Mix Sustentável

Thermal performance of Green Roofs: Comparative evaluation of Construction Systems

Desempenho térmico de telhados verdes: avaliação comparativa de sistemas construtivos

Rendimiento térmico de techos verdes: evaluación comparativa de sistemas de construcción

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Abstract: This study evaluated the thermal performance of different Green Roof (GR) models compared to conventional ceramic roofs (CCR) in urban environments. Roof prototypes with different construction systems were used: Conventional Roof (CCR), Conventional Green Roof (CGR), Tray Green Roof (TGR), and Alveolar Green Roof (AGR). The prototypes underwent thermal tests to measure external and internal temperatures under varying climatic conditions. The results indicated that Green Roofs, especially the Alveolar model (AGR), demonstrated superior thermal performance compared to the conventional ceramic roof, with milder temperatures on hot days and more stable temperatures on cold days, providing greater indoor thermal comfort. The vegetation, such as Emerald Grass, contributed to cooling the environment and helped mitigate urban heat islands. The presence of drainage systems and water reservoirs in the AGR and TGR models also increased thermal efficiency, reducing the need for irrigation and improving stormwater management. The results highlight that Green Roofs are an effective and sustainable solution to improve thermal comfort in urban areas, while also contributing to reducing environmental impact and building more resilient cities. Future studies may explore the application of these systems in different climatic and urban contexts, as well as the economic and social impacts of this technology.
Keywords: Green roofs; Thermal performance; Urban heat island; Thermal comfort; Sustainable construction

Resumo: Este estudo avaliou o desempenho térmico de diferentes modelos de Telhados Verdes (TV) em comparação com telhados cerâmicos convencionais (TCC) em ambientes urbanos. Foram utilizados protótipos de coberturas com distintos sistemas construtivos: Telhado Convencional (TCC), Telhado Verde Convencional (TVC), Telhado Verde em Bandeja (TVB) e Telhado Verde Alveolar (TVA). Os protótipos foram submetidos a ensaios térmicos para a medição das temperaturas externas e internas sob diferentes condições climáticas. Os resultados indicaram que os Telhados Verdes, especialmente o modelo Alveolar (TVA), apresentaram desempenho térmico superior ao telhado cerâmico convencional, proporcionando temperaturas mais amenas em dias quentes e maior estabilidade térmica em dias frios, o que resulta em maior conforto térmico interno. A presença de vegetação, como a grama-esmeralda, contribuiu para o resfriamento do ambiente e auxiliou na mitigação das ilhas de calor urbano. Além disso, a presença de sistemas de drenagem e reservatórios de água nos modelos TVA e TVB aumentou a eficiência térmica, reduzindo a necessidade de irrigação e melhorando o manejo das águas pluviais. Os

Author Contributions according to the CrediT Taxonomy

IRCO: conceptualization, data curation, formal analysis, methodology, project administration, validation, visualization, writing – original draft, review & editing.
LTC: writing – original draft, review & editing.
BMT: methodology, project administration, resources, supervision, validation, writing – original draft.

resultados destacam que os Telhados Verdes constituem uma solução eficaz e sustentável para a melhoria do conforto térmico em áreas urbanas, além de contribuírem para a redução dos impactos ambientais e para a construção de cidades mais resilientes. Estudos futuros podem explorar a aplicação desses sistemas em diferentes contextos climáticos e urbanos, bem como os impactos econômicos e sociais dessa tecnologia.
Palavras-chave: Telhados verdes; Desempenho térmico; Conforto térmico; Ilhas de calor urbano; Construção sustentável

Resumen: Este estudio evaluó el desempeño térmico de diferentes modelos de Techos Verdes en comparación con un techo convencional de cerámica en entornos urbanos. Se utilizaron prototipos de cubiertas con distintos sistemas constructivos: techo convencional de cerámica, techo verde convencional, techo verde de bandeja (TVB) y techo verde alveolar (TVA). Los prototipos fueron sometidos a ensayos térmicos para medir las temperaturas externas e internas bajo diversas condiciones climáticas. Los resultados indicaron que los techos verdes, especialmente el modelo alveolar (TVA), presentaron un desempeño térmico superior en comparación con el techo convencional de cerámica, con temperaturas más suaves en días calurosos y mayor estabilidad térmica en días fríos, proporcionando un mejor confort térmico en el interior de las edificaciones. La vegetación utilizada, como el césped Esmeralda, contribuyó a la reducción de la temperatura superficial y a la mitigación del efecto de isla de calor urbana. Asimismo, la presencia de sistemas de drenaje y reservorios de agua en los modelos TVA y TVB incrementó la eficiencia térmica, reduciendo la necesidad de riego y favoreciendo el control de las aguas pluviales. En conjunto, los resultados evidencian que los techos verdes constituyen una solución eficaz y sostenible para mejorar el confort térmico en áreas urbanas, además de contribuir a la reducción del impacto ambiental y al fortalecimiento de la resiliencia urbana. Estudios futuros pueden explorar la aplicación de estos sistemas en diferentes contextos climáticos y urbanos, así como sus implicaciones económicas y sociales.
Palabras clave: Cubiertas verdes; Desempeño térmico; Confort térmico; Islas de calor urbanas; Arquitectura sostenible

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1 INTRODUCTION

The urban landscape, characterized by high building density and extensive use of impervious materials such as concrete and asphalt, directly influences both environmental conditions and human well-being. In this context, the incorporation of green areas into urban environments has been increasingly recognized as a relevant strategy to improve environmental quality and promote closer interaction with natural elements, contributing to thermal regulation and urban livability.

Green roofs have emerged as an effective solution to promote a more integrated relationship between buildings and the urban environment while addressing several challenges associated with contemporary cities. By installing a layer of substrate and vegetation on rooftops—often underutilized surfaces—green roofs provide multiple environmental benefits. These include the reduction of urban temperatures, improvement of air quality, mitigation of surface runoff and urban flooding, reuse of rainwater, and the potential for urban food production. In addition, green roofs may contribute to increased property value, support the achievement of environmental certifications such as Green Seal and LEED, expand the functional use of buildings, and enhance overall urban environmental quality (JAMEI et al., 2023; LEE et al., 2024; LYNCH, 2018).

