes mejoraron el rendimiento térmico, reduciendo las temperaturas superficiales y aumentando el confort térmico. La diferencia máxima de temperatura observada entre las unidades con fachadas verdes y la unidad de control alcanzó los 12,6 °C. Las imágenes termográficas validaron visualmente estos resultados, confirmando el efecto de enfriamiento. Los análisis de la Temperatura Fisiológicamente Equivalente (PET) demostraron un aumento del confort térmico en las unidades con fachada verde, registrándose la mayor diferencia de PET en 6,5 °C el día 24 de febrero. La investigación refuerza la importancia de adoptar esta estrategia en viviendas sociales para mitigar desafíos ambientales, mejorar la eficiencia energética y promover el bienestar en zonas urbanas.

PALABRAS CLAVE

Temperatura Fisiológicamente Equivalente; Microclima; Confort Térmico.

1. INTRODUCTION

The social housing sector in many developing countries, and, particularly in Brazil, focuses on maximizing the number of house units with limited investment (FTD, 2010; BODACH; HAMHABER, 2010). As a result, the cost per housing unit is low, leading to poor construction quality and making it challenging to prioritize environmental quality, energy efficiency goals, and thermal comfort. The improvement of energy efficiency in existing structures is imperative in reducing greenhouse gas emissions and addressing climate change (TANASA et al., 2020; KARAKAS et al., 2023). Additionally, issues of environmental quality, encompassing aspects like thermal, acoustic, visual comfort, and air quality, directly influence the comfort, health, and productivity of occupants (OH et al., 2023; WOODS-BALLARD et al., 2015; CARSON et al., 2013; LARSEN et al., 2015). However, despite the rapid proliferation of new constructions, there is limited emphasis on the adoption of energy-efficient and environmentally friendly technologies for heat relief, particularly in developing nations (FENSTERSEIFER et al., 2022; GABRIEL et al., 2023; KUMAR et al., 2023).

Several techniques have been proposed to optimize economic performance in buildings and address socio-environmental issues in urban areas. The adoption of construction strategies that reduce energy demand, lower CO_2 emissions, and the use of vegetation (ZITARS et al., 2022; SUN et al., 2017) are two common practices. Increasing green area in cities has been common research in most of the studies so far (CARTER et al., 2015; VANHARI et al., 2017; MUMTAZ, 2021). Urban green spaces are one method of not only saving energy within cities mitigating the UHI effect but also have the potential to improve human thermal comfort (LAM et al., 2020; XU et al., 2017). Within urban green spaces, green walls are gaining popularity, being an attractive, renewable, and eco-friendly solution (KUMAR et al., 2023). Several benefits have been explored for green walls to moderate the negative effects of urban sprawl (TEOTÓNIO et al., 2021). These benefits fall into three main fields, namely environmental, including UHI mitigation, absorption of dust and noise, and the potential to consume carbon dioxide and release oxygen (RAHMAN et al., 2023; GHAZZALI et al., 2019), economic, with greenery functioning as shading devices (CONVERTINO et al., 2019; JIA; ZHANG, 2021), and the main social criterion of human thermal comfort and its relation to temperature in different geographic areas (ARAM et al., 2019; CHAN et al., 2017).

When assessing the outdoor thermal environment, it is crucial to consider microclimatic conditions of geographic location, the physiological factors such as metabolism rate, and the behavioral elements for an improved understanding of thermal comfort (CHAN et al., 2017). Since urban green spaces do not show identical thermal performances, research focused on different climates and conditions are necessary to control and improve urban microclimates and user comfort. Many methods have been used to evaluate thermal comfort, with the physiological equivalent temperature (PET) as one of the most appropriate indices of thermal comfort evaluation in urban microclimate (HÖPPE, 1999). PET serves as a foundational measure for evaluating the thermal environment, requiring adjustments based on individual factors like clothing and activity levels. Due to its thermophysiological basis, PET offers greater versatility and relevance compared to traditional thermal indices (MATZARAKIS et al, 1999; ALFANO et al., 2014; HIRASHIMA et al., 2016; LIN et al., 2019; DAVTALAB et al., 2020; LI; LIU, 2020; WIDIASTUTI et al., 2020).

The previously mentioned studies consistently demonstrated the benefits of green walls on both building thermal efficiency and outdoor thermal environment. Nevertheless, in subtropical regions, especially in developing countries, the influence of green façades on thermal comfort remains relatively constrained. The majority of the aforementioned studies primarily concentrated on examining building thermal characteristics, such as temperature reduction on the building façade and the ambient environment both indoors and outdoors surrounding green façades. This study aimed to evaluate the thermal efficiency of a low-cost green wall on reducing the wall temperatures and improving users' comfort on five affordable houses located in subtropical Brazil. Over 1-year monitoring, highlighting the summer performance, the thermal difference was assessed using a set of thermal sensors installed on five building walls protected by a green façade. In addition, field surveys were conducted to determine the impact of the plant layer on users' well-being.

2. METHODOLOGY

2.1. Experiment and green façade characteristics

The study assessed six affordable houses in a residential unit under the federal program "Minha Casa, Minha Vida" in the city of Santa Maria, southern Brazil (latitude 29º42'36'' S, longitude 53º45'36'' W, 151 m.a.s.l.). The city is classified as Humid Subtropical (Cfa) (WORLD METEOROLOGICAL ORGANIZATION, 2006) climate and has a long, hot and humid summer, with daily air temperature reaching up to 40 ºC, and mild to cool winter, when the temperature drops down to negative values over the night. The annual average temperature is 19.3 ºC, and the city also encounters some of the most intense levels of sunlight in Brazil, with an annual average of 237.8 hours of sunlight during the summer and a total of 2203.9 hours throughout the year (INMET, 2018).

To determine the influence of the green façade on the thermal performance, a comparison was carried out between five house units (C48, C96, C292, C332 and C404), each one shaded by a plant layer, and one house unit defined as the control unit, without a green façade (C40). All the houses are single-story, attached, have openings in all rooms, and have the analyzed façade west-oriented (Figure 1). It is important to notice that none of the analyzed units have air conditioning.

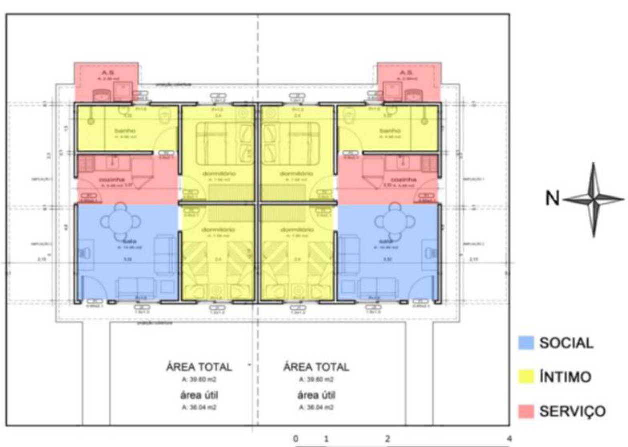

Figure 1: House plan typology.
Source: The authors.

