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# Green Roofs on Shipping Containers: How Substrate Thickness Affects Thermal Performance

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**Abstract:** Green roofs have become a popular sustainable solution in urban areas, and in recent years, shipping containers have gained popularity as a sustainable alternative for housing. A promising proposal is to combine these two solutions. This research aims to analyze the thermal behavior of experimental modules of scale constructions. Four modules were constructed with different substrate thicknesses (4, 6, 8, and 12 cm) to verify the impact on thermal behavior and provide guidance for this technology. Additionally, another module was built without a green roof for control purposes. The indoor and outdoor air temperatures and humidities, soil moistures, and temperatures between green roof layers were recorded in a tropical climate in summer. The behavior was similar between the different thicknesses for the whole period but with significant differences in the indoor temperature amplitudes (13.8 °C for the thinner substrate, 9.7 °C for the thicker one, and 38.7 °C for the bare roof). This study also revealed considerable heat conduction between the side walls and the slab, which resulted in an upward heat flow to the substrate during a day with a clear sky, which is the opposite of what is observed in conventional roofs. During the night and rainy periods, temperatures tend to become closer between the roof's layers when the substrate dissipates the energy absorbed throughout the day.

**Keywords:** green roof; shipping container; thermal performance; sustainable solution

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## 1. Introduction

With the growing world population, housing has become a major urban challenge worldwide. Unfortunately, green areas, which are crucial for human well-being, have increasingly been supplanted by urban development, creating additional issues that make it difficult to invest in green infrastructure. Some sustainable solutions have emerged to address the effects of the growth of unstructured communities, such as repurposing shipping containers for use in civil construction. Utilizing containers in civil construction is a sustainable option that has some benefits. It provides a solution for disposing of outdated materials that would otherwise take up natural space. Additionally, it minimizes the waste produced during conventional masonry and may reduce costs during construction.

Green roofs are gaining popularity in urban architecture due to their numerous benefits. They can help create comfortable temperature zones, lower energy costs by reducing the need for air conditioning, retain rainwater, improve air quality, mitigate heat islands, and promote interaction with local flora and fauna [1].

A green roof is considered to be any covering of a building with vegetation growing on its surface. The process of constructing a green roof involves the application of overlapping layers that support the healthy development of plants. These layers include the waterproofing membrane, drainage layer, filter layer, anti-root and protection layer, and substrate for establishing the vegetation [2]. Green roofs are either extensive or intensive. Extensive roofs have soil less than 20 cm thick and use low-maintenance plants. They can be installed on sloping roofs and cost less but have a lower load capacity. Intensive roofs have a thicker soil layer and can support larger vegetation, but they require a more robust building structure and are more expensive [3,4].

This study proposes analyzing the impact of different substrate thicknesses on green roofs' thermal performance. The thickness of the substrate, as well as its composition and humidity, can contribute to the efficiency and energy savings [4,5]. A greater substrate thickness can lead to a higher water storage capacity for vegetation and allow for the selection of larger plant species. However, the structural constraints of the construction limit the thickness that can be used [5].

There are several recent studies in the scientific literature regarding the thermal behavior of green roofs. Some researchers have constructed experimental modules to test different configurations, while others have analyzed the use of green roofs in existing buildings. Typically, sensors are used to measure the temperatures and humidities of the external and internal air, the temperatures of some layers of the green roof, the meteorological conditions, and the soil moisture.

Some studies have compared the thermal performance of traditional and green roofs, showing their significant effect on reducing internal temperature and heat gain on hot days. Parizotto and Lamberts [6] investigated the thermal performance of a green roof over an experimental single-family residence and found that the green roof reduced the heat gain by 92% and 97% compared with ceramic and metal roofs during a hot period, respectively, and Kostadinovic et al. [7] found a reduction in conductive heat flow of 57% for a green roof with mineral wool substrate installed on a school building. Lin et al. [8] analyzed extensive green roofs in urban areas and showed that green roofs can reduce the indoor temperature's rise by 8% during the day, while Bevilacqua et al. [9] found that, on average, green roofs in a university building can reduce indoor temperatures by 2.3 °C.

Other studies have explored the impact of the green roof substrate thickness on thermal performance, as well as this work's proposal. They showed that the substrate thickness can significantly affect the regulation of room temperature. He et al. [10] compared green roofs with 4, 8, and 12 cm soil depths in experimental modules with cold and conventional roofs. During the summer, the three soil depths showed a decrease in the maximum temperature underneath the substrate by 20.5, 21.2, and 21.7 °C in relation to the conventional roof, respectively. Their findings are similar to the results of Tam et al. [11], who analyzed green roofs with thicknesses of 15, 10, and 5 cm, reaching slab temperatures of 19.2, 20.8, and 21.1 °C, respectively, and similar vegetation temperatures between the experimental modules. Eksi et al. [12] compared a roof with pre-vegetated sedum mats (5 cm deep) with a deeper roof (20 cm deep) planted with herbs and grasses. The thinner soil experienced more extreme fluctuations in temperatures. Among the soil thicknesses tested by Zhang et al. [13] (10, 15, and 20 cm), 20 cm was the most efficient, saving from 30.2% to 56.4% of the energy consumption throughout the year. With a green roof combined with a 25 mm thermal insulation board, according to Yang et al. [14], the thickness of the substrate, ranging from 10 to 20 cm, has little impact on the roof's thermal performance.

In addition to the thickness, the substrate and vegetation composition can influence the green roof's thermal performance. For instance, commercial growing substrate (without aggregates) provides better cooling than mixed substrates [15], and taller plants can also contribute to better cooling [16]. Another important factor is the substrate moisture. In general, higher moisture levels help maintain lower temperatures, as verified by Chen [17] in experimental modules and by Jim and Peng [18] in the green roof of a train station. Zheng et al. [19] investigated the temporal evolution of green roofs during a severe drought and found that the average heat transfer to the interior space through the green roof compared with the bare roof decreased from 81% to 40% until the plants wilted with the substrate's drying.