Despite the numerous studies highlighting the advantages of green roofs, most of the existing literature primarily focuses on thermal performance and the comfort provided by different types of green roof systems. These studies typically evaluate performance under various climatic conditions based on field measurements (BECK et al., 2013; JOHANNESSEN et al., 2019; PENG; SMITH; STOVIN, 2019).

According to Givoni (1992), building roofs are among the most vulnerable components of a structure in terms of thermal variation, largely due to their extensive direct exposure to climatic conditions. In hot climate regions such as Brazil, it is essential for roofs to possess characteristics that minimize solar radiation absorption. They must exhibit high thermal resistance and adequate thermal inertia to reduce temperature fluctuations, thereby improving indoor thermal comfort and limiting heat transfer into the building interior (OSUNA-MOTTA; HERRERA-CÁCERES; LÓPEZ-BERNAL, 2017). In tropical countries, the high incidence of solar radiation is particularly significant due to the angle at which sunlight reaches surfaces (LIZ, 2016), resulting in substantial heat gains within buildings—often accounting for 30% or more of internal thermal loads (OSUNA-MOTTA; HERRERA-CÁCERES; LÓPEZ-BERNAL, 2017).

Lopes (2007) emphasizes that the thermal properties of building materials can be strategically leveraged to improve indoor thermal conditions through the use of thermal inertia. In this process, heat absorbed by the building envelope during the daytime is stored within the structure and gradually released, contributing to a more stable indoor temperature. As a result, indoor environments tend to remain cooler during the day and warmer at night.

Complementing this perspective, Givoni (1976) highlights that the energy required for water evaporation can be harnessed as part of a building's passive cooling strategies. This can occur either through the evaporative cooling of outdoor air or indirectly via building components in contact with water—such as roofs with water reservoirs—which absorb heat during the evaporation process and thereby contribute to reducing indoor temperatures.

In summary, vegetation established on rooftops positively affects both indoor air quality and the surrounding outdoor environment, while also contributing to the reduction of cooling energy demand in buildings. This effect occurs because vegetation limits direct solar radiation on the roof surface, increases the thermal capacity and thermal resistance of the roofing system, and promotes a more stable indoor thermal environment—cooler during summer and warmer during winter.

However, green roofs should not be regarded solely as a strategy for improving indoor thermal comfort. According to Lombardo (1985), reduced evaporation, increased aerodynamic roughness, and the thermal properties of buildings and paved surfaces are among the factors that intensify the Urban Heat Island (UHI) phenomenon. Within this context, green roofs emerge as an important mitigation strategy by partially restoring vegetation lost during the urbanization process and contributing to improved urban microclimatic conditions.

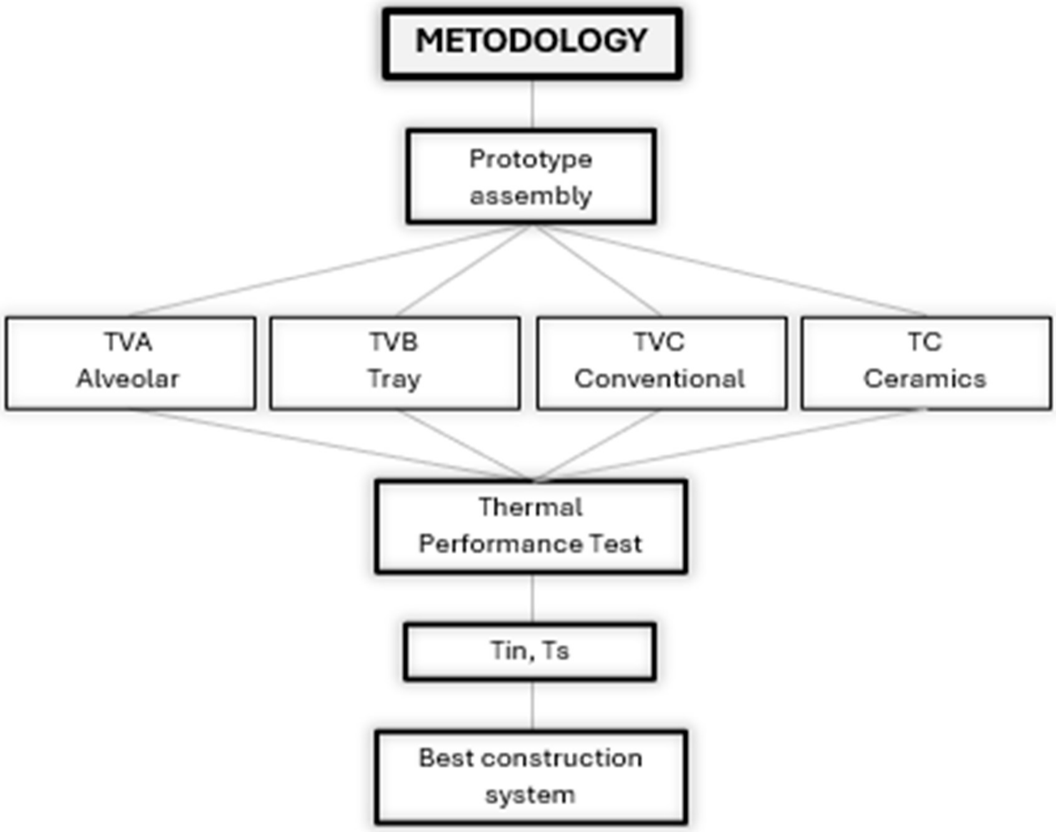
Although several studies have evaluated the thermal performance of green roofs, most investigations focus on a single construction system or analyze green roofs under different environmental conditions, limiting direct comparisons. This study contributes to the literature by experimentally comparing four roof systems—one conventional ceramic roof and three green roof construction models—using full-scale prototypes exposed to identical climatic conditions. The analysis highlights how differences in modular configuration, drainage systems, and water storage capacity influence thermal performance, providing practical insights for the selection of green roof systems in urban buildings.