Furthermore, one of the selection criteria was that the units should have an unobstructed façade, free from elements such as pergolas, coverings, or large vegetation in the front. Regarding the envelope materials, the façade materials are consistent across all units; however, the color of the exterior paint may vary, as residents are allowed to modify it.

The creeper Wisteria floribunda was chosen as an appropriate plant species for the location due to its performance in Southern Brazil, considering the potential for energy savings and the correlation between climatic seasons and the leaf density (SCHERER et al., 2018; FENSTERSEIFER et al., 2022; GABRIEL et al., 2023) (Figure 2).

Figure 2: Position of green façade. a) and b) House units. c) side view of plant layer. d) west view of plant layer.
Source: The authors.

2.2. Sensors and logging

Air temperature (Tar - ºC), superficial temperature (Tsup ºC) and relative humidity (RH), were measured on both sides of the walls, internally and externally. Due to the required number of sensors, based on the number of study objects (12 temperature and humidity dataloggers), it was not possible to use the same sensor model for all study objects. Therefore, the devices used in the research were: Onset HOBO Data Loggers UX100-023, Onset HOBO Temperature Relative Humidity Data Logger H08-003-02, Onset HOBO Relative Humidity/Temperature/Light/External Data Logger H08-004-02, MISOL WS-DS102 Data Logger for air temperature and relative humidity, a spot thermal camera (FLIR TG165), and an infrared digital thermometer with laser sighting for superficial temperature (LASERGRIP GM400) (Table 1).

All sensors were set up to collect air temperature and humidity data every 15 minutes, from May 2020 to March 2021. Two sensors were installed in each house unit.

Sensors	Measurements range	Accuracy	Software
Onset HOBO Data Loggers UX100-023	-20°C and 70°C	± 0,21°C de 0°C a 50°C	HOBOware
Onset HOBO Temperature Relative Humidity Data Logger H08-003-02	-20°C and 70°C	± 1,5°C de 0°C a 40°C	BoxCar
Onset HOBO Relative Humidity/Temperature/Light/External Data Logger H08-004-02	-20°C and 70°C	± 1,5°C de 0°C a 40°C	BoxCar
MISOL WS-DS102 Data Logger	-40°C a 60°C	± 1,0°C de 0°C a 50°C	DataLogger 3.3

Table 1: Sensor's characteristics.
Source: The Authors.

2.3. Selecting time periods for analysis

Although the measurements took place over a period of almost a year (from May 2020 to March 2021), the data analysis focused mainly on the warm period to align with the research objectives. The thermographic monitoring and interviews took place on 6 days, during the summer (Table 2). The surface temperatures (internal and external) were measured in person with an infrared digital thermometer with laser sighting for superficial temperature (LASERGRIP GM400) on nine days (Table 2). The recording of surface temperatures was carried out at eight designated points around the shaded opening (Figure 3a). The number of points was chosen to ensure a homogeneous representation of surface temperature behavior.

From the monitoring period, the six days from Table 2 were analyzed regarding the Physiologically Equivalent Temperature – PET. For the thermal difference analysis, one typical day from each season was chosen (January 18th for autumn, September 7th for winter, October 8th for spring and January 6th for summer). As for the thermographic images, three typical summer days were chosen to represent each case unit, compared to the control unit (January 26th, February 24th and February 28th). The days were not the same for all the analysis due to limitations in the availability of users' to respond to the survey and experimental data and equipment.

2.4. Thermal analysis

The five green façades were assessed by means of a field survey linked to a thermal comfort analysis, and thermal differences between air and surfaces temperatures.

Interview dates for PET analysis	Surface temperature measure-ment dates for thermal difference analysis	Thermographic dates
January 18, 2021	June 18, 2020 (autumn)	December 22, 2020
January 25, 2021	July 25, 2020 (winter)	January 06, 2021
February 07, 2021	August 15, 2020 (winter)	January 12, 2021
February 14, 2021	September 07, 2020 (winter)	January 18, 2021
February 24, 2021	October 10, 2020 (spring)	January 25, 2021
February 28, 2021	November 21, 2020 (spring)	February 07, 2021
	January 06, 2021 (summer)	February 14, 2021
	January 25, 2021 (summer)	February 24, 2021
	February 07, 2021 (summer)	February 28, 2021

Table 2: Monitoring periods.
Source: The Authors.

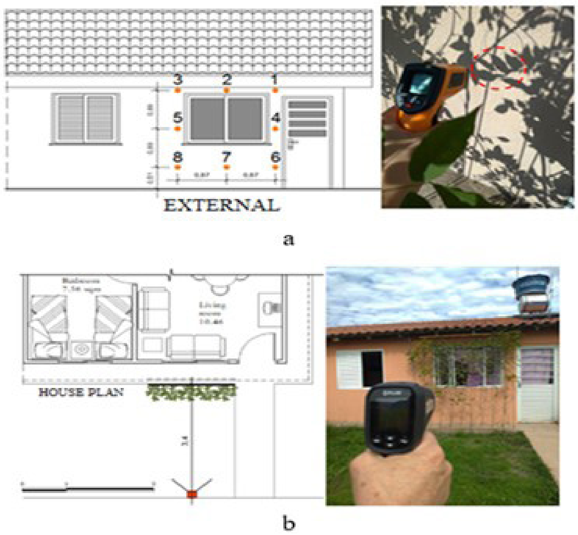

Figure 3: Diagram of monitoring sensors. a) west view, and b) house plan.
Source: The authors.

2.4.1. Field survey and thermal comfort

The PET index relies on the Munich Energy-Balance Model for Individuals, a thermophysiological model of heat balance. It evaluates human thermal comfort in Celsius (°C) based on air temperature, mean radiant temperature, wind speed, vapor pressure, and personal human factors like metabolic rate. PET considers a light metabolic activity of 80W, clothing insulation of 0.9 clo, and a reference indoor climate with average radiant temperature equal to the air temperature (MAYER; HÖPPE, 1987; MATZARAKIS; AMELUNG, 2008). Since this method is mainly applicable in northern cold countries (CHEN; MATZARAKIS, 2018; CANAN et al., 2019), the PET was adapted to suit the local climate, with thermal comfort varying from 31-35 ºC, respectively (FONG et al., 2019; LIU et al., 2018).

In order to assess the PET index, survey was administered during surface temperature measurement and thermographic recording, specifically during the most critical heat period. It included a section for recording the time, environmental variables (temperature, humidity, and air velocity), and questions regarding general information about the respondents (gender, age, weight); information about physical and physiological factors (clothing, activity level); information about psychological factors (thermal sensation and preference); information about residents' perception of thermal comfort in the house unit; and information about daily habits and the most commonly used alternatives to mitigate the sensation of heat. The questions served as an input to Rayman v1.2 software to perform the PET index calculations (MATZARAKIS et al., 2007).

