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THERMAL PERFORMANCE OF GREEN ROOFS INFLUENCED BY SUBSTRATE COMPOSITION

Matheus Schmidt[1*], Samuel N. M. de Souza[1], Deonir Secco[1], Aline Snak[1], Doglas Bassegio[1]

[1*]Corresponding author. Universidade Estadual do Oeste do Paraná (UNIOESTE)/Cascavel - PR, Brasil.
E-mail: matheus.schmidt@unioeste.br | ORCID ID: https://orcid.org/0000-0001-7585-0809

KEYWORDS

ecological roof, energy efficiency, soil properties.

ABSTRACT

The selection of materials and substrates is essential for optimizing the thermal performance of green roofs. However, there has been limited research on green roof characteristics under subtropical conditions. Therefore, this study aims to evaluate the internal and substrate temperatures of six green roof prototypes and one control prototype. Prototypes with clay tiles (control), clay substrates with and without vegetation, sandy substrates with and without vegetation, and organic matter substrates with and without vegetation are evaluated. The experimental design involves randomized blocks and the internal and substrate temperatures are monitored. The vegetated sandy substrate prototype exhibits the highest thermal performance, with internal temperatures 0.6 °C lower than those of other green roof prototypes and 1.7 °C lower than that of the control with clay tiles. This is attributed to the high porosity of the sandy substrate, which enhances thermal insulation. To provide optimal thermal performance, the substrate must have a water retention capacity that is sufficient to guarantee vegetation development, but not excessive so that it constantly increases the thermal conductivity owing to substrate saturation.

INTRODUCTION

There is a clear cause-and-effect relationship between temperature and energy consumption. Changes in heating and precipitation patterns, referenced by the Intergovernmental Panel on Climate Change, have increased global surface temperatures by 1.1-6.4 °C between 1990-2100. An ecological solution is the implementation of green roofs (or eco-roofs), which comprise several overlapping layers on a structural surface, incorporating vegetation cover (Bevilacqua, 2021; Leite & Antunes, 2023).

Green roofs provide shade and insulation, save energy, and mitigate the urban heat island effect. Green roofs can also improve the performance of photovoltaic electricity (Chemisana & Lamnatou, 2014; Lamnatou & Chemisana, 2015), offering aesthetic and social benefits (Jungels et al., 2013). Green roofs can reduce heat transport (during and after construction) and energy consumption for heating and cooling (Werdin et al., 2021; O'Carroll et al., 2023). Green roofs also retain stormwater runoff and improve water quality in urban areas (Gong et al., 2019; Liu et al., 2019; Zhang et al., 2021).

Green roof systems are not standardized and vary depending on the choice of materials used in the growing substrate, drainage layer, and plant composition (Vandegrift et al., 2019), as well as the thickness of the different components (Wang et al., 2022; Tan & Wang, 2023). Each component influences the thermal potential of a green roof. The thermal performance is directly related to the thermal characteristics of the substrate (Dimitrijević et al., 2016; Kostadinović et al., 2022; Chen, 2022).

Although there are several guidelines in the literature for selecting substrate components and their basic characteristics, few studies have combined information on different substrates, soil types, and covers. Therefore, this study aims to evaluate the internal and substrate temperatures of different prototype green roofs with different substrates, soils, and cover types in subtropical Brazil.

[1] Universidade Estadual do Oeste do Paraná (UNIOESTE)/Cascavel - PR, Brasil.
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MATERIAL AND METHODS

This study was conducted at the State University of Western Paraná, UNIOESTE, Cascavel, PR, Brazil, located at Latitude 24°59'14" South, Longitude 53°26'58" West, and an altitude of 750 m above sea level. The local climate is classified as subtropical (Cfa) according to the Köppen-Geiger system. The 30 year mean annual temperature is 22.1 °C with a July minimum of 16.8 °C, January maximum of 27.6 °C, and mean annual precipitation of 1800 mm.

The prototypes were positioned in an open, grassy area to eliminate potential shading from nearby structures, trees, or other objects. Each unit had approximate dimensions of 1 m in length, width, and height (Fig. 1), with a 2 m gap. To maintain proper elevation, the prototypes were placed 15 cm above the ground level and supported by bricks.