This proposal shares similarities with some discussed works regarding the experimental modules used. These works had modules with similar dimensions and a control module with a bare roof, and they explored different green roof configurations. In addition to these, Coma et al. [20] conducted experiments in experimental modules using an air conditioning system, showing that the green roof modules consumed less electricity during hot periods while the heating system consumed more electricity during cold periods. Collins et al. [21]

analyzed how green roofs affect the energy performance of buildings in cold climate conditions, and Wang et al. [22] verified from experimental modules and simulations that a green roof with water storage can reduce the average temperature of a room in summer by 1–2 °C. Studies also used experimental modules to evaluate the performance of green roofs with photovoltaic panels, showing an 18% increase in energy yield [23] and a reduction in the internal temperature of 4.3 °C in a hot region [24].

Currently, several container models are available on the market. The International Organization for Standardization standardizes their characteristics and dimensions. With a useful life of 10–20 years, depending on the type of cargo it transports, the container has been seen as a sustainable solution in civil construction [25]. In architecture, the most used ones are those in the 20 and 40 foot dry categories. Their external dimensions are 2.44 m wide, 2.59 m high, and 6.06 or 12.92 m long. In order to make a shipping container livable, some modifications are necessary. The foundation is typically constructed with concrete floating slabs or footings. The container itself has a plywood floor that needs to be treated, and a subfloor can also be added. The container's original roof can be used, or another one can be added to the top to improve thermal comfort. Openings for doors and windows must be made. Thermal insulation is a major requirement for making a shipping container habitable since steel has high thermal conductivity. The exterior coating can be made with materials that help with insulation, such as ceramic paints. Inside, it includes insulating material, such as polyurethane foam, supported by a wooden structure and interior wall cladding with materials such as plasterboard [26].

This study aims to analyze how green roofs regulate temperature when used on shipping containers that have been converted into buildings. The analysis involves experimenting on container modules with substrates of varying thicknesses. As far as we know, little existing scientific research explores the thermal behavior of green roofs when applied to containers.

The findings of this study can provide data on the use of alternative thermal insulation solutions in the construction technology of metallic containers. The variation in the thickness of the substrate can contribute to a design decision to maintain thermal comfort regarding the cost and building structure.

## 2. Materials and Methods

Five experimental modules were constructed to evaluate the effect of the substrate thickness on green roofs' thermal performance. Four modules featured green roofs with varying substrate thicknesses (1–4). The fifth module was utilized as a control (without a green roof) for comparative analysis (details in Table 1). The thickness of the roofs used in the study ranged from 8 to 20 cm, with a substrate thickness from 4 to 16 cm. These thicknesses were chosen to cover the entire range of extensive roof usage, from the minimum required to grow vegetation roots to the maximum typically considered in this category. Additionally, the study included two roofs with intermediate thicknesses to observe the thermal behavior across the entire range.

**Table 1.** Individual characteristics of module roofs.

| Module | Green Roof | Substrate Thickness (mm) | Total Thickness (mm) |
|---|---|---|---|
| 1 | yes | 40 | 80 |
| 2 | yes | 80 | 120 |
| 3 | yes | 120 | 160 |
| 4 | yes | 160 | 200 |
| 5 | no | 0 | 0 |

The prototypes were designed to highlight the heat flow through the roof. Thermal insulation was applied to the lateral walls and floor to reduce heat transfer through other walls and into the ground. Temperature and moisture sensors were strategically placed to measure the roof layers' temperature gradients and the variations in temperature and relative humidity of the indoor and outdoor air above the vegetation.

*2.1. Features of the Experiment Site*

The experiment was conducted on the campus of Centro Universitário FEI in the city of São Bernardo do Campo. The location's coordinates are latitude 23°43′ S and longitude 46°34′ W at an altitude of 803 m. The place is on triangular terrain at the top of a slope, as shown in Figure 1.

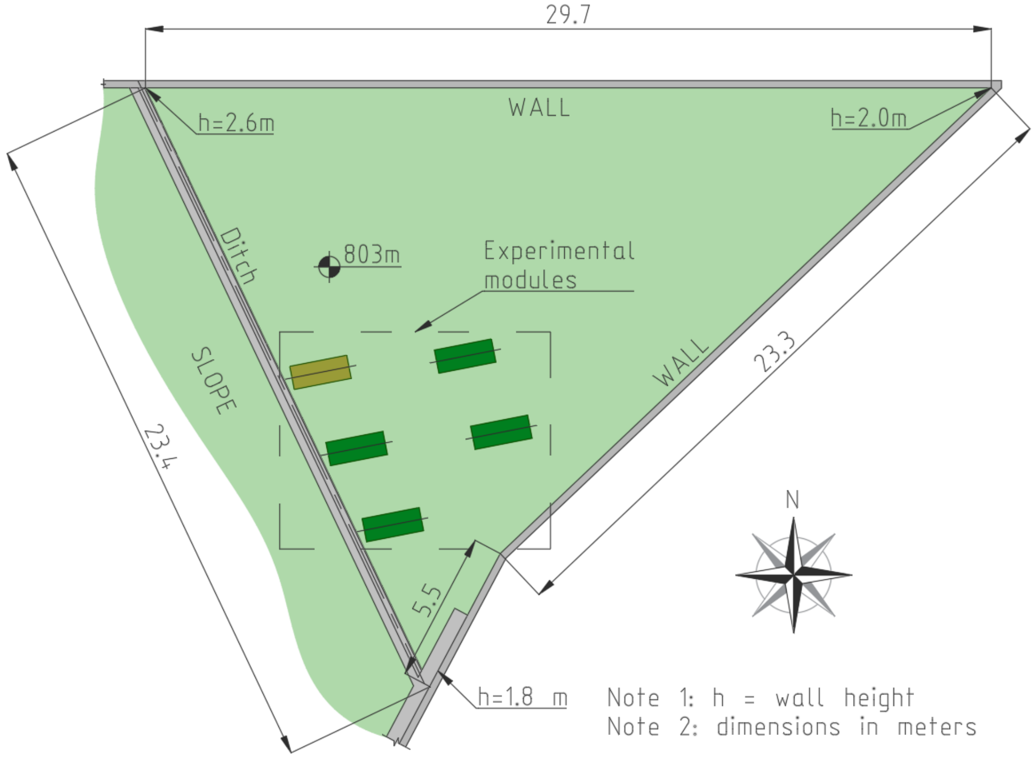


**Figure 1.** Location of experimental modules in the field.

*2.2. The Experimental Modules*

The modules were built on a 1:3 reduction scale, simulating 20 foot containers to approximate their constructive characteristics to those used in a building (Figure 2). The interior walls and floors of the modules were covered with thermal insulation, while the ceilings were left uncovered. Expanded polystyrene sheets, also known as Styrofoam, with a 30 mm thickness were fixed onto the internal surfaces. Side supports of 10 mm thick plywood sheets were used to support the layers of the green roof around the entire perimeter of the container.