2.4.2. Thermal difference

The thermal difference (Eq. 1) illustrates the extent of temperature variation in the wall during a time of the day in relation to the ambient temperature (KAWASHIMA et al., 2000; FENSTERSEIFER et al., 2022).

$$Td = Tsup - At \qquad (1)$$

where, Td is the thermal difference (ºC), Tsup is the surface temperature (whether internal or external) (ºC) and At is the air temperature (internal or external). If the resulting value of Td is positive, it indicates that the temperature of the wall surface is higher than that of the surrounding air. In such cases, the wall surface emits heat to either the indoor or outdoor environment.

3. RESULTS

3.1. Climate conditions during the monitoring

The average, maximum, and minimum air temperatures (Te), along with the average and maximum solar radiation (Rad), were recorded at both the experiment site and gathered from the INMET (2021) weather station across different seasons during the monitoring period (Table 3).

Higher average temperature values were observed from October 2020, springtime, until February 2021, summertime in the different housing units (Figure 4). The lower temperatures happened in July 2020, during the winter. The higher temperature difference between the control unit (C40) and a unit with the green façade (C292) happened on February 2021, and it was equal to 6.7 ºC.

3.2. Comfort index and thermographic monitoring

For simplicity, this analysis focused on the hot period of the year, since it represents the most critical effect that a green façade can have on users (Table 4).

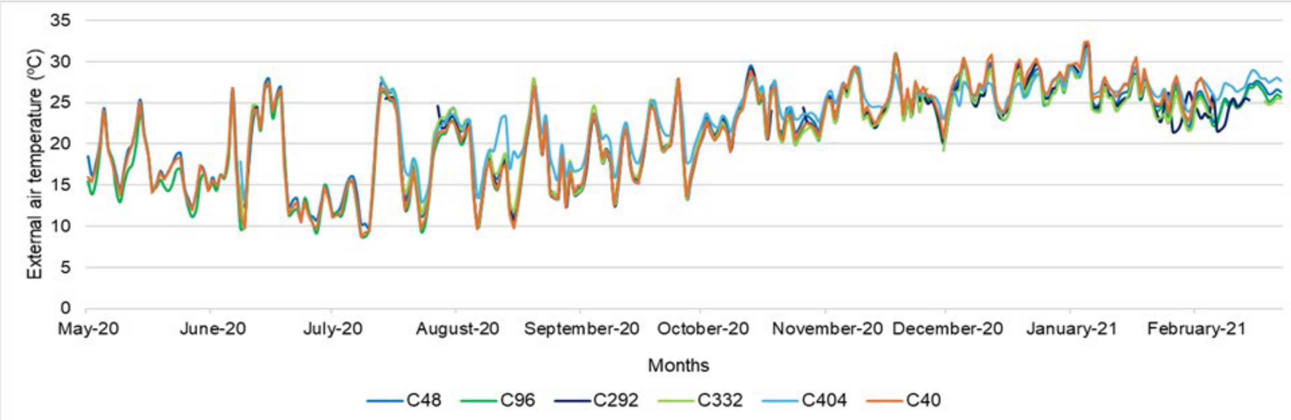

Figure 4: Daily temperatures obtained at the experiment site from May 2020 to February 2021.
Source: The authors.

Climatic variable	Autumn	Winter	Spring	Summer
Ta_average (ºC) (INMET)	15.4	14.9	23.2	23.8
Ta_min (ºC) (INMET)	2.1	-1.6	7.3	11.6
Ta_max (ºC) (INMET)	30	31.2	38.5	38
It_average (W/m²) (INMET)	115.3	128.3	521.3	267.0
It_max (W/m²) (INMET)	833.1	913.7	1100.6	1087.5
RH_average (%) (INMET)	79.8	78.6	61.3	76.4
RH_average (%) (site)	58.8	56.1	50.6	52.4
Ta_average (ºC) (site)	18.4	18.0	24.1	26.2
Ta_min (ºC) (min)	2.9	-0.7	9.2	10.6
Ta_max (ºC) (site)	41.1	49.6	37.7	48.0

Table 3: Climatic data recorded between May 01, 2020, and March 01, 2021.
Source: The Authors.

The highest air temperatures (ranging from 32.9 to 36.2 ºC) were achieved on January 25, suggesting that on this day, higher physiologically equivalent temperatures were observed for each case unit. The highest PET difference (6.5 ºC) occurred on February 24, between C40 and C332, which can be explained due to the air temperature difference, 36 ºC and 30 ºC, respectively. On this day, the clothing and metabolism parameters were quite similar for both case unit surveys, indicating that the PET difference was an effect of the plant layer. Regarding the thermal comfort temperatures, C49 presented a “slightly warm” thermal sensation, according to a classification from Fong et al. (2019) and Abaas and Khalid (2023) for subtropical climates.

Several studies confirmed the positive and direct relationship between the air temperature and physiological comfort level; however, as seen in Table 4, by adopting sustainable solutions a huge temperature decrease is observed. Comparing the six case units, it is clear the influence of the plant layer on the PET, as the highest physiological comfort levels, i.e., lowest PETs, occurred for the vegetated cases. A study by Abaas and Khalid (2023) showed similar results, comparing six selected sites, the prototype with high- albedo materials and dense, selective local trees helped to minimize PET outcomes and improve the local thermal environment.

Day	C40	C48	C96	C292	C332	C404
January 18, 2021	-	27.7	27.6	27.7	-	29.5
January 25, 2021	34.9	33.5	31.3	32.2	30.9	33.0
February 07, 2021	33.7	27.4	28.6	29.1	28.3	31.2
February 14, 2021	-	27.2	27.7	-	30.0	32.3
February 24, 2021	34.0	28.8	30.4	28.3	27.5	30.4
February 28, 2021	31.5	28.8	30.5	30.5	29.9	-

Table 4: Physiologically Equivalent Temperature (ºC).
Source: The Authors.

The external thermographic survey proved to be a qualitative evaluation tool that assisted in validating the results obtained through measurements of external surface temperatures, which occurred on the same days and times. It allowed the analysis of the thermal behavior of the case units' envelopes during the period from December 22nd, 2020, to February 28th, 2021. Since this methodological step relied on the presence of users for access to the case unit, some days during the measurement period were not fully completed by the thermographic photo, real photo of the façade, and surface thermal measurements. Therefore, the analysis included the comparison between objects considering the common days among them. The analysis was carried out by means of a thermogram, utilizing a range of color palettes that represent the thermal response of the surfaces (Figure 5).