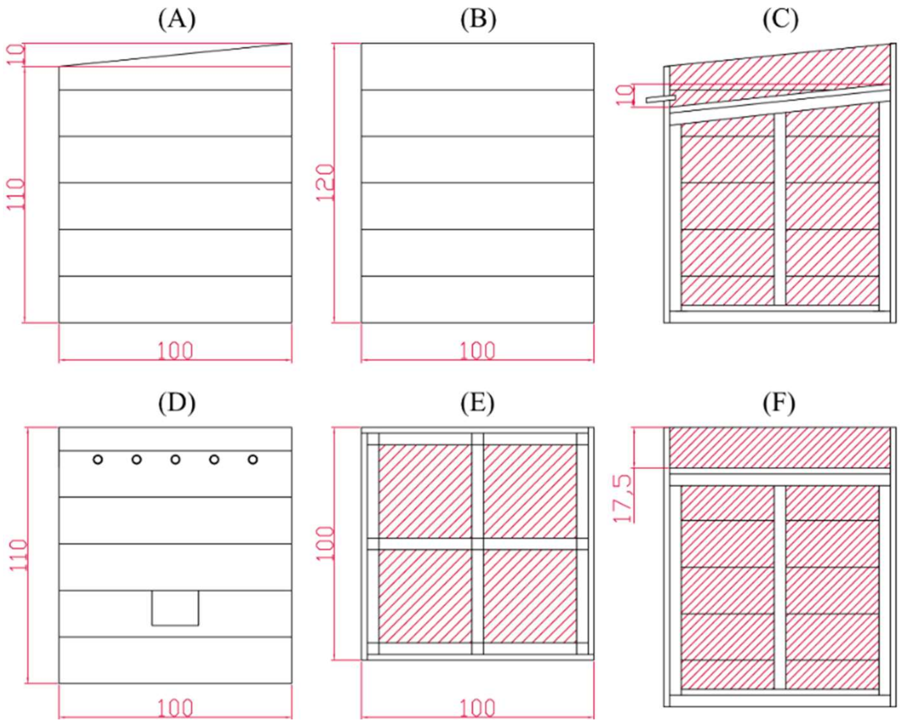

FIGURE 1. Dimensions and technical drawing of green roof prototypes, including side view (A), rear view (B), section of side view (C), front view (D), top view (E), and section of rear view (F)

Prototypes covered with clay tiles (control), clay substrates with and without vegetation, sandy substrates with and without vegetation, and organic matter substrates with and without vegetation were evaluated. A conventional roof prototype with clay tiles was adopted as a control to compare the internal structure temperature between green and conventional roofs. The constituent layers of the green roof were installed as illustrated in Fig. 2.

The prototype structures were built with pine boards and rafters and nails. The prototype surface exhibited a 10% decrease in rainwater drainage. The waterproofing layer material was a self-adhesive asphalt blanket, which is commonly used in slabs. The draining and filtering layers comprised expanded clay and geotextile filters, respectively. Emerald grass (*Zoysia japônica*) was selected as the plant layer species (Fig. 2) because of its high drought tolerance and low temperatures, which are ideal for the climate of Cascavel-PR.

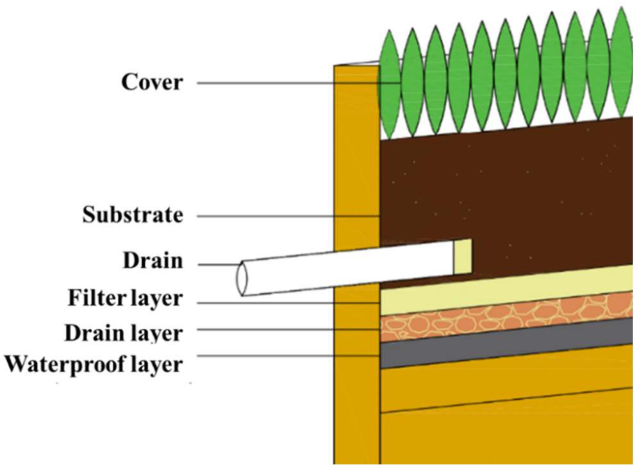

FIGURE 2. Green roof prototypes implemented.

To drain the excess rainwater not absorbed by the substrate, barbican drains were installed in the retaining walls to allow the passage and avoid accumulation of water. These drains were composed of 20 mm × 10 cm PVC pipes installed on the front of the green roof prototypes and lined internally with a geotextile filter to prevent the substrate from passing through them.