Table 2 and Figure 3 show the materials and thicknesses of each layer of the green roofs installed in modules 1–4. The substrate used was commercial peat topsoil (Suzan Humus Company, Suzano, SP, Brazil) fertilized with earthworm humus aggregated to organic compost.

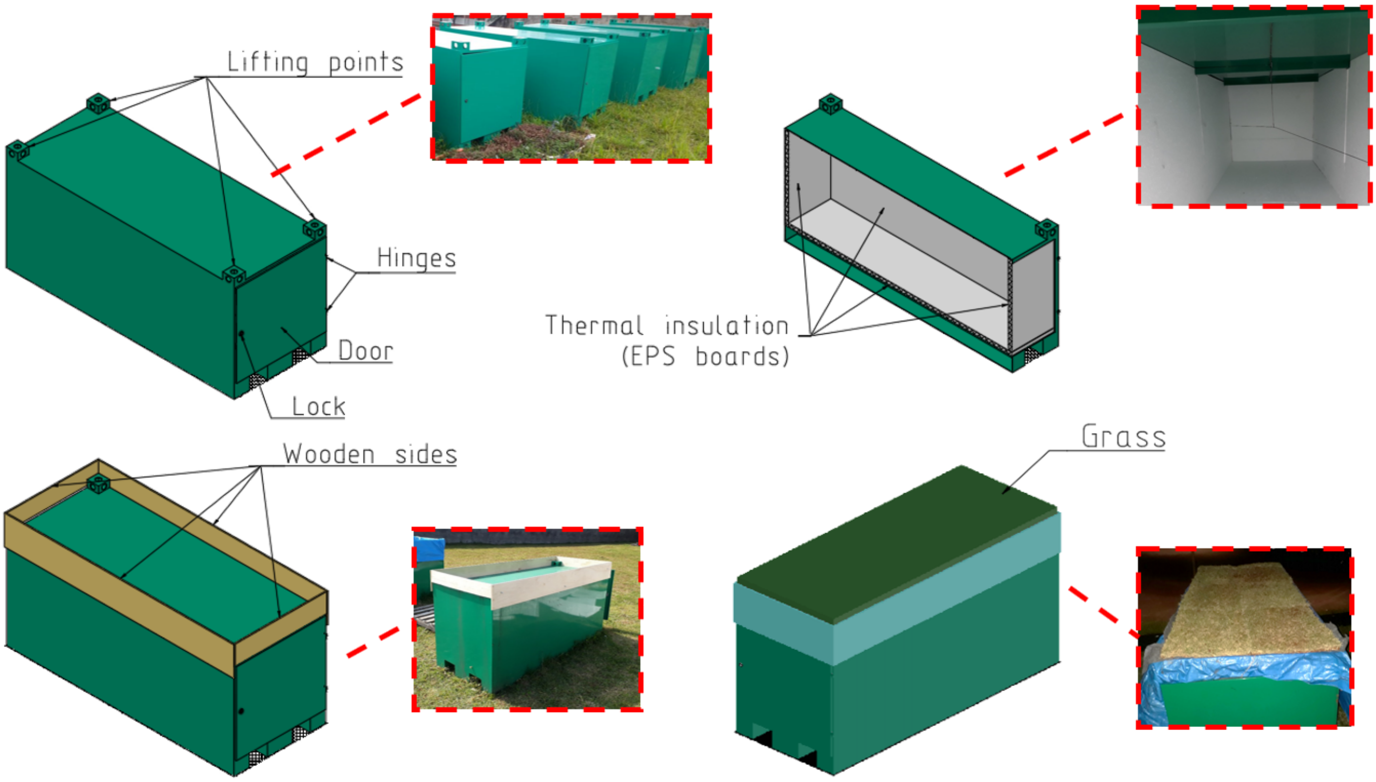


**Figure 2.** Constructive details of the experimental modules.

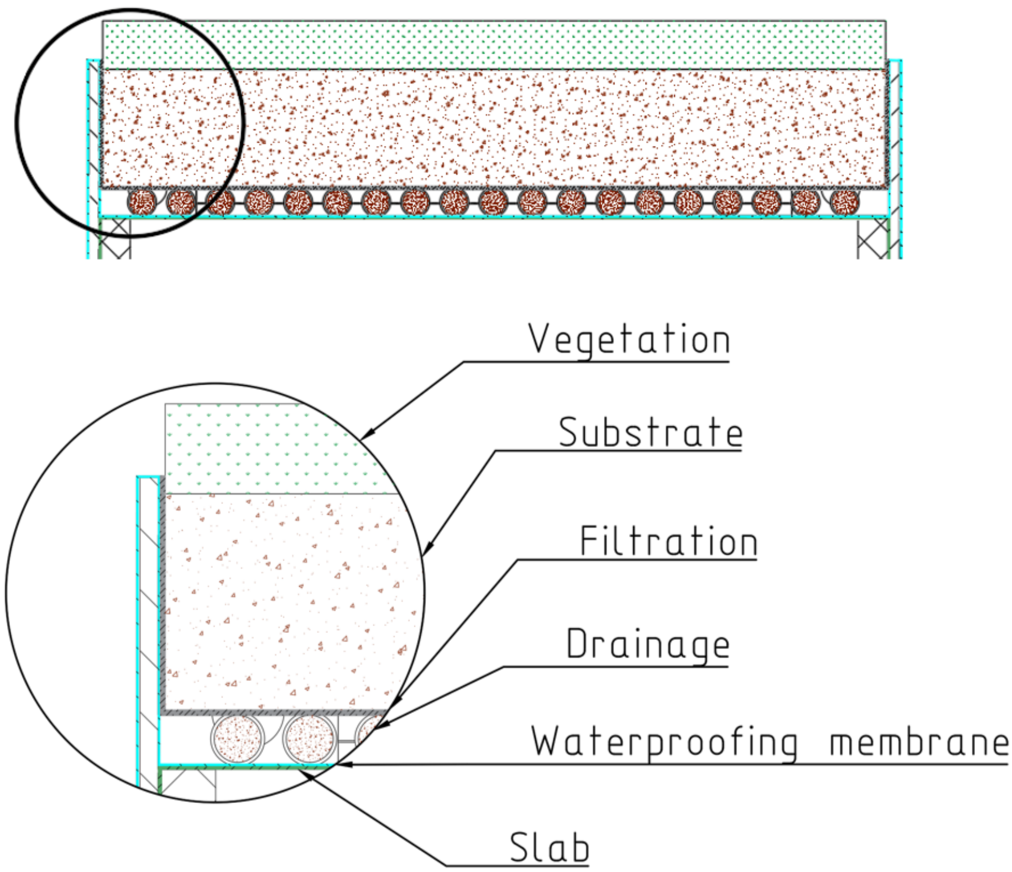


**Figure 3.** Section details of the layers of the green roofs.

**Table 2.** Composition of the layers of the green roofs.

| Layer | Thickness | | | |
|---|---|---|---|---|
| | **Module 1** | **Module 2** | **Module 3** | **Module 4** |
| Vegetation (Emerald Zoysia grass) | 1 cm | 1 cm | 1 cm | 1 cm |
| Substrate (topsoil) | 4 cm | 8 cm | 12 cm | 16 cm |
| Filtration (geotextile fabric) | ≈2 mm | ≈2 mm | ≈2 mm | ≈2 mm |
| Drainage (expanded clay) | 3 cm | 3 cm | 3 cm | 3 cm |
| Waterproofing membrane (polyethylene tarp) | 150 µm | 150 µm | 150 µm | 150 µm |
| Slab (carbon steel sheet) | 2 mm | 2 mm | 2 mm | 2 mm |
| Total | 8 cm | 12 cm | 16 cm | 20 cm |

Six temperature sensors were set up in each prototype to monitor the indoor air conditions. Three sensors were used to measure the dry-bulb temperatures, whereas the other three were used for the wet-bulb temperatures. Three sensors were installed between the slab and the waterproofing membrane, three were set up between the geotextile fabric and the substrate, and three were placed over the vegetation. Furthermore, six more sensors were positioned 10 cm above the five prototypes to measure the influence of the roof on the external air behavior. These six sensors were also equally divided to measure the dry-bulb and wet-bulb temperatures. All temperature data were obtained from NTC-type thermistors (10 kΩ, 3 mm in diameter, MF52 model). Additionally, three capacitive soil moisture sensors were placed inside the substrate of each green roof (Figure 4).