Regarding the control unit C40, it is noted that the middle to lower portion of the envelope is more affected by the heat – especially between the openings, as it is fully exposed, unlike the upper portion which receives shading from the building's eaves. Contrariwise, the units with green façades showed that the points of highest temperatures, indicated by thermal contrast in red color, were found at the opening (to the right in the images), in a portion of the roof (above), and at specific points in the lower portion of the plant layer, close to the ground, the basal region of the species, with fewer leaves. The highest average surface temperatures occurred in the control unit C40, as expected (Figure 5). The differences in the average surface temperatures were higher between C40 and C332, reaching up to 12.6 ºC, similar results were found by Fensterseifer et al. (2022), around 13 ºC of difference between the bare and the green façade external surfaces in March 2019. While the lowest difference occurred between C40 and C48 (3.2 ºC). The unit C48 showed the second highest average surface temperature, reaching up to 39.6 ºC in the lower exposure portion of the façade.

In general, the highest average surface temperatures occurred on January 25th, the same day the showed the highest PET values, except for units C48, C96 and C292. However, as mentioned before, the high average surface temperature of unit C48 was influenced by the lower portion of the façade which was not covered by the plant layer. In the case unit C96, the average surface temperatures were quite similar in the three summer days (35.2 ºC, 34.6 ºC and 36.6 ºC). Although the green façade showed satisfactory growth in C292, on some days during the analyzed period, there are noticeable areas with deficiencies, represented by red patches in the middle to upper part of the plant layer. Nevertheless, the green façade proved to be an effective thermal barrier in the building's envelope, confirmed by external surface temperatures up to 11.1°C lower than the control unit C40 - on January 25th.

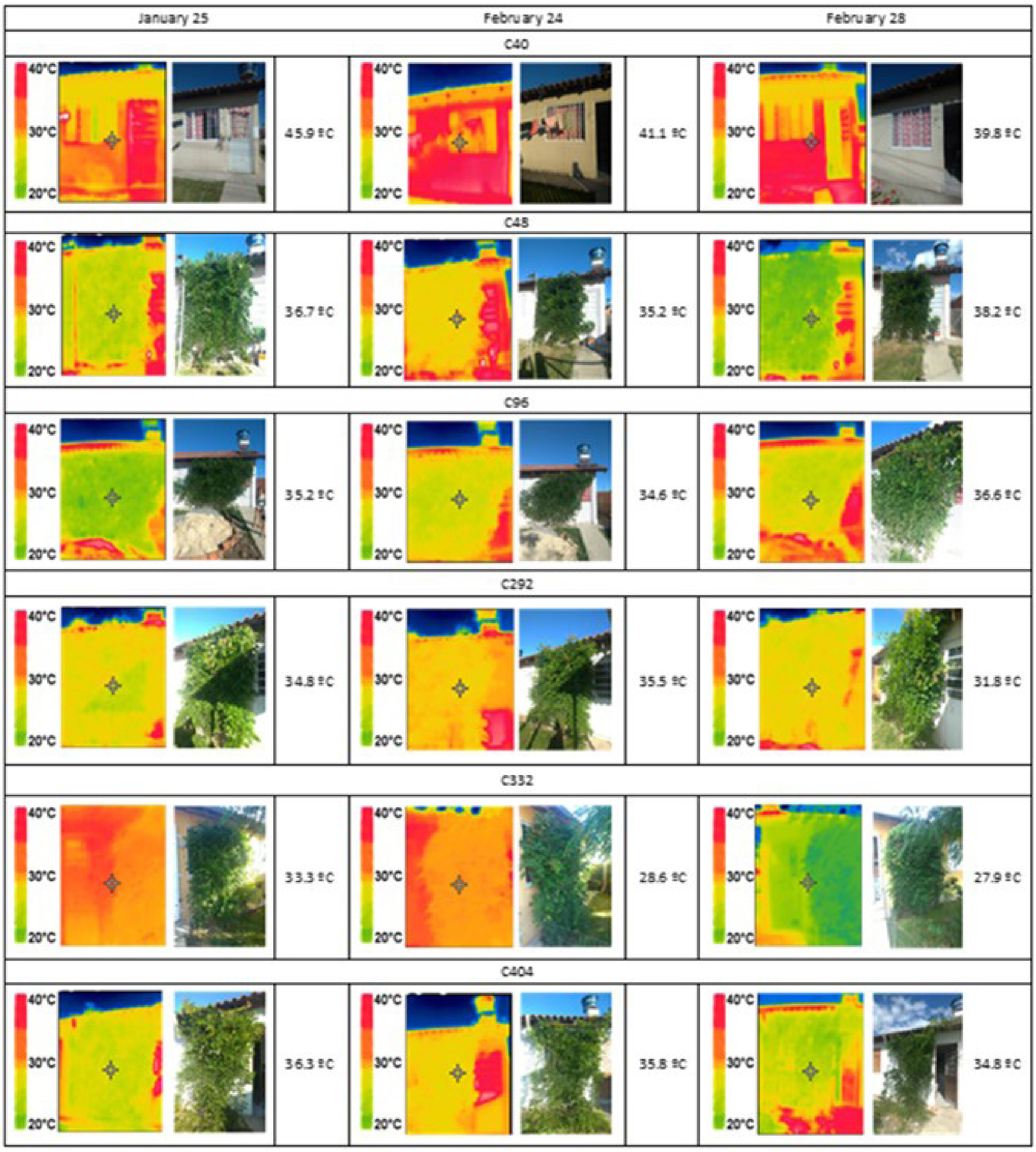

Figure 5: Daily temperatures obtained at the experiment site from May 2020 to February 2021.
Source: The authors.

The analysis of the thermal index was made by comparing the control unit (C4) with the other five green façade units (C48, C96, C292, C332, C404). Positive values indicate that the surface temperature was higher than the air temperature (Figure 6). Overall, the internal thermal difference was negative for all cases, except for the control unit (C40). This shows that the internal air temperature was higher than the internal surface temperature of the wall in the vegetated cases, suggesting that the green façades from the five units were releasing less heat to the indoor environment than the bare wall in C40.

The external thermal differences varied for each case, since the external air temperatures fluctuated more during the day, but it was always greater for the control unit, reaching up to +2.6 ºC. For example, C96 and C332 showed opposite behavior for external thermal differences during spring, +3.1 ºC and -3.4 ºC, respectively. This can be explained by the fact that C332 had a surface temperature 2 ºC higher than C96. This analysis shows that one limitation of this work was the impossibility of gathering hourly data of surface temperatures, in order to analyze thermal differences throughout each day.