The difference in texture between the substrates is essential to determine the influence of each soil type on the thermal performance of green roofs, because each soil type has distinct physical and chemical characteristics.

In soil-based substrates, particle size and density tests were conducted to accurately determine the clay, silt, and sand contents, and specific mass of the soil. Humus was added until an organic matter content of approximately 5% was reached to ensure adequate conditions for the nutrition and survival of vegetation cover. A mixture of bovine manure and dry vegetable matter (branches and leaves) was used as the organic matter substrate. Table 1 presents the data for each substrate.

TABLE 1. Granulometry and apparent density of the substrates.

	Substrate		
Parameters	Clay	Sandy	Organic matter
% sand	12.7[1]	69.8[1]	-
% clay	53.7[1]	17.3[1]	-
% silt	33.6[1]	12.9[1]	-
Density (g cm^{-3})	1.09[2]	1.46[3]	0.29[3]

1 - Densimeter method. 2 - Volumetric ring method. 3 - Test tube method.

Capacitive (AM2302 DHT-22) and digital (DS18B20) sensors were employed to monitor the internal and surface temperatures of the prototypes, respectively. The internal sensors were placed at the geometric center of the prototype, 50 cm from each side, whereas the sensors used to measure the surface temperature were positioned at the center of the substrate. Data were recorded and stored every 15 s to obtain a high data volume and confidence during the 24 h period of the 30 monitored days. Data were collected in late spring between November 18 and December 19, 2019. This period was selected to evaluate the results at reasonably high rather than extreme temperatures, as would be likely to occur in summer or winter.

A thorough multi-step analysis was conducted to statistically analyze the influence of the substrate composition on the internal and substrate temperatures. Examining the internal temperature across the entire data collection period alone would provide detailed insights into the thermal efficiency of the prototypes. For example, Schmidt (2020) observed that sandy substrates had significantly lower average temperatures during midday (noon to 2 p.m.), but reached the highest internal temperatures at night compared to other treatments. This finding demonstrates that analyzing daily temperature averages could obscure meaningful differences among substrates, as thermal efficiency relates more to the reduction in the heat transfer rate than simply minimizing the temperature levels.

To better interpret the results, internal temperatures were analyzed according to the substrate type and time of day. A randomized block design (RBD) was applied, treating the substrate type and time of day as factors and days as blocks. The 24 h cycle was treated as a qualitative variable to allow for distinct analyses. Data were subjected to an analysis of variance (ANOVA) test followed by a post-hoc Tukey test at a 5% significance level. The data were grouped monthly to ensure significant variations in performance under extreme conditions were observed to capture critical moments of green roof functionality.

The statistical approach considered the impact of external factors, such as ambient temperature, solar radiation, and substrate moisture on the internal temperatures of the prototypes. Given the substantial variability at different times of the day, the use of a completely randomized design would likely have increased the overall variability, potentially masking important differences. To mitigate this, hours of the day were treated as blocks within the RBD, enabling the precise identification of temperature patterns over time and isolating the effects of substrate composition.

This methodology resembles approaches used in crossover designs, where sequential treatments and time-based blocking control confounding factors, such as learning effects or fatigue. As highlighted by Meier (2022), blocking by time ensures that external conditions, such as wind or precipitation, which simultaneously influence all prototypes, do not create random variability. This design effectively isolated the impact of the substrate composition on the internal temperatures, eliminating noise from daily temperature fluctuations.

Moreover, incorporating ANOVA and the post-hoc Tukey test within this framework allowed for robust differentiation among treatments, ensuring that the observed differences were attributable to the substrate composition rather than external variability. This approach proved essential for understanding the subtle thermal dynamics of each prototype and identifying the conditions under which each substrate type excelled.

RESULTS AND DISCUSSION

The internal average temperature of each prototype varied throughout the day, reaching maximum temperatures between 2-4 p.m. and minimum temperatures between 5-6 a.m. (Fig. 3). At times when the temperature was higher, the significant discrepancy ($p<0.05$) between the internal temperatures of the prototypes was also high, whereas at times of milder temperatures, the thermal performances of the prototypes seemed to differ slightly. However, the control prototype with clay tiles (P1) had the highest temperature. These results were expected, considering the established efficiency of the thermal performance of green roofs. This is explained in terms of thermal inertia, which is the time required to exchange thermal energy between the internal and external environments, explaining the heat absorbed during the day and released throughout the night.