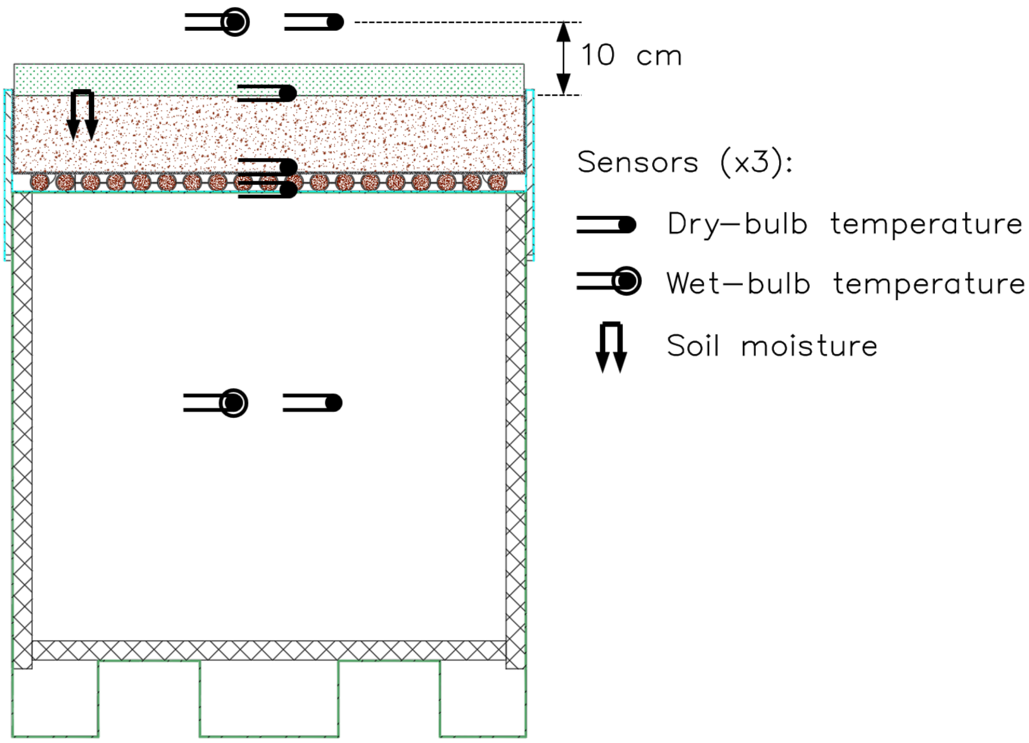


**Figure 4.** Instrumentation position.

Temperature and soil moisture measurements were recorded periodically using an acquisition system developed for this work. The system was powered by a battery-charged photovoltaic cell.

### 2.3. Test Plan

The data acquisition system monitored the experiment over 48 h (29–30 November 2018). The experiment was planned to take place on typical summer days in the region's tropical climate with high-temperature characteristics, thus representing more thermal discomfort in indoor environments. These days were chosen because they were two consecutive days with similar performance and without any failure in the acquisition system or solar energy supply.

After assembling and identifying the thermistors, calibration data were collected, using as a reference a platinum resistance thermometer (Isotech, model 909) installed together with a precision multimeter (HP, model 3457A). The tests were carried out under four different temperature conditions (0.0, 22.5, 42.5, and 73.0 °C), reading the resistances of the reference thermometer and the thermistors simultaneously. The coefficients of each NTC thermistor were adjusted by the least squares method. The error limit found after calibration for all the thermistors was 0.8 °C. The soil moisture sensors were adjusted to the condition of total soil saturation. Their uncertainties depended on several factors that could influence the electrical behavior of the soil. Still, in this work, they helped compare the moisture levels between modules since the soils were the same.

Readings were taken every 10 min. At that moment, the system collected a sample of 10 points for 1 min, allowing the average and standard deviation for that minute to be obtained. As there were three sensors at each location, each point had a sample of 30 measurements.