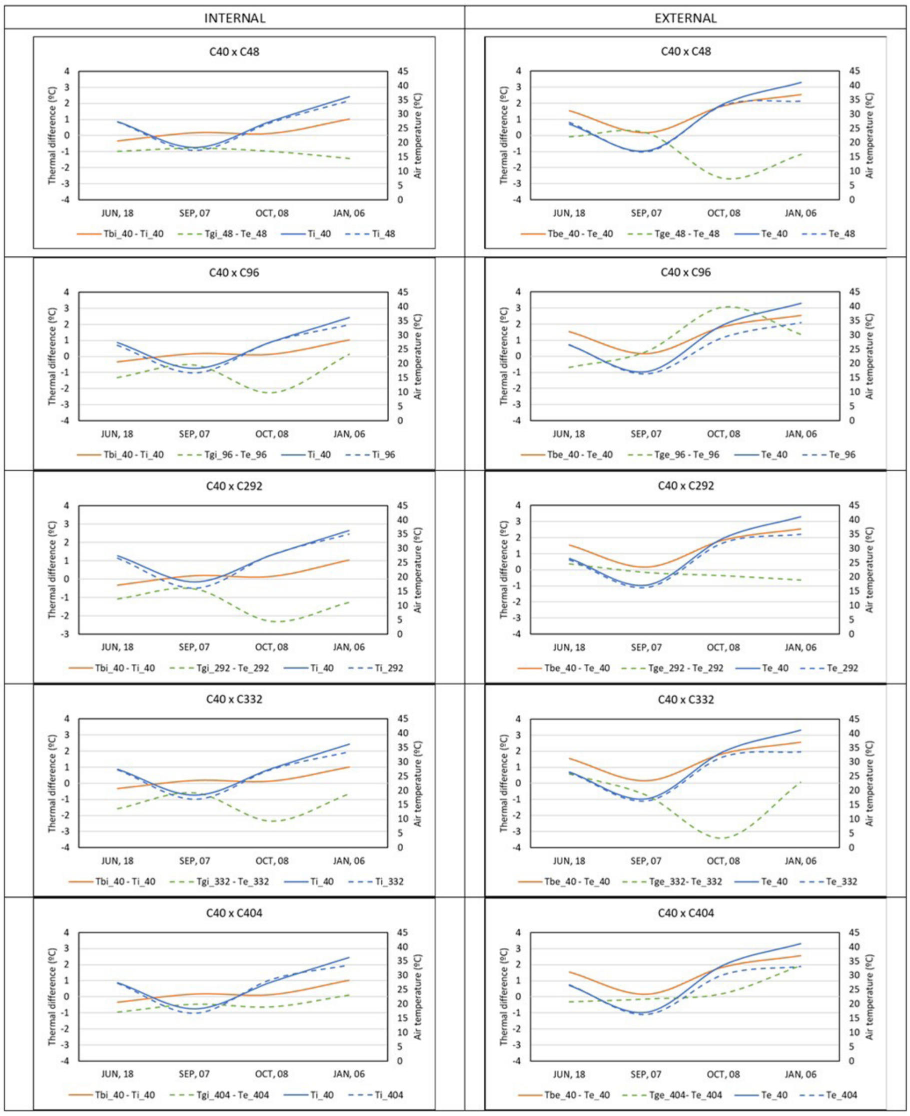

Figure 6: Thermal difference between C40 and each vegetated unit .
Source: The authors.

The control unit's external surface temperature showed greater magnitude of positive thermal differences (+2.6 ºC) than the vegetated units (+1.9 ºC for C404) during the summer, which means that the control unit's bare wall released more heat to the indoor environment than the green façade wall (Table 5). Similar results were found by Fensterseifer et al. (2022), +4.8 ºC for the bare wall and +3.3 ºC for a vegetated wall during a typical summer day in the subtropical climate. Regarding the internal thermal differences during the summer, the control unit showed positive values (+1.0 ºC), while the best performance was from C48 (-1.3 ºC). This demonstrates the collaborative impact of shading alongside the evaporative cooling process enabled by the green façade on a summer day (HOELSCHER et al., 2016).

During the winter, the thermal differences between the control unit and the vegetated units were similar, reaching absolute maximum differences of 1.0 ºC, between C40 (-0.2 ºC) and C48 (-0.8 ºC). During this season, all vegetated units presented negative internal thermal differences, i.e., air temperature higher than surface temperatures. It was expected that due to the leaf shedding, the green façade would allow more heat in the environment, however, the negative thermal difference could indicate that the trellis and branches acted as shading decreasing surface temperature, as stated by Fensterseifer et al. (2022). The amplitude between air temperature and surface temperature was less significant for the external conditions for all units during the winter. Lastly, during Autumn and Spring the units presented quite similar behavior, with the highest negative internal thermal differences for C96, C292 and C332.

	Jun, 18		Sep, 07		Oct, 08		Jan, 06	
Case Unit	Internal	External	Internal	External	Internal	External	Internal	External
C40	-0.3	+1.5	+0.2	+0.2	+0.1	+1.9	+1.0	+2.6
C48	-1.0	-0.1	-0.8	+0.1	-1.0	-2.7	-1.4	-1.2
C96	-1.3	-0.7	-0.5	+0.3	-2.3	+0.9	+0.1	+1.4
C292	-1.1	+0.4	-0.5	-0.2	-2.3	-0.4	-1.3	-0.6
C332	-1.6	+0.6	-0.6	-0.7	-2.4	-3.4	-0.7	+0.1
C404	-0.9	-0.3	-0.5	-0.1	-0.6	+0.2	+0.1	+1.9

Table 5: Internal and external seasonal thermal difference.
Source: The Authors.

This thermal analysis confirms the year-round thermal insulation effect facilitated by the green façade, aligning with various studies (DAHANAYAKE; CHOW, 2017; FENSTERSEIFER et al., 2022; GABRIEL et al., 2023). The shading provided by the green façade, along with the air gap between the building wall and the vertical structure, acted as a thermal buffer. This buffer prevented indoor heat loss to the outdoor environment while simultaneously cooling the wall during warm and hot periods, as documented in several studies (SUSOROVA et al., 2013; TAN et al., 2014; BIANCO et al., 2016; LEE; JIM, 2017). This capability arises from the structure's ability to minimize air movement across the surface, thus altering convection and radiation coefficients.

4. CONCLUSIONS

This study provided a comprehensive assessment of the impact of green façades on surface temperatures and user comfort in five affordable case units in subtropical Brazil. Through a year-long monitoring, including internal and external air temperature measurements, relative humidity assessments, and user surveys, the thermal benefits of five green façades were elucidated. The results consistently demonstrated that green façades reduce surface temperatures compared to the control unit, especially during summer months, effectively mitigating heat transfer into indoor environments.

The plant layer acted as a thermal buffer, providing shading and promoting evaporative cooling, which significantly enhanced users' thermal comfort as indicated by reduced Physiologically Equivalent Temperatures (PET). Notably, the green façade had a greater impact on external thermal differences. During the summer, green façades maintained lower internal thermal differences, highlighting their role in cooling the indoor spaces. In contrast, during the winter, the trellis and branches of the deciduous Wisteria floribunda contributed to shading, though to a lesser extent due to leaf shedding.