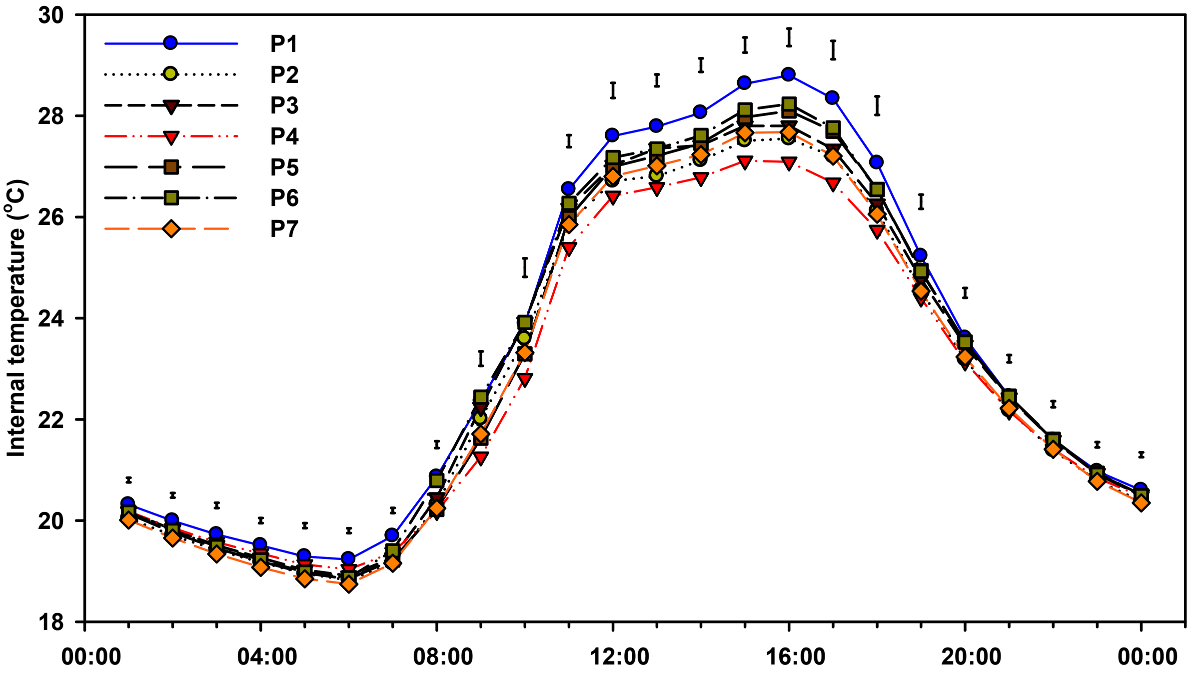

FIGURE 3. Average internal temperature in the prototype with clay tiles (P1), clay substrate with vegetation (P2), sandy substrate without vegetation (P3), sandy substrate with vegetation (P4), organic matter substrate without vegetation (P5), clay substrate without vegetation (P6), and substrate of organic matter with vegetation (P7). Within each hour range, vertical bars represent the least significant difference at $p < 0.05$ according to Tukey test.

The prototypes of clay and sandy substrates with vegetation (P2 and P4) predominated in lower temperature ranges than those without vegetation (P3 and P5; Fig. 3). This can be explained by the benefits of the plant layer above the substrate: reducing the temperature through evapotranspiration; increasing the thermal inertia by adding plant mass; decreasing the overall thermal conductivity of the system as a function of the air present among the vegetation; generating shading, and consequently reducing direct sun exposure of the substrate, which significantly increased the albedo of the structure (MacIvor & Lundholm, 2011; Ouédraogo et al., 2023). Furthermore, substrate prototypes without vegetation had lower thermal performances, as they reached temperatures similar to those of the prototype control with clay tiles (P1), which was attributed to the dark color of these substrates, decreasing the albedo.