## 3. Results and Discussion

The two days of measurement (29–30 November 2018) had similar climatic behavior, with high outdoor air temperatures exceeding 30 °C throughout the day. There was significant rainfall in the afternoon on both days. On the first day, the rainfall occurred between 2:00 p.m. and 6:00 p.m., and on the second day, it was between 3:30 p.m. and 7:00 p.m.

Figure 5 shows the outdoor air temperature over the two days of measurement. The curve surrounding the temperature line represents the standard deviation of the 10 measurements taken at that moment. The graph also shows the global solar irradiation data obtained from a reference meteorological station owned by the environmental company of the state of São Paulo, located 4.5 km away from the site. The gray bands in the figure indicate the periods of rain.

Figure 6 presents the temperature behavior in three modules: the one with the lowest substrate thickness (4 cm), the one with the highest substrate thickness (16 cm), and the one without a green roof.

Figure 7 displays the temperature variation of the external air, vegetation, substrate, slab, and internal air in the four modules with green roofs. The curves filled around the temperature curves indicate the standard deviation of the measurements at each moment. Additionally, Figure 8 shows the behavior of the outdoor air humidity (10 cm above the vegetation), indoor air humidity, and substrate humidity for the same four modules.

Table 3 shows data about the general behavior of the modules throughout each day. The time delay was determined by the difference between the times at which the maximum internal air temperature and the maximum external air temperature were reached. The decrement factor is the ratio between the temperature amplitude of the internal air and the external air, with the temperature amplitude being the difference between the highest and lowest temperature of a day.

Table 4 shows the average temperature and humidity results for some representative time intervals during the night (between 12:00 a.m. and 4:00 a.m.), a day with a clear sky (between 10:00 a.m. and 2:00 p.m.), and a rainy period (between 4:00 p.m. and 6:00 p.m.). These measurements were meant to assist in explaining the transfer of energy between the roof layers and the surrounding air.

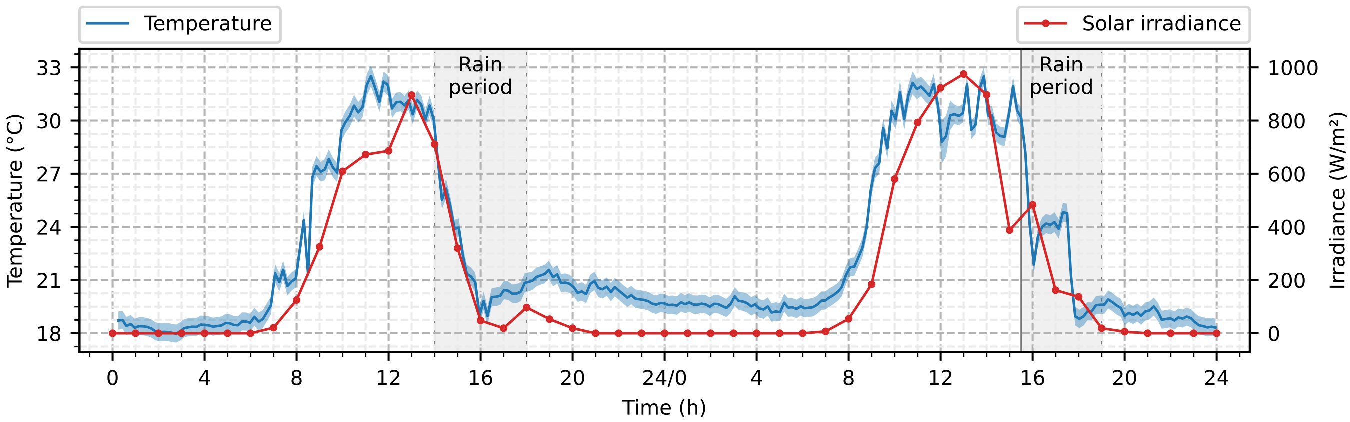


**Figure 5.** Outside air temperature, solar irradiation, and periods of rain on measurement days. The filled curve represents the standard deviation.