Thermographic images from three summer days illustrated substantial temperature differences between the green and bare façades, with the highest average surface temperatures occurring in the control unit, i.e. without vegetation, and differences reaching up to 12.6 ºC, reinforcing the PET results.

Despite the study's limitations, such as the use of different measuring devices, user modifications to the study units, and data collection restricted to specific times of the da, the findings robustly support the integration of green façades in affordable housing. This integration is a viable strategy for enhancing thermal comfort and energy efficiency without adding extra cost or maintenance. By reducing surface temperatures and providing a thermal buffer, green façades can significantly improve living conditions in subtropical climates.

REFERENCES

ABAAS, Zaynab Radi; KHALID, Zainab. Towards local sustainability: a case study to evaluate outdoor urban spaces in baghdad using physiological equivalent temperature index. **City And Environment Interactions**, [S.L.], v. 20, p. 100115, dez. 2023. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.cacint.2023.100115>.

ALFANO, Francesca Romana D'ambrosio; OLESEN, Bjarne W.; PALELLA, Boris Igor; RICCIO, Giuseppe. Thermal comfort: design and assessment for energy saving. **Energy And Buildings**, [S.L.], v. 81, p. 326-336, out. 2014. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.enbuild.2014.06.033>.

ARAM, Farshid; SOLGI, Ebrahim; HOLDEN, Gordon. The role of green spaces in increasing social interactions in neighborhoods with periodic markets. **Habitat International**, [S.L.], v. 84, p. 24-32, fev. 2019. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.habitatint.2018.12.004>.

ASHRAE, Thermal environmental conditions for human occupancy, in: ANSI/ASHRAE Standard 55, American Society of Heating, **Refrigerating and Air Conditioning Engineers**, Atlanta, 2013.

BESIR, Ahmet B.; CUCE, Erdem. Green roofs and facades: a comprehensive review. **Renewable And Sustainable Energy Reviews**, [S.L.], v. 82, p. 915-939, fev. 2018. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.rser.2017.09.106>.

BIANCO, Lorenza; SERRA, Valentina; LARCHER, Federica; PERINO, Marco. Thermal behaviour assessment of a novel vertical greenery module system: first results of a long-term monitoring campaign in an outdoor test cell. **Energy Efficiency**, [S.L.], v. 10, n. 3, p. 625-638, 8 set. 2016. Springer Science and Business Media LLC. Available at: <http://dx.doi.org/10.1007/s12053-016-9473-4>.

BODACH, Susanne; HAMHABER, J.. Energy efficiency in social housing: opportunities and barriers from a case study in Brazil. **Energy Policy**, [S.L.], v. 38, n. 12, p. 7898-7910, dez. 2010. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.enpol.2010.09.009>.

CANAN, Fatih; GOLASI, Iacopo; CIANCIO, Virgilio; COPPI, Massimo; SALATA, Ferdinando. Outdoor thermal comfort conditions during summer in a cold semi-arid climate. A transversal field survey in Central Anatolia (Turkey). **Building And Environment**, [S.L.], v. 148, p. 212-224, jan. 2019. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2018.11.008>.

CARSON, T B; MARASCO, De; CULLIGAN, P J; MCGILLIS, W R. Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems. **Environmental Research Letters**, [S.L.], v. 8, n. 2, p. 024036, 1 jun. 2013. IOP Publishing. Available at: <http://dx.doi.org/10.1088/1748-9326/8/2/024036>.

CARTER, Jeremy G.; CAVAN, Gina; CONNELLY, Angela; GUY, Simon; HANDLEY, John; KAZMIERCZAK, Aleksandra. Climate change and the city: building capacity for urban adaptation. **Progress In Planning**, [S.L.], v. 95, p. 1-66, jan. 2015. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.progress.2013.08.001>.

CHAN, S.y.; CHAU, C.K.; LEUNG, T.M. On the study of thermal comfort and perceptions of environmental features in urban parks: a structural equation modeling approach. **Building And Environment**, [S.L.], v. 122, p. 171-183, set. 2017. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2017.06.014>.

CHEN, Yung-Chang; MATZARAKIS, Andreas. Modified physiologically equivalent temperature—basics and applications for western European climate. **Theoretical And Applied Climatology**, [S.L.], v. 132, n. 3-4, p. 1275-1289, 27 maio 2017. Springer Science and Business Media LLC. Available at: <http://dx.doi.org/10.1007/s00704-017-2158-x>.

CONVERTINO, Fabiana; VOX, Giuliano; SCHETTINI, Evelia. Convective heat transfer in green façade system. **Biosystems Engineering**, [S.L.], v. 188, p. 67-81, dez. 2019. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.biosystemseng.2019.10.006>.

DAHANAYAKE, Kalani C.; CHOW, Cheuk Lun. Comparing reduction of building cooling load through green roofs and green walls by EnergyPlus simulations. **Building Simulation**, [S.L.], v. 11, n. 3, p. 421-434, 20 out. 2017. Springer Science and Business Media LLC. Available at: <http://dx.doi.org/10.1007/s12273-017-0415-7>.

DAVTALAB, Jamshid; DEYHIMI, Shahram Poor; DESSI, Valentina; HAFEZI, Mohammad Reza; ADIB, Morteza. The impact of green space structure on physiological equivalent temperature index in open space. **Urban Climate**, [S.L.], v. 31, p. 100574, mar. 2020. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.uclim.2019.100574>.

FENSTERSEIFER, Paula; GABRIEL, Elaise; TASSI, Rutineia; PICCILLI, Daniel Gustavo Allasia; MINETTO, Bruna. A year-assessment of the suitability of a green façade to improve thermal performance of an affordable housing. **Ecological Engineering**, [S.L.], v. 185, p. 106810, dez. 2022. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.ecoleng.2022.106810>.

FONG, Chng Saun; AGHAMOHAMMADI, Nasrin; RAMAKRESHNAN, Logaraj; SULAIMAN, Nik Meriam; MOHAMMADI, Parviz. Holistic recommendations for future outdoor thermal comfort assessment in tropical Southeast Asia: a critical appraisal. **Sustainable Cities And Society**, [S.L.], v. 46, p. 101428, abr. 2019. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.scs.2019.101428>.

FTD (Financial Times Deutschland), 2010. Mein Haus, mein Leben, mein Praesident. 4.8. p. 13.

GABRIEL, Elaise; PICCILLI, Daniel Gustavo Allasia; TASSI, Rutineia; KÖHLER, Manfred; KREBS, Lisandra Fachinello. Improving indoor environmental quality in an affordable house by using a vegetated wall: a case study in subtropical Brazil. **Building And Environment**, [S.L.], v. 250, p. 111146, fev. 2024. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2023.111146>.

GHAZALLI, Aini Jasmin; BRACK, Cris; BAI, Xuemei; SAID, Ismail. Physical and Non-Physical Benefits of Vertical Greenery Systems: a review. **Journal Of Urban Technology**, [S.L.], v. 26, n. 4, p. 53-78, 26 jul. 2019. Informa UK Limited. Available at: <http://dx.doi.org/10.1080/10630732.2019.1637694>.