The observed difference between the green roof prototypes and the control in this study is consistent with the findings of other studies that have highlighted the effectiveness of green roofs in reducing internal temperatures compared with conventional roofs. For example, Lokesh et al. (2023) demonstrated that green roofs could lower indoor temperatures by 2.4 °C at the peak afternoon hour (2 p.m.), attributing this effect to the ability of vegetation to absorb solar radiation and dissipate heat through processes such as evapotranspiration and photosynthesis. Similarly, Ahmadi et al. (2015) found that green roofs reduced indoor air temperatures by 2.6 °C in Athens, 2.0 °C in La Rochelle, and 1.4 °C in Stockholm, illustrating the broad potential of this technology to improve energy efficiency across diverse climatic conditions.

The sandy substrate prototype with vegetation (P4) tended to maintain lower internal temperatures, particularly during the hottest periods of the day. For example, between 3-4 p.m., a temperature difference of up to 0.6 °C was noted when compared to the green roof prototype with a clay substrate (P2) and up to 1.7 °C when compared to the control with clay tiles (P1).

The high porosity of sandy soil, which prevents it from retaining water for long period and consequently increases its thermal conductivity, is a factor that explains its high thermal performance. As an elevated water retention capacity is a partially undesirable factor for thermal insulation, it was assumed that the substrate prototype composed of organic matter with vegetation (P7) would demonstrate comparable or improved thermal insulation performance, given its low water retention capacity. However, similar or higher temperatures were observed compared to the clay prototype, with a high water retention capacity. In addition, vegetation did not develop in a manner similar to that of the other prototypes. This can be explained by the very low apparent density (0.29 g cm^{-3}) of this substrate, which produced the lowest thermal capacity.

The thermal conductivity of soil is significantly influenced by the moisture content, with the porosity and thermal conductivity of the solid fraction also being critical factors (Cosenza et al., 2003). Several studies have confirmed that the thermal conductivity of a soil is directly proportional to its moisture content. This is because the thermal conductivity of air is significantly lower than that of water or solid matter, as shown in Table 2, resulting in low thermal conductivity in soils with high air or low water contents (Cosenza et al., 2003; Dimitrijević et al., 2016; Farouki, 1981; Hillel, 2005; Tarnawski & Leong, 2000).

TABLE 2. Thermal conductivity of soil components (AT 10°C). Modified from Hillel (2005, p. 159); modified from Hamdhan & Clarke (2010).

Material	$Wm^{-1} k^{-1}$
Organic Matter	0.25
Water	0.57
Air	0.025
Soils in General	0.15 - 4.0
Saturated Soils	0.6 - 4.0
Dry Sand	0.15 - 0.25
Moist Sand	0.25 - 2.0
Saturated Sand	2.0 - 4.0
Clay (Dry to Moist)	0.15 - 1.8
Saturated Clay	0.6 - 2.5
Organic Soil	0.15 - 2.0

This observation explains why the sandy substrate maintained lower internal temperatures during the hottest periods of the day, given that its thermal conductivity was among the lowest in the list of materials presented, in its dry state. In addition, as described by Farouki (1981), this behavior can be attributed to the differences in porosity and particle arrangement among the substrates. Sand, predominantly composed of silica grains, features a more open and porous structure than clay, which consists of finer particles arranged in a denser and more compact manner. The greater porosity of sand leads to a higher air content in the voids between the grains, which lowers its thermal conductivity. In contrast, the tightly packed particles in clay create more contact points, facilitating heat transfer and resulting in a higher thermal conductivity than that of sand.

This corroborates the results of Sandoval et al. (2015), who, when analyzing different models of prototypes with substrates without superficial vegetation, noted that the clay substrate with ground bricks demonstrated not only the lowest water retention capacity, but also the smallest increase in thermal conductivity when saturated. Despite this, the substrate composed of perlite and peat, which in addition to having a greater water retention capacity, had a greater increase in thermal conductivity, was the substrate that most attenuated the external temperature. As referenced by previous studies, the results of this study suggest that the thermal behavior of green roofs depends on the association and interaction of the thermal and hydraulic properties of the substrate.

In general, the prototypes with more efficient thermal performance exhibited lower substrate temperatures during the hottest periods and higher substrate temperatures during the coldest periods of the day (Fig. 4). The sandy substrate with vegetation (P4) had lower temperatures during the sunnier periods, with thermal inversion occurring at dawn (Fig. 4). This low temperature unlikely translates to a reduction in the internal temperature of the prototype because of the low natural thermal conductivity provided by the organic matter to the soil (Abu-Hamdeh & Reeder, 2000), which means that it does not tend to retain heat. However, owing to the negligible density of organic matter, it does not offer significant protection from solar radiation and heat.