Given all these aspects, the objective of this study is to evaluate the thermal potential of different green roof solutions, seeking to understand more deeply their benefits and impacts on the thermal performance of urban buildings.

2 METHODOLOGICAL PROCEDURES

The methodology of the present study was carried out according to the flowchart in Figure 01 below.

Figure 1. Methodology flowchart.



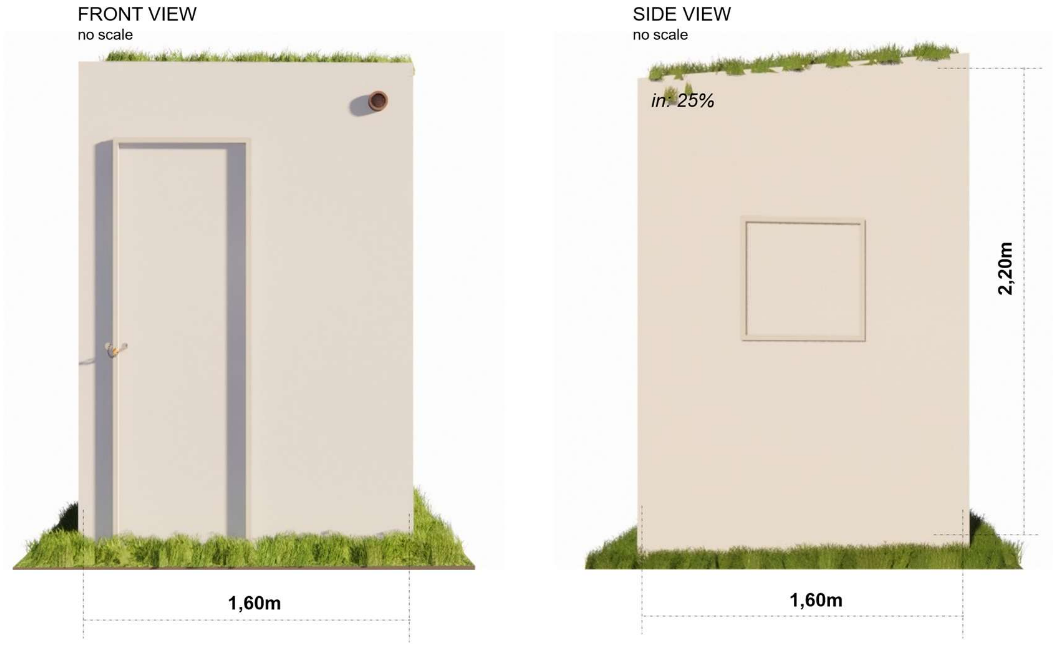
Source: prepared by the authors.

For the "testing" stage, detailed prototypes were built in items 2.1 and 2.2, according to Nakamura (2011), who highlights that the assembly of prototypes is ideal for conducting tests, as they are easy to assemble and disassemble, requiring less labor and, consequently, reducing costs.

2.1. Structure, dimensions, and elements of the prototypes

In the present study, the initial design of the prototype was based on Figure 02 below:

Figure 2. Prototype design.



Source: prepared by the authors.

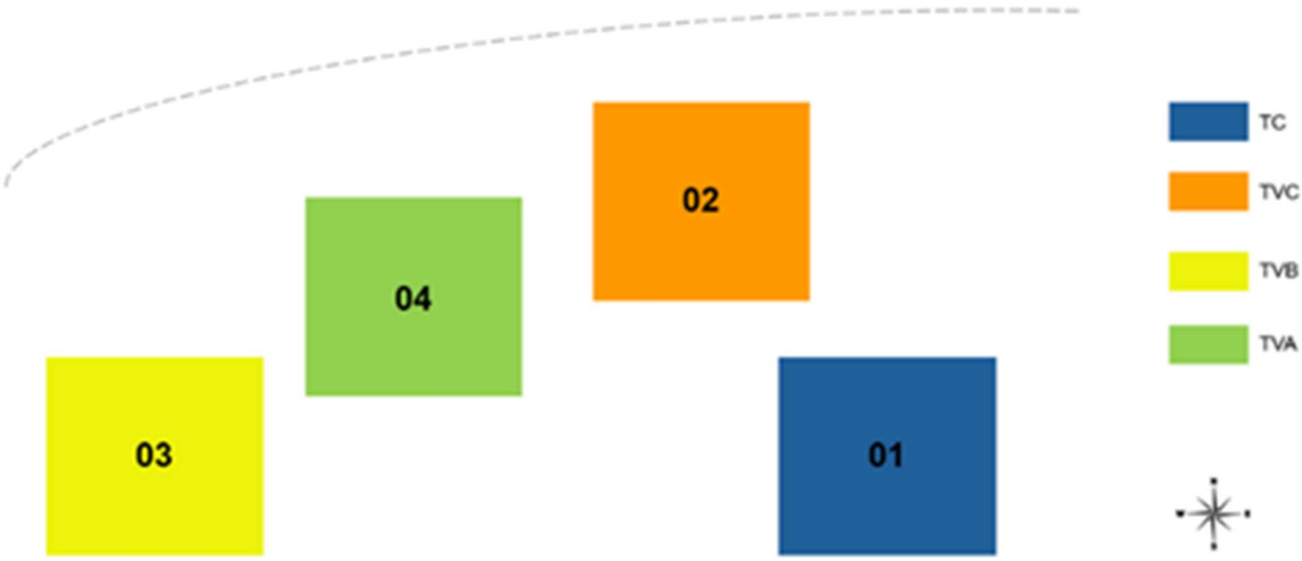
Prototypes of different types of roofing (1.60m x 1.60m x 2.20m, with an incline of up to 25%) were constructed in MDF at the Civil Construction Laboratory of USP – São Carlos, SP. The prototypes were positioned identically in relation to the Sun, without shadows from other buildings, and with windows and doors in the same positions to isolate the "roof" variable in the analysis.