HIRASHIMA, Simone Queiroz da Silveira; ASSIS, Eleonora Sad de; NIKOLOPOULOU, Marialena. Daytime thermal comfort in urban spaces: a field study in Brazil. **Building And Environment**, [S.L.], v. 107, p. 245-253, out. 2016. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2016.08.006>.

HOELSCHER, Marie-Therese; NEHLS, Thomas; JÄNICKE, Britta; WESSOLEK, Gerd. Quantifying cooling effects of facade greening: shading, transpiration and insulation. **Energy And Buildings**, [S.L.], v. 114, p. 283-290, fev. 2016. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.enbuild.2015.06.047>.

HÖPPE, P. The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. **International Journal Of Biometeorology**, [S.L.], v. 43, n. 2, p. 71-75, 25 out. 1999. Springer Science and Business Media LLC. Available at: <http://dx.doi.org/10.1007/s004840050118>.

INMET. Gráficos Anuais de Estações Automáticas. **Instituto Nacional de Meteorologia**, Brasília, 2021. In Portuguese. Available at: <https://tempo.inmet.gov.br/Graficos/A001>.

INMET. Normais Climatológicas do Brasil 1981–2010. Instituto Nacional de Meteorologia, Brasília, 2018. In Portuguese.

JIA, Jia; ZHANG, Xiaoqing. A human-scale investigation into economic benefits of urban green and blue infrastructure based on big data and machine learning: a case study of Wuhan. **Journal Of Cleaner Production**, [S.L.], v. 316, p. 128321, set. 2021. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.jclepro.2021.128321>.

KARAKAS, Filiz; GRASSIE, Duncan; SCHWARTZ, Yair; DONG, Jie; BAGKERIS, Emmanouil; MUMOVIC, Dejan; MILNER, James; CHALABI, Zaid; MAVROGIANNI, Anna. A Multi-Criteria decision analysis framework to determine the optimal combination of energy efficiency and indoor air quality schemes for English school classrooms. **Energy And Buildings**, [S.L.], v. 295, p. 113293, set. 2023. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.enbuild.2023.113293>.

KAWASHIMA, Shigeto, ISHIDA, Tomoyuki, MINOMURA, Mitsuo, MIWA, Tetsuhisa. Relations between Surface Temperature and Air Temperature on a Local Scale during Winter Nights. **Journal Of Applied Meteorology**, 39, 9, 1570-1579, set. 2000. Available at: <http://dx.doi.org/10.1175/1520-0450(2000)0392.0.co;2>.

KUMAR, T.s. Sigi; SHAFI, K.A.; THOMAS, Rijo Jacob; MOHAMMED, Jesna. Experimental evaluation of the thermal performance of coir mat and green facade as wall insulation in a tropical climate. **Thermal Science And Engineering Progress**, [S.L.], v. 40, p. 101757, maio 2023. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.tsep.2023.101757>.

LAM, Cho Kwong Charlie; GALLANT, Ailie J.e.; TAPPER, Nigel J. Does irrigation cooling effect intensify during heatwaves? A case study in the Melbourne botanic gardens. **Urban Forestry & Urban Greening**, [S.L.], v. 55, p. 126815, nov. 2020. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.ufug.2020.126815>.

LARSEN, Silvana Flores; FILIPPÍN, Celina; LESINO, Graciela. Modeling double skin green façades with traditional thermal simulation software. **Solar Energy**, [S.L.], v. 121, p. 56-67, nov. 2015. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.solener.2015.08.033>.

LEE, Louis S.H.; JIM, C.y.. Thermal-cooling performance of subtropical green roof with deep substrate and woodland vegetation. **Ecological Engineering**, [S.L.], v. 119, p. 8-18, ago. 2018. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.ecoleng.2018.05.014>.

LI, Jianwei; LIU, Naiyuan. The perception, optimization strategies and prospects of outdoor thermal comfort in China: a review. **Building And Environment**, [S.L.], v. 170, p. 106614, mar. 2020. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2019.106614>.

LIN, Hankun; XIAO, Yiqiang; MUSSO, Florian; LU, Yao. Green Façade Effects on Thermal Environment in Transitional Space: field measurement studies and computational fluid dynamics simulations. **Sustainability**, [S.L.], v. 11, n. 20, p. 5691, 15 out. 2019. MDPI AG. Available at: <http://dx.doi.org/10.3390/su11205691>.

LIU, Zhixin; ZHENG, Senlin; ZHAO, Lihua. Evaluation of the ENVI-Met Vegetation Model of Four Common Tree Species in a Subtropical Hot-Humid Area. **Atmosphere**, [S.L.], v. 9, n. 5, p. 198, 21 maio 2018. MDPI AG. Available at: <http://dx.doi.org/10.3390/atmos9050198>.

MATZARAKIS, Andreas; AMELUNG, Bas. Physiological Equivalent Temperature as Indicator for Impacts of Climate Change on Thermal Comfort of Humans. Seasonal Forecasts, **Climatic Change And Human Health**, [S.L.], p. 161-172, 2008. Springer Netherlands. Available at: <http://dx.doi.org/10.1007/978-1-4020-6877-5_10>.

MATZARAKIS, Andreas; MAYER, H.; IZIOMON, M.G. Applications of a universal thermal index: physiological equivalent temperature. **International Journal Of Biometeorology**, [S.L.], v. 43, n. 2, p. 76-84, 25 out. 1999. Springer Science and Business Media LLC. Available at: <http://dx.doi.org/10.1007/s004840050119>.

MATZARAKIS, Andreas; RUTZ, Frank; MAYER, Helmut. Modelling radiation fluxes in simple and complex environments—application of the RayMan model. **International Journal Of Biometeorology**, [S.L.], v. 51, n. 4, p. 323-334, 9 nov. 2006. Springer Science and Business Media LLC. Available at: <http://dx.doi.org/10.1007/s00484-006-0061-8>.

MAYER, H.; HÖPPE, P. Thermal comfort of man in different urban environments. **Theoretical And Applied Climatology**, [S.L.], v. 38, n. 1, p. 43-49, 1987. Springer Science and Business Media LLC. Available at: <http://dx.doi.org/10.1007/bf00866252>.

MUMTAZ, Muhammad. Role of civil society organizations for promoting green and blue infrastructure to adapting climate change: evidence from Islamabad city, Pakistan. **Journal Of Cleaner Production**, [S.L.], v. 309, p. 127296, ago. 2021. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.jclepro.2021.127296>.

OH, Jeongyoon; WONG, Wingyin; CASTRO-LACOUTURE, Daniel; LEE, Jeehee; KOO, Choongwan. Indoor environmental quality improvement in green building: occupant perception and behavioral impact. **Journal Of Building Engineering**, [S.L.], v. 69, p. 106314, jun. 2023. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.jobe.2023.106314>.