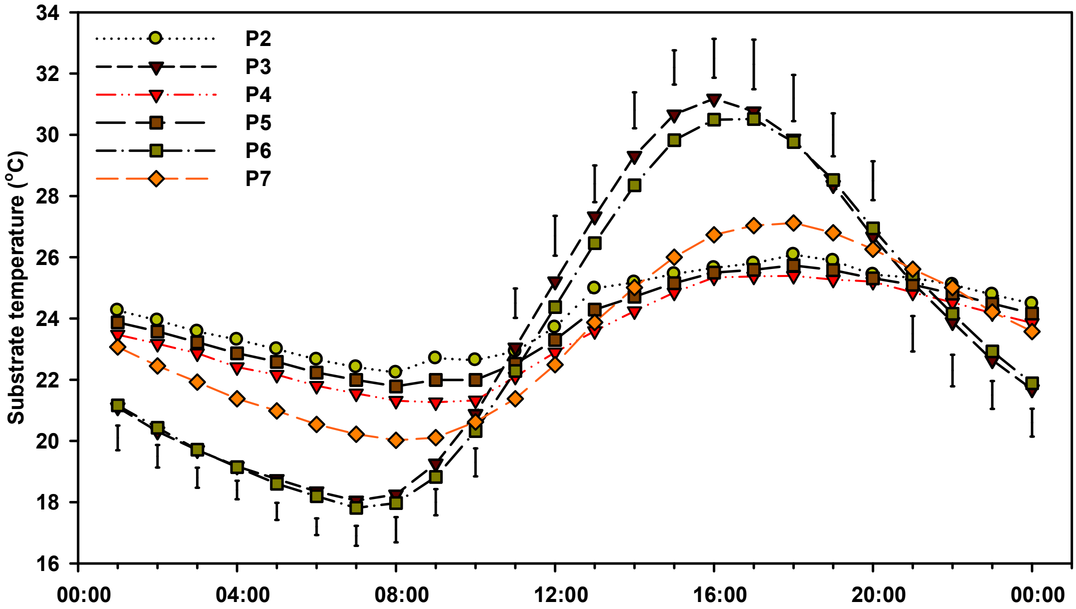

FIGURE 4. Average substrate temperature in the prototype of clay substrate with vegetation (P2), sandy substrate without vegetation (P3), sandy substrate with vegetation (P4), organic matter substrate without vegetation (P5), clay substrate without vegetation (P6), and substrate of organic matter with vegetation (P7). Within each hour range, vertical bars represent the least significant difference at $p < 0.05$ according to Tukey test.

The thermal variations between the afternoon and night periods tended to be more visible in the prototypes in which the vegetation was properly developed (P2 and P4), whereas in the prototypes without vegetation, the discrepancy was reduced (P3 and P6; Fig. 4). The vegetation cover intercepts solar radiation before it reaches the ground (Lee & Jim, 2020). In this way, plants dissipate heat more easily because they have physiological defense mechanisms, such as perspiration, which prevent overheating and keep them cool.

The findings of this study have practical implications, particularly when considering recent research emphasizing the ability of green roofs to enhance thermal comfort and reduce energy consumption. For example, Abuseif et al. (2021) revealed that green roofs, particularly those incorporating tree cover, can decrease cooling energy requirements by as much as 60%, underscoring their potential to improve energy efficiency in urban settings. Additionally, Meng et al. (2022) demonstrated that green roofs are capable of lowering external surface temperatures by up to 13.7 °C during daytime hours, further highlighting their critical role in alleviating the urban heat island effect.

CONCLUSIONS

The prototypes with the best results were the sandy vegetation substrate (P4), clayey substrate with vegetation (P2), and organic matter substrate with vegetation (P7). Thermal conductivity appears to be a more relevant factor than the volumetric thermal capacity (thermal inertia) in the case of heat exchange on green roof substrates, except when the initial density of the substrate is significantly lower. Albedo is an equally important factor in the internal cooling of structures. However, green roofs with equally developed vegetation did not appear to exert considerable influence. Finally, for the substrate to exhibit ideal thermal performance, it must have a water retention capacity sufficient to guarantee vegetation development but not excessive enough to constantly increase the thermal conductivity due to the saturation of the substrate. The results of this study can be used to guide integrated green roof strategies under subtropical conditions.

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