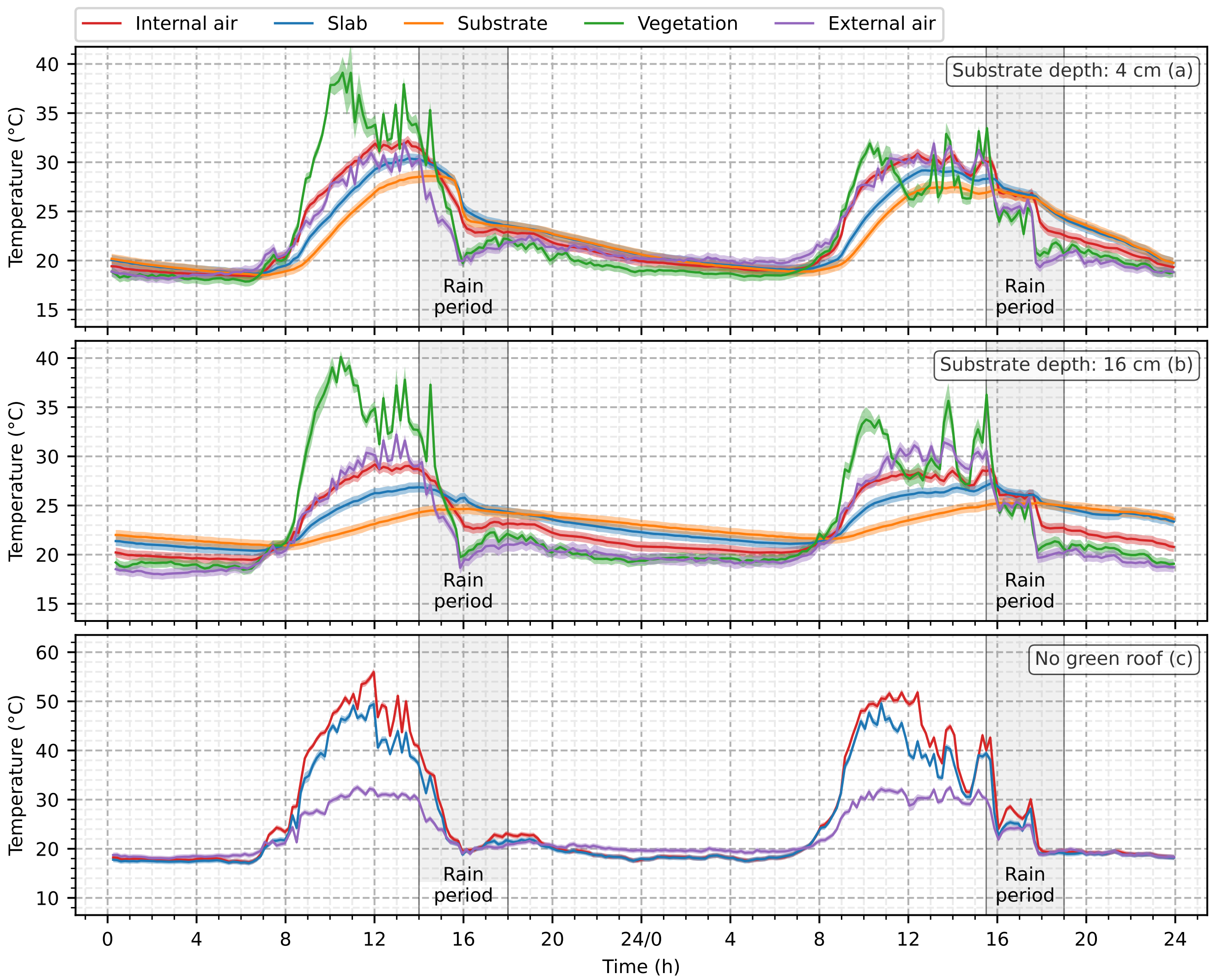


**Figure 6.** Temperature variation of the roof and air layers for the modules with substrate depths of 4 cm (**a**) and 16 cm (**b**) and for the module without a green roof (**c**). The filled curve represents the standard deviation.

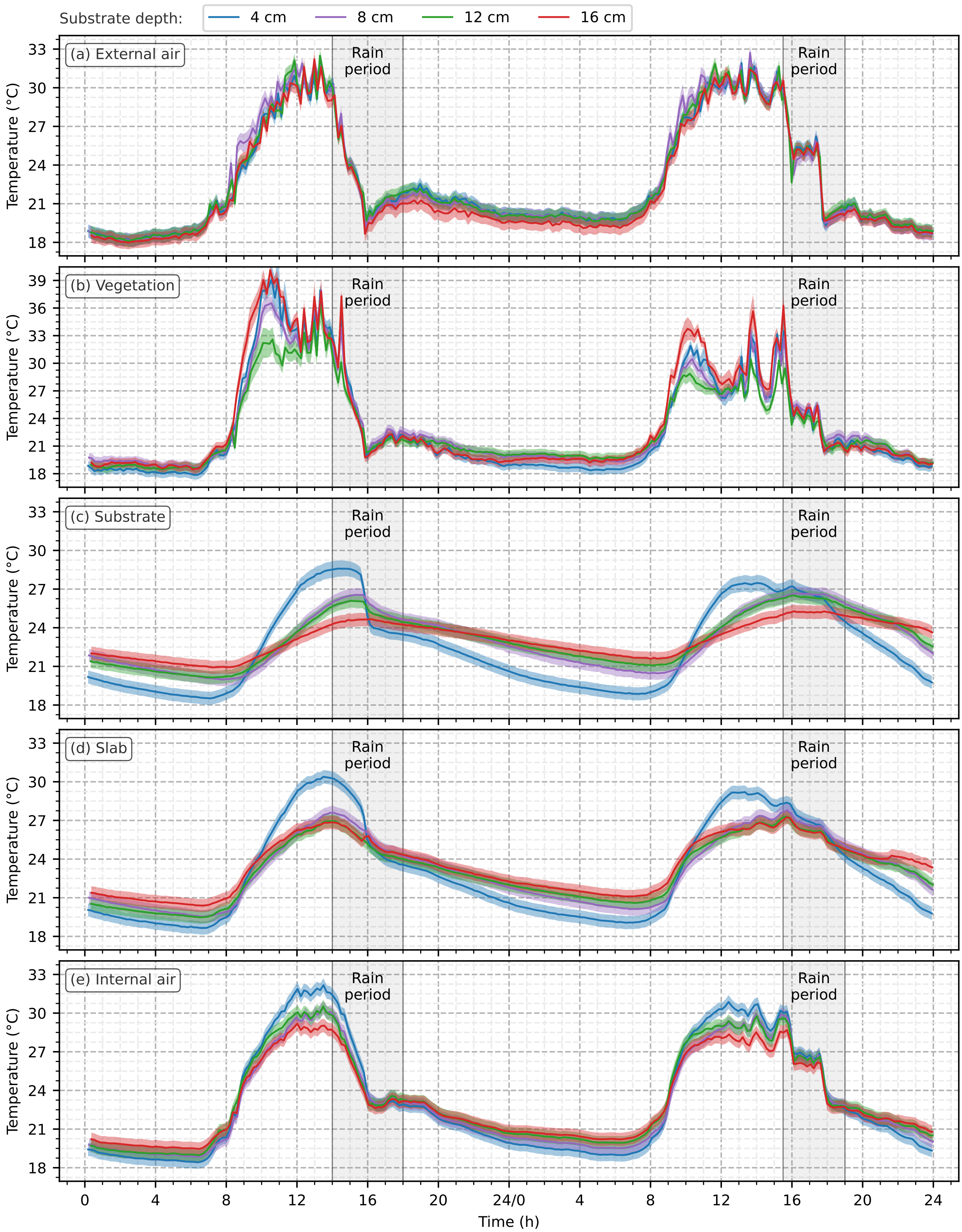


**Figure 7.** Variation in external air (**a**), vegetation (**b**), substrate (**c**), slab (**d**), and indoor air (**e**) temperatures for modules with different green roof thicknesses. The filled curve represents the standard deviation.