The experimental prototypes were installed in an open outdoor area, free from direct shading by nearby buildings or trees, allowing full exposure to local climatic conditions. The site is located in the urban area of São Carlos, São Paulo, Brazil, characterized by low- to mid-rise buildings and predominantly residential land use. The surrounding surfaces consist mainly of paved areas and built structures, representative of typical urban conditions.

This configuration was chosen to ensure that the thermal behavior of the roof systems was influenced primarily by local environmental conditions, minimizing interference from external obstructions.

Figure 03 below shows the types of roofing: TC = Conventional Roof (01); TVC = Conventional Green Roof (02); TVB = Tray Green Roof (03); TVA = Cellular Green Roof (04).

Figure 3. Positioning of prototypes.



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São Carlos is located in a subtropical climate zone, with well-defined seasonal variations, characterized by hot and humid summers and mild winters. The region presents high levels of solar radiation throughout the year, which play a significant role in influencing the thermal performance of building envelopes and urban microclimates (SILVA et al., 2021; SANTAMOURIS et al., 2021).

Climatic variables such as air temperature, relative humidity, wind speed and direction, and precipitation were considered to contextualize the experimental results and to support the interpretation of the thermal behavior observed in the evaluated roof systems.

2.2. Roofs

According to NRCA (2000), the roof of a building is one of the largest and most important investments in buildings because it ensures that the building remains waterproof and thermally insulated under all conditions to which it is subjected throughout its entire useful life.

The roofs in this study were installed after the assembly of the prototypes, following the necessary layers presented in Table 4 below and later detailed in items 3.2.1 and 3.2.2.

Conventional Roof (TC01)

There are several models of ceramic tiles, such as capa-canal, colonial, romana, portuguesa, and flat. The design, size, and weight of each piece limit the variations between them (LESSA, 2009). For this study, the

French-type ceramic tile was chosen to represent the conventional roof due to its low cost and good aesthetic acceptance, being widely used in roof coverings (MORAES, 2013; FARRENY et al., 2014).

Green Roofs

A green roof is composed of layers of waterproofing, drainage, mat, substrate, and vegetation, with these components being constant, although construction systems may vary. All roofs in the study received plastic sheeting.

The "extensive" green roof was chosen for being feasible, low-cost, and ideal for small-scale vegetation, such as grasses and herbs, allowing for greater slope and requiring less maintenance, such as pruning, during dry periods (VIJAYARAGHAVAN, 2016).

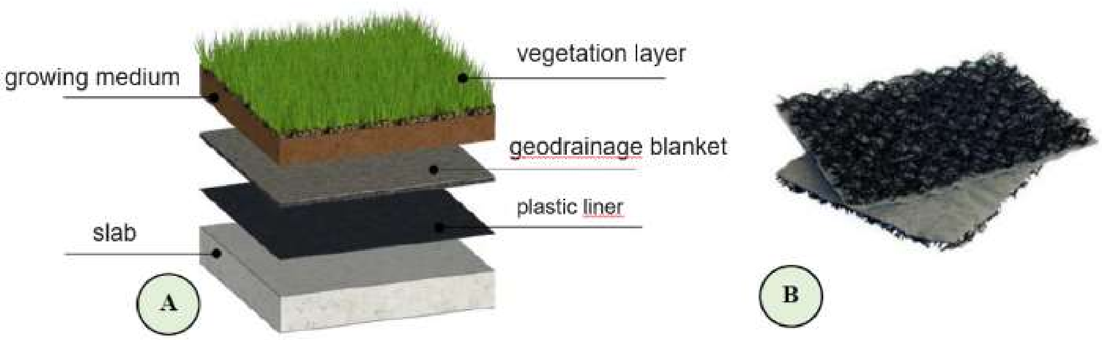
The substrate, composed of soil and organic compounds, provides an environment for plant growth, ensuring lightness and durability. The presence of organic matter is essential for proper compaction (SANTOS, 2016). The depth of the substrate also defines the chosen vegetation.

For this study, a lightweight substrate (a mixture of organic matter, humus, and sand) and Emerald Grass were used due to their adaptation to the Southeast region's climate and low maintenance (QUINTELLA, 2012). Irrigation was carried out twice a day to prevent damage to the plants.

2.2.1 Geodrainage Membrane System (TVC02)

The first system chosen was the geodrain mat system, which is the closest to what exists in the Conventional Green Roof. However, the distinguishing feature is the drainage system integrated with the mat, as shown in Figure 04.

Figure 4. Geodrainage Blanket.



Source: prepared by the authors.

The MacDrain geocomposite is a three-dimensional polypropylene geomat with 90% voids, ensuring drainage efficiency even in extreme conditions (MACCAFERRI, 2023).

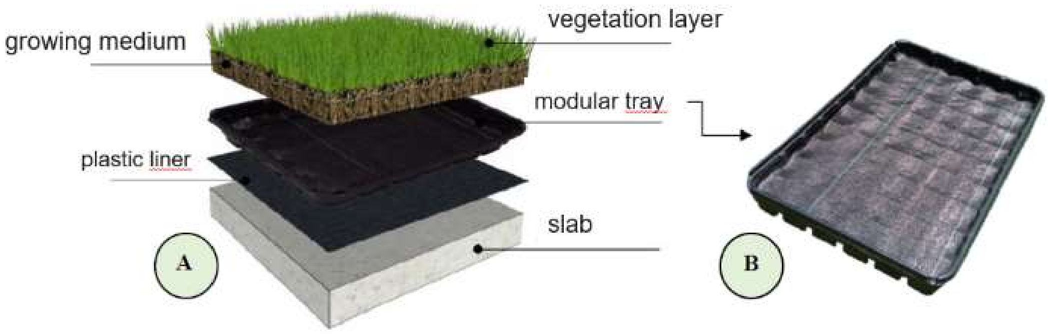
For the study, the MacDrain® J (Garden) model was used, which combines a geotextile filter and a fine drainage core, making it ideal for planters and flower beds, as it reduces flow and retains soil moisture (MACCAFERRI, 2023).

Approximately 12m² of the material were needed.