RAHMAN, Md Sazan; MACPHERSON, Sarah; LEFSRUD, Mark. A study on evaporative cooling capacity of a novel green wall to control ventilating air temperature. **Journal Of Building Engineering**, [S.L.], v. 77, p. 107466, out. 2023. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.jobe.2023.107466>.

SCHERER, Minéia Johann; ALVES, Thales Severo; REDIN, Janaína. Envoltórias vegetadas aplicadas em edificações: benefícios e técnicas. **Revista de Arquitetura Imed**, [S.L.], v. 7, n. 1, p. 84, 11 out. 2018. Complexo de Ensino Superior Meridional S.A.. Available at: <http://dx.doi.org/10.18256/2318-1109.2018.v7i1.2693>.

SUN, Shibo; XU, Xiyan; LAO, Zhaoming; LIU, Wei; LI, Zhandong; GARCÍA, Ester Higueras; HE, Li; ZHU, Jianning. Evaluating the impact of urban green space and landscape design parameters on thermal comfort in hot summer by numerical simulation. **Building And Environment**, [S.L.], v. 123, p. 277-288, out. 2017. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2017.07.010>.

SUSOROVA, Irina; ANGULO, Melissa; BAHRAMI, Payam; STEPHENS, Brent. A model of vegetated exterior facades for evaluation of wall thermal performance. **Building And Environment**, [S.L.], v. 67, p. 1-13, set. 2013. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2013.04.027>.

TAN, Chun Liang; WONG, Nyuk Hien; JUSUF, Steve Kardinal. Effects of vertical greenery on mean radiant temperature in the tropical urban environment. **Landscape And Urban Planning**, [S.L.], v. 127, p. 52-64, jul. 2014. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.landurbplan.2014.04.005>.

TANASA, C.; DAN, D.; BECCHIO, C.; CORGNATI, S.P.; STOIAN, V. Cost-optimal and indoor environmental quality assessment for residential buildings towards EU long-term climate targets. **Energy For Sustainable Development**, [S.L.], v. 59, p. 49-61, dez. 2020. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.esd.2020.09.002>.

TEOTÓNIO, Inês; SILVA, Cristina Matos; CRUZ, Carlos Oliveira. Economics of green roofs and green walls: a literature review. **Sustainable Cities And Society**, [S.L.], v. 69, p. 102781, jun. 2021. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.scs.2021.102781>.

WIDIASTUTI, Ratih; ZAINI, Juliana; CAESARENDRA, Wahyu. Field measurement on the model of green facade systems and its effect to building indoor thermal comfort. **Measurement**, [S.L.], v. 166, p. 108212, dez. 2020. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.measurement.2020.108212>.

Woods-Ballard, P., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., Kellagher, R. 2015. The SUDS manual. London: Construction Industry Research and Information Association.

World Meteorological Organization Statement on the Status of the Global Climate in 2005. WMO - No. 998 (2006) ISBN: 978-92-63-10998-9.

XU, Xiyan; SUN, Shibo; LIU, Wei; GARCÍA, Ester Higueras; HE, Li; CAI, Qi; XU, Sijing; WANG, Jingjing; ZHU, Jianning. The cooling and energy saving effect of landscape design parameters of urban park in summer: a case of beijing, china. **Energy And Buildings**, [S.L.], v. 149, p. 91-100, ago. 2017. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.enbuild.2017.05.052>.

ZITARS, Jillian; SPADAFORE, Brittany; COULOMBE, Simon; RIEMER, Manuel; DREYER, Bianca C.; WHITNEY, Stephanie. Understanding the psycho-environmental potential functions of a green building to promote employee health, wellbeing and productivity: a theoretical perspective. **Building And Environment**, [S.L.], v. 205, p. 108268, nov. 2021. Elsevier BV. Available at: <http://dx.doi.org/10.1016/j.buildenv.2021.108268>.

VENHARI, Armaghan Ahmadi; TENPIERIK, Martin; HAKAK, Alireza Mahdizadeh. Heat mitigation by greening the cities, a review study. **Environment, Earth And Ecology**, [S.L.], v. 1, n. 1, p. 5-32, 28 fev. 2017. Mlodzi Naukowcy dr Jedrzej Nyckowiak. Available at: <http://dx.doi.org/10.24051/eee/67281>.

AUTHORS

ORCID: 0000-0002-1091-1735
RENATA SERAFIN DE ALBERNARD | Mestre em Tecnologias e Sustentabilidade do Ambiente Construído (UFSM) | Universidade Federal de Santa Maria (UFSM) | Programa de Pós-Graduação em Arquitetura, Urbanismo e Paisagismo | Santa Maria, RS - Brasil | Correspondência para: Cidade Universitária - Prédio 8 (INPE), sala 2061 - Camobi, Santa Maria - RS, 97105-900
e-mail: renata.albernard@gmail.com.

ORCID: 0000-0001-6242-4544
ELAISE GABRIEL | Doutora em Engenharia Civil (UFSM) | Universidade Federal de Santa Maria (UFSM) | Curso de Arquitetura e Urbanismo | Cachoeira do Sul, RS - Brasil | Correspondência para: Rodovia Taufik Germano, nº 3013, sala 23B, Bairro Universitário II, Cachoeira do Sul - RS, 96503-205.
e-mail: elaise.gabriel@ufsm.br

ORCID: 0000-0001-5060-3924
MINÉIA JOHANN SCHERER | Doutora em Arquitetura (UFRGS) | Universidade Federal de Santa Maria (UFSM) | Curso de Arquitetura e Urbanismo | Cachoeira do Sul, RS - Brasil | Correspondência para: Rodovia Taufik Germano, nº 3013, sala 22C, Bairro Universitário II, Cachoeira do Sul - RS, 96503-205.
e-mail: mineia.scherer@ufsm.br

HOW TO CITE THIS ARTICLE:

ALBERNARD, R. S.; GABRIEL E.; SCHERER, M. J. Enhancing termal efficiency and comfort with green façades in affordable housings in subtropical climate. **MIX Sustentável**, v.11, n.2, p.93-108. ISSN 2447-3073. Disponível em: <http://www.nexos.ufsc.br/index.php/mixsustentavel>. Acesso em: _/_/_.

SUBMITTED ON: 07/05/2025
ACCEPTED ON: 01/09/2025
PUBLISHED ON: 12/09/2025
RESPONSIBLE EDITORS: Lisiane Ilha Librelotto e Paulo Cesar Machado Ferroli

Record of authorship contribution:
CRediT Taxonomy (http://credit.niso.org/)

RSA: conceptualization, investigation, data curation, and visualization.

EG: formal analysis, methodology, visualization, writing – original draft, writing – review & editing.

MJS: supervision and project administration.

Conflict declaration: nothing to declare.