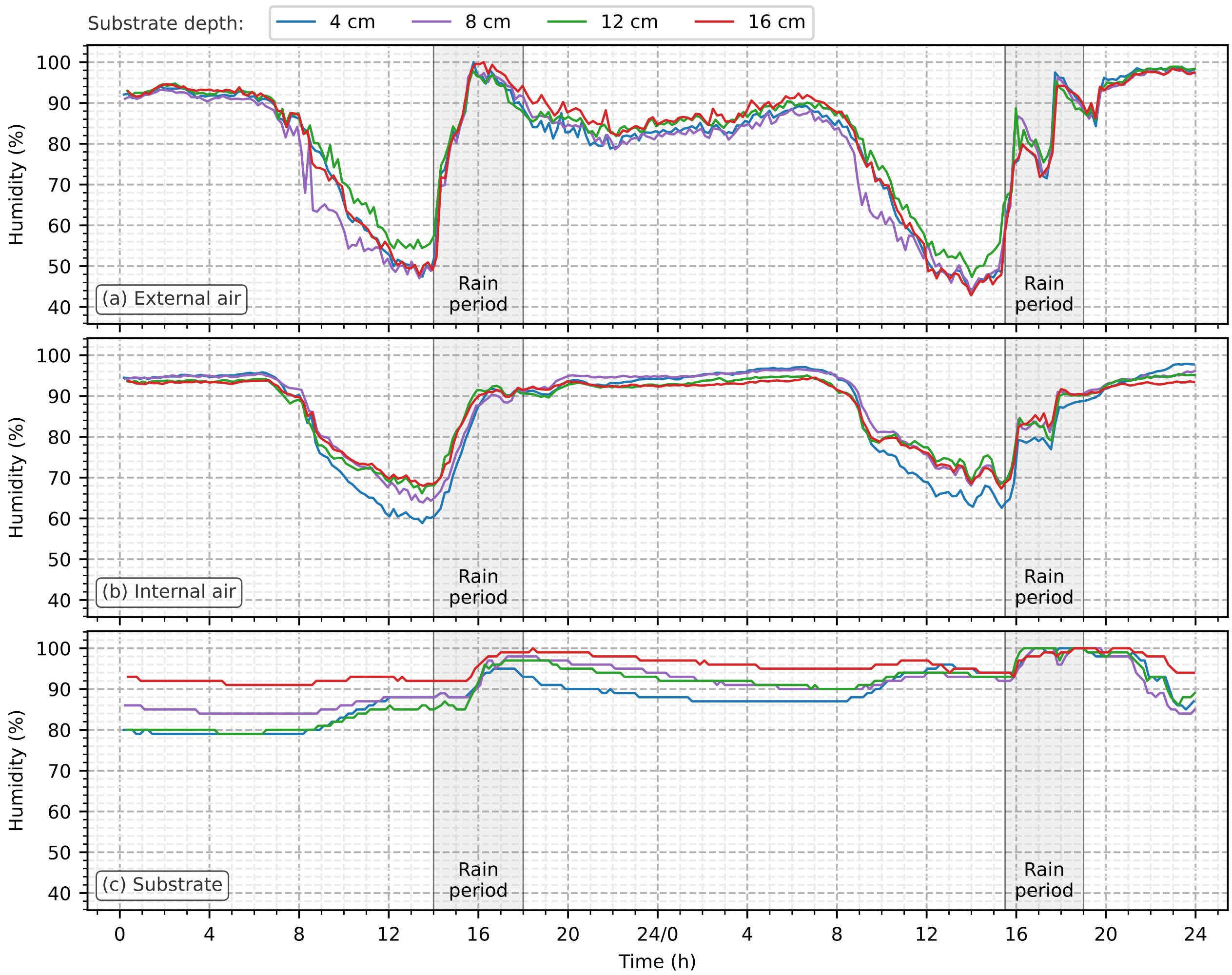


**Figure 8.** Variation of outdoor air (**a**), indoor air (**b**), and substrate (**c**) humidity for modules with different green roof thicknesses.

**Table 3.** Description data from temperature results on both days.

| **Day** | | **First** | | | | | **Second** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Substrate Thickness** | | **4 cm** | **8 cm** | **12 cm** | **16 cm** | **Bare** | **4 cm** | **8 cm** | **12 cm** | **16 cm** | **Bare** |
| Maximum temperature (°C) | External air | 32.0 | 31.0 | 32.5 | 32.2 | 32.5 | 31.9 | 32.7 | 31.9 | 31.4 | 32.5 |
| | Vegetation | 39.1 | 37.9 | 36.4 | 40.1 | - | 33.5 | 33.6 | 30.4 | 36.3 | - |
| | Substrate | 28.6 | 26.6 | 26.1 | 24.7 | - | 27.5 | 26.7 | 26.5 | 25.3 | - |
| | Slab | 30.4 | 27.6 | 27.0 | 26.9 | 49.4 | 29.2 | 27.8 | 27.3 | 27.3 | 49.6 |
| | Internal air | 32.2 | 30.4 | 30.5 | 29.2 | 56.0 | 30.9 | 29.9 | 29.8 | 28.7 | 51.8 |
| Minimum temperature (°C) | External air | 18.1 | 18.1 | 18.1 | 18.0 | 18.0 | 18.8 | 18.6 | 18.9 | 18.7 | 18.3 |
| | Vegetation | 17.9 | 18.7 | 18.5 | 18.5 | - | 18.4 | 19.1 | 19.1 | 19.0 | - |
| | Substrate | 18.5 | 20.0 | 20.1 | 20.9 | - | 18.9 | 20.5 | 21.1 | 21.6 | - |
| | Slab | 18.7 | 19.5 | 19.5 | 20.4 | 17.1 | 19.1 | 20.1 | 20.6 | 21.1 | 17.5 |
| | Internal air | 18.4 | 18.9 | 19.0 | 19.5 | 17.2 | 19.0 | 19.5 | 19.9 | 20.2 | 17.6 |
| Temperature amplitude (°C) | External air | 13.8 | 13.7 | 14.4 | 14.2 | 14.5 | 13.2 | 14.1 | 13.0 | 12.7 | 14.1 |
| | Vegetation | 21.3 | 19.2 | 18.0 | 21.7 | - | 15.1 | 14.5 | 11.3 | 17.3 | - |
| | Substrate | 10.1 | 6.6 | 6.0 | 3.7 | - | 8.6 | 6.2 | 5.4 | 3.7 | - |
| | Slab | 11.7 | 8.1 | 7.5 | 6.5 | 32.3 | 10.1 | 7.7 | 6.7 | 6.1 | 32.1 |
| | Internal air | 13.8 | 11.5 | 11.6 | 9.7 | 38.7 | 11.9 | 10.4 | 9.8 | 8.5 | 34.3 |
| Time lag (h) | | 0.80 | 0.72 | 0.82 | 0.78 | 0.73 | 1.63 | 1.62 | 1.63 | 1.67 | 0.72 |
| Decrement factor | | 0.95 | 0.79 | 0.80 | 0.67 | 2.66 | 0.84 | 0.73 | 0.69 | 0.60 | 2.42 |