2.2.2. Tray System (TVB03)

Another construction system chosen for testing was the use of HDPE trays with a water reservoir, mat for substrate support, drainage/aeration holes, and locks that allow the trays to interlock with each other (VERTA, 2024), as shown in Figure 05.

Figure 5. TVB Tray.



Source: prepared by the authors.

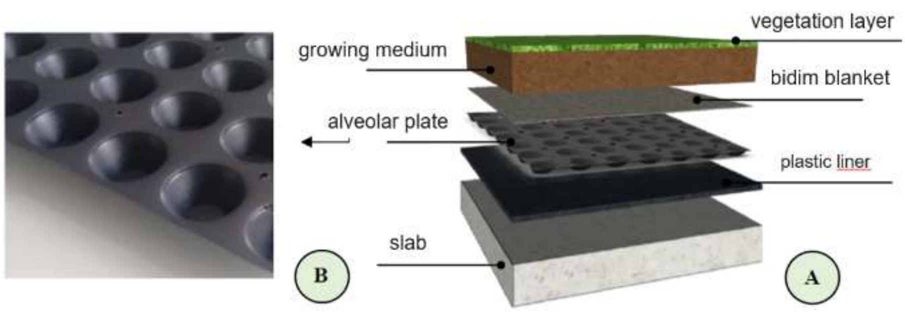
This system is provided by Verta Ecossoluções, model 7558 SB (according to the company's guidelines). Each panel has dimensions of 75x50x80cm with a reservoir capacity of 7.2 l/m².

For this work, 11 panels were supplied, and they needed to be cut to fit the space of the roof.

2.2.3. Alveolar System (TVA04)

The Alveolar System provides vegetation coverage for low-slope roofs, improving thermal comfort and contact with nature. Its cellular membrane facilitates drainage and stores water for the plants. Made from 100% recycled HDPE, it is lightweight and low in weight. Figure 06 illustrates the system.

Figure 6. TVB Tray.



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The geosynthetic was applied on waterproofed slabs treated with root-resistant materials. The selected GARDEN version has perforations in the membrane, allowing for both water storage and drainage simultaneously. Each panel was installed with the relief facing down, allowing the water cup to fill up.

A bidim fabric was placed over the geomembrane, facilitating water passage and protecting the membrane from clogging, ensuring its drainage function. About 5 panels of 2.2 x 1.1m were installed, being cut when necessary for better fit.

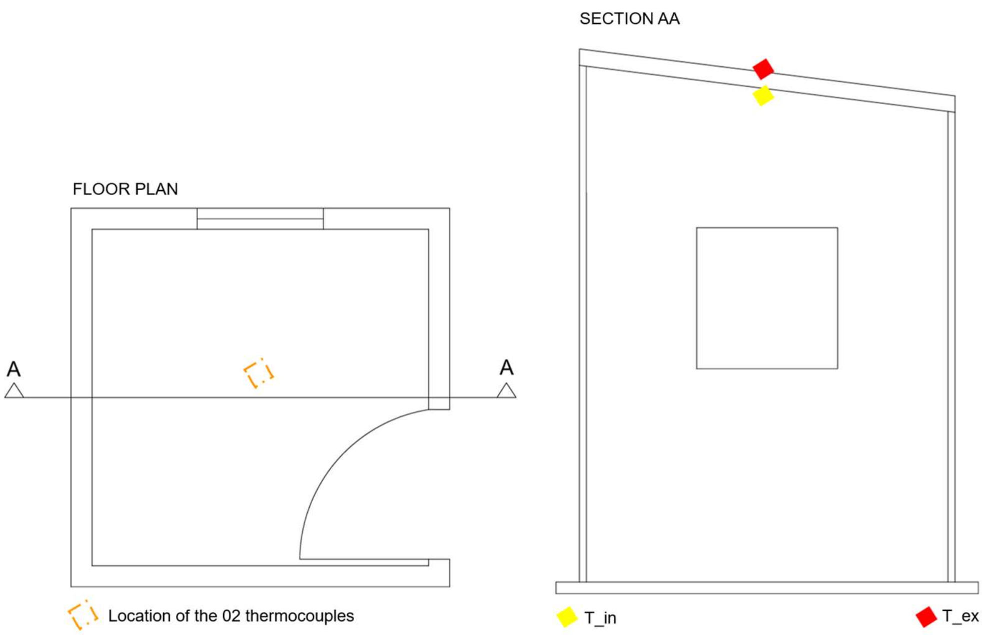
The installation of the Green Roofs was carried out by the laboratory technicians, without the need for specialized labor, due to the ease of installation.

2.3 Thermal Gain Tests

To assess the thermal efficiency of green roofs in urban centers, tests were conducted on the four types of roofs. Each prototype received 2 thermal sensors (Copper-Constantan Thermocouples), connected to a Data Logger (Campbell CR10x with AM16/32 multiplexer), which collected data every 10 minutes over a period of 10 days.

External and internal air temperatures (just below the roof) were recorded to measure the thermal differences between the roofs. The sensor positions on the prototypes are illustrated in Figure 07.

Figure 7. Schematic section of the sensor positioning.



Source: prepared by the authors.

Thermal monitoring was conducted between May and June, a transition period between autumn and winter in southeastern Brazil, which is characterized by significant thermal variability. During this period, both relatively cold and warm days were observed, allowing the assessment of roof thermal performance under contrasting environmental conditions.

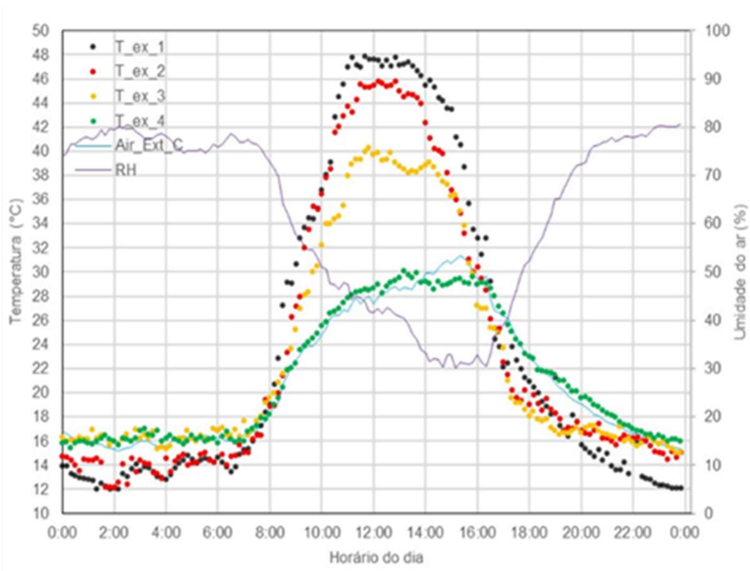
Measurements were recorded over full daily cycles, covering daytime and nighttime periods, in order to capture temperature fluctuations associated with different atmospheric conditions. This seasonal variability provided a suitable context for evaluating the thermal response of the roof systems under distinct temperature regimes.

3 RESULTS AND DISCUSSIONS

From the period of the tests, 3 days were selected (hottest day, coldest day, and day with the largest thermal amplitude). After analysis, it was concluded that, regarding the thermal tests, the best model is TVA (number 04).

The first of these presents a scenario of high temperature and low humidity, where the air temperature reached 32ºC and relative humidity was 30%. Figure 8 shows the result of the behavior of the roofs in relation to Surface Temperature (T_ex).

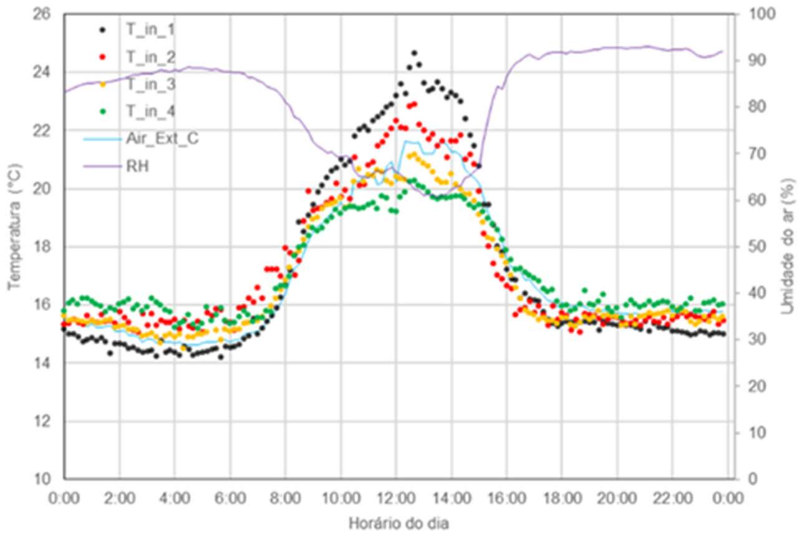
Figure 8. Day 1 - External roof temperatures



Source: prepared by the authors.

Regarding the graph in Figure 9, the same pattern is repeated when measuring the Ceiling Temperatures (T_in) of the prototypes.

Figure 9. Day 1 - Internal roof temperatures



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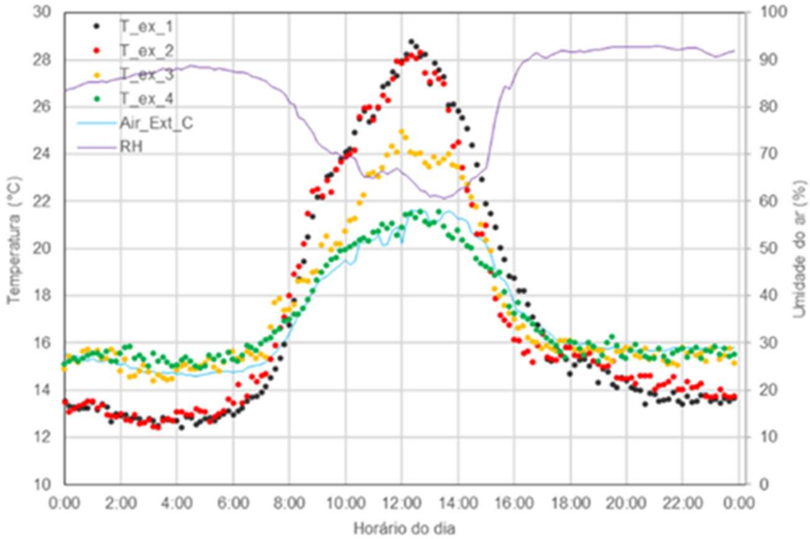
According to the graphs (Figures 08 and 09), TVA showed superior thermal performance, especially when compared to TC. During the hottest time of the day, the surface external temperature (T_ex) of TC reached 47ºC, while TVA remained at 30ºC. In contrast, the internal ceiling temperature (T_in) of the ceramic roof reached 33ºC, which is 8ºC higher than TVA under those conditions.

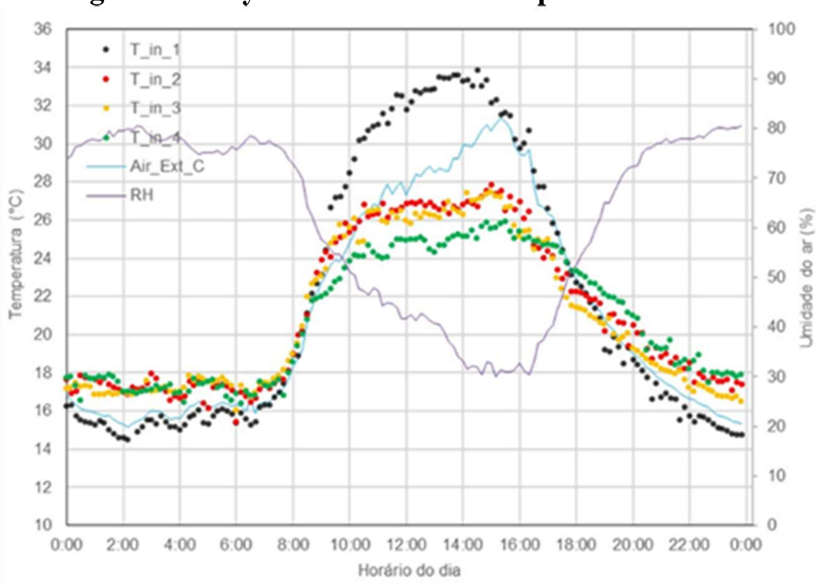
On the second day of evaluation, the maximum and minimum temperatures were milder (15ºC and 21ºC), with high relative humidity (92%), which directly impacted the air temperature. Figures 10 and 11 illustrate the behavior of the roofs in relation to T_ex and T_in under these conditions.

Figure 10. Day 2 - External roof temperatures



Source: prepared by the authors.

Figure 11. Day 2 - Internal roof temperatures



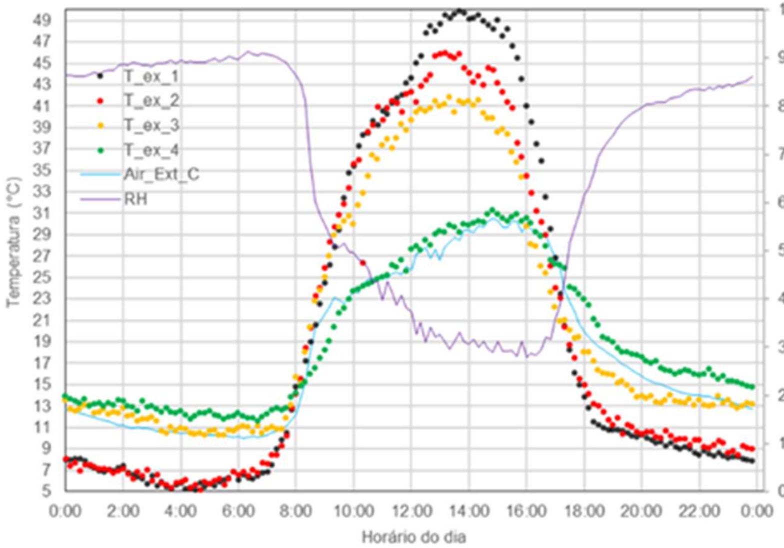
Source: prepared by the authors.

On this day with milder conditions, the results showed opposite values: during the coldest period, the ceramic tile roof had an external surface temperature 2ºC higher, while the internal ceiling temperature only decreased by 0.10ºC.

Meanwhile, the cellular green roof maintained the same performance pattern observed in the previous graphs, with a 1ºC increase in internal temperature during the colder period, providing greater thermal comfort.

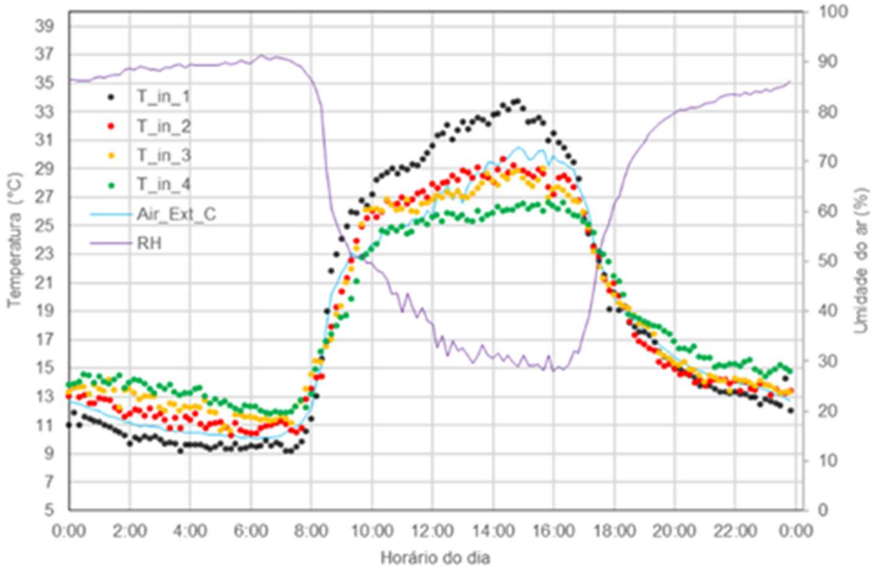
On the third and final day of evaluation, a significant thermal variation was recorded, with a minimum temperature of 10ºC and a maximum of 30.5ºC, as well as relative humidity fluctuating between 27% and 91%. Figures 12 and 13 display the measurement behavior, similar to the previous ones.

Figure 12. Day 3 - External roof temperatures



Source: prepared by the authors.

Figure 13. Day 3 - Internal roof temperatures



Source: prepared by the authors.

According to the graphs in Figures 12 and 13, TVA maintained the same pattern as the other results, with green roofs showing smoother temperature variations, indicating that, even with large thermal fluctuations, TVA had fewer internal changes.

Overall, green roofs exhibited thermal behavior favorable to environmental comfort, characterized by lower temperatures on hot days and higher temperatures on cold days. This behavior contributes significantly to the improvement of thermal comfort in urban environments. These findings are consistent with the analysis presented by Ferraz (2012), who demonstrated that green roofs provide enhanced thermal insulation. During hot periods, indoor temperatures beneath green roofs tend to remain lower than outdoor temperatures, whereas during colder periods, these systems help maintain higher indoor temperatures. Therefore, thermal insulation stands out as one of the primary advantages of green roofs, particularly in urban contexts where climatic conditions may be extreme.

The consistency in the thermal performance of the green roofs is also supported by studies by Wark (2012), which emphasize the importance of the low thermal conductivity of the plant substrates and water in green roofs. These elements act as natural insulators, absorbing heat more efficiently. Similarly, Ferreira (2019) observed, in a study conducted in São Paulo, that areas with greater vegetation cover and higher levels of verticalization had significantly lower surface temperatures during the day and higher temperatures at night. This phenomenon is characteristic of urban heat islands, where vegetation and the city's configuration directly influence local temperatures, providing a more comfortable microclimate.

The results obtained in these studies reinforce the importance of vegetation and urban form in the thermal dynamics of cities, indicating that green roofs outperformed the thermal performance of ceramic roofs, regardless of the type of construction system used. The main similarity between the different types of green roofs ystems was the use of the same type of plant substrate and vegetation, which underscores the importance of these components in thermal performance.

In the study conducted by Pimentel et al. (2023), the thermal performance of different substrates used in green roofs was comparatively evaluated. The authors concluded that the commercial planting substrate adopted in their research exhibited the best thermal performance under both hot and cold conditions. This substrate presented the highest average temperature variation (4.5 °C) and the largest difference between maximum substrate temperature and air temperature (7.2 °C), indicating superior thermal insulation capacity. During summer periods, substrate temperatures remained significantly lower than ambient air temperatures, reinforcing the role of green roof substrates in moderating thermal conditions.

Additionally, the research also revealed that plant substrates maintain higher minimum temperatures compared to the air temperature, providing a greater sense of thermal comfort during the winter. This superior thermal performance can be attributed to the higher porosity and moisture retention capacity of the plant substrate, as well as its higher proportion of organic matter, as pointed out by Liberaresso et al. (2021), Sandoval et al. (2017), and Cascone et al. (2018).

The plant cover, specifically the Emerald Grass chosen for the study, plays an important role in cooling the air. The evapotranspiration of the grass can reduce the ambient temperature by up to 15°C, which can result in a significant decrease in the need for air conditioning systems, potentially reducing air conditioning energy consumption by up to 25% (University of Minnesota, 2006). This effect is particularly important in urban areas, where the heat islands generated by the concentration of buildings and lack of vegetation can make cities hotter and uncomfortable for residents.

Regarding the different types of green roofs analyzed, the Cellular Green Roof (TVA) and Tray Green Roof (TVB) systems stood out in terms of thermal performance when compared to the Conventional Green

Roof

(TVC). This thermal superiority is mainly due to the presence of a layer of recycled HDPE (high-density polyethylene) and a water reservoir, elements that significantly contribute to thermal insulation. HDPE, due to its thermal properties and high resistance, increases the durability of green roofs while also helping to reduce the need for irrigation and control water runoff. The water stored in the roofing system helps keep the plants self-sufficient while moderating thermal fluctuations.

Among the systems analyzed, the Cellular Green Roof (TVA), which has a lightweight modular system and an efficient water reservoir, showed the best thermal performance on all days of the study. Its installation is simpler and less demanding in terms of specialized labor, unlike the Conventional Green Roof (TVC), which requires more logistics and effort during installation. Therefore, TVA stands out not only for its thermal efficiency but also for its ease of installation, making it a more accessible and effective solution for implementing green roofs in urban environments.

3.1 Socioeconomic applicability

Beyond technical termal performance, the implementation of green roofs involves relevant socioeconomic considerations that have been increasingly discussed in recent literature. Although green roof systems provide multiple environmental benefits, several studies indicate that their higher initial costs—associated with materials, installation, and maintenance—remain a significant barrier to widespread adoption, particularly in low-income or resource-constrained urban contexts (CASTLETON et al., 2020; BERARDI, 2021).

Recent cost–benefit analyses, however, suggest that these initial investments may be offset over the life cycle of the system. According to studies published after 2020, green roofs can contribute to reductions in building energy demand, extend roof service life, and mitigate urban heat island effects, resulting in economic benefits at both building and urban scales (SANTAMOURIS et al., 2021; ZHANG et al., 2024). In addition, the valuation of non-market benefits—such as improved urban microclimate, stormwater management, and public health—has gained relevance in assessing the overall socioeconomic feasibility of green roof systems (LI et al., 2022).

From an urban policy perspective, recent research highlights that the economic viability and equitable distribution of green roof benefits are strongly influenced by public incentive programs and regulatory frameworks. Empirical evidence from different cities indicates that subsidies, tax incentives, and mandatory regulations have played a crucial role in increasing green roof adoption and reducing socioeconomic disparities in access to urban green infrastructure (BERARDI, 2021; KÖHLER; POLL, 2022). Therefore, integrating green roofs into urban planning strategies and sustainability policies may enhance their feasibility and promote broader social and environmental benefits, especially in regions increasingly affected by heat stress and climate change.

4 FINAL CONSIDERATIONS

The results of this research demonstrated that Green Roofs, particularly the Cellular Green Roof model (TVA), offer superior thermal performance compared to conventional ceramic roofs (TVC). TVA exhibited milder temperatures on hot days and more stable temperatures on cold days, promoting greater internal thermal comfort. This performance is due to the combination of the commercial plant substrate and the modular system, which facilitates installation and improves thermal control.

Vegetation, such as Emerald Grass, contributes to cooling the environment and reduces the need for artificial climate control, helping to mitigate urban heat islands. The presence of recycled HDPE and water reservoirs in the TVA and TVB models also contributes to greater thermal efficiency and sustainability, with less need for irrigation and reduced stormwater runoff.

Thus, Green Roofs, particularly the Cellular model, provide an efficient and sustainable solution to improve urban thermal comfort, reduce environmental impact, and create more resilient cities. Future studies may explore their application in different climatic and urban contexts, as well as the economic and social impacts of this technology.

Although the results obtained in this study demonstrate the thermal benefits of green roof systems, some limitations should be acknowledged. The experimental monitoring was conducted over a limited period, which may not fully represent long-term seasonal variability. Additionally, the measurements were carried out under the specific climatic conditions of São Carlos, São Paulo, Brazil, characterized by a subtropical climate, which may restrict the direct extrapolation of the results to regions with different climatic profiles.

Another limitation concerns the use of a single plant species and a specific substrate composition in the green roof prototypes. Different vegetation types, substrate depths, and material properties may lead to distinct thermal behaviors. Finally, although the experimental setup allowed for a detailed comparison between roof typologies, external factors such as wind speed, solar radiation intensity, and rainfall events were not continuously controlled, which may have influenced the thermal responses observed.

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