**Table 4.** Average temperature and humidity during some periods.

| **Day** | | | **First** | | | | | **Second** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Substrate Thickness** | | | **4 cm** | **8 cm** | **12 cm** | **16 cm** | **Bare** | **4 cm** | **8 cm** | **12 cm** | **16 cm** | **Bare** |
| Night period (12:00 a.m.–4:00 a.m.) | Temperature (°C) | External air | 18.4 | 18.4 | 18.4 | 18.2 | 18.3 | 20.1 | 20.1 | 20.0 | 19.5 | 19.7 |
| | | Vegetation | 18.4 | 19.3 | 18.8 | 19.1 | - | 18.8 | 19.8 | 20.1 | 19.6 | - |
| | | Substrate | 19.6 | 21.3 | 21.0 | 21.7 | - | 19.9 | 21.9 | 22.3 | 22.6 | - |
| | | Slab | 19.5 | 20.5 | 20.1 | 21.0 | 17.5 | 20.0 | 21.2 | 21.5 | 21.8 | 18.2 |
| | | Internal air | 18.9 | 19.3 | 19.3 | 19.8 | 17.9 | 19.6 | 20.1 | 20.5 | 20.6 | 18.3 |
| | Humidity (%) | External air | 92.5 | 92.0 | 93.2 | 93.2 | 94.4 | 83.6 | 82.7 | 85.6 | 86.5 | 89.5 |
| | | Internal air | 94.7 | 94.7 | 93.6 | 93.3 | 98.5 | 95.0 | 95.1 | 93.4 | 92.8 | 98.7 |
| | | Soil | 79.4 | 85.1 | 79.7 | 92.2 | - | 87.4 | 92.4 | 92.0 | 96.4 | - |
| Clear sky day period (10:00 a.m.–2:00 p.m.) | Temperature (°C) | External air | 29.5 | 30.3 | 29.9 | 29.5 | 31.0 | 29.8 | 30.4 | 30.1 | 29.7 | 30.9 |
| | | Vegetation | 35.2 | 34.2 | 32.0 | 35.3 | - | 29.1 | 28.7 | 27.6 | 30.6 | - |
| | | Substrate | 26.3 | 23.5 | 23.6 | 23.2 | - | 25.9 | 23.9 | 23.9 | 23.5 | - |
| | | Slab | 28.4 | 25.6 | 25.6 | 26.0 | 43.8 | 27.7 | 25.6 | 25.5 | 26.0 | 42.1 |
| | | Internal air | 30.7 | 28.9 | 29.4 | 28.3 | 48.5 | 29.8 | 28.5 | 28.8 | 27.9 | 47.3 |
| | Humidity (%) | External air | 54.6 | 52.1 | 59.7 | 54.5 | 60.8 | 54.6 | 52.7 | 59.3 | 54.0 | 60.7 |
| | | Internal air | 63.2 | 69.3 | 70.2 | 71.0 | 39.8 | 69.4 | 75.2 | 76.6 | 75.0 | 42.1 |
| | | Soil | 86.7 | 87.4 | 84.9 | 92.5 | - | 94.3 | 93.0 | 93.8 | 95.8 | - |
| Rainy period (4:00 p.m.–6:00 p.m.) | Temperature (°C) | External air | 21.0 | 21.2 | 21.5 | 20.7 | 20.6 | 24.2 | 24.0 | 24.1 | 24.3 | 23.2 |
| | | Vegetation | 21.6 | 22.0 | 21.4 | 21.3 | - | 23.8 | 24.6 | 23.5 | 24.0 | - |
| | | Substrate | 23.7 | 24.8 | 24.5 | 24.2 | - | 26.6 | 26.6 | 26.3 | 25.2 | - |
| | | Slab | 24.1 | 24.4 | 24.0 | 24.4 | 20.9 | 26.9 | 26.7 | 26.2 | 26.2 | 24.2 |
| | | Internal air | 23.0 | 23.0 | 23.0 | 22.9 | 21.6 | 26.4 | 26.3 | 26.1 | 25.8 | 26.4 |
| | Humidity (%) | External air | 93.8 | 90.8 | 89.8 | 93.0 | 95.5 | 80.1 | 81.9 | 82.1 | 78.1 | 89.0 |
| | | Internal air | 90.8 | 91.0 | 91.1 | 91.6 | 93.3 | 80.0 | 83.6 | 83.3 | 84.4 | 99.4 |
| | | Soil | 94.4 | 96.9 | 96.2 | 98.7 | - | 98.7 | 98.4 | 99.5 | 98.0 | - |

### *3.1. Overall Performance*

The temperature profiles of all prototype green roofs were similar. During the night, the temperatures were closer to each other, whereas during the day, they were more distant. This proximity was also noticed during rainy periods, when there was a significant drop in the external air temperature and the incidence of solar radiation. The prototype without a green roof also exhibited similar behavior but with larger temperature fluctuations.

The prototypes with green roofs tended to have temperature profiles of the layers that were closer to each other when there was less substrate. This is because lower thermal capacities result in faster temperature variations, leading to greater temperature amplitudes throughout the day. On the first and second days, the thinner substrate exhibited temperature ranges of 13.8 and 11.9 °C, respectively. The greatest substrate thickness showed a narrower range of 9.7 and 8.5 °C, respectively. The control module, which lacked a green roof, experienced a much wider temperature difference, reaching 38.7 and 34.3 °C on the first and second days, respectively.

During the first day, before the beginning of the rain period, the vegetation on the roof had the highest temperature due to the incidence of solar radiation on all the modules. Since the temperature of the vegetation was higher than that of the surrounding air, heat was transferred from the vegetation to the air. This heat transfer occurred through convection and long-wave radiation. In addition to these phenomena, there was an outflow of energy through vegetation evapotranspiration. At this time, the relative humidity of the air was lower than that of the soil. On the second day, the temperature difference between the vegetation and the external air was much smaller. Therefore, during this time, the dominant phenomena were solar incidence and energy loss through evapotranspiration.

Both on the first and second day, the temperature differences on the lower side of the substrate indicate that the heat flowed upward. The higher internal air temperature was caused by the heating of the metallic side walls from solar irradiation. Even though they were insulated on the inside, heat could still be conducted through the high thermal conductivity metal sheets.

For a green roof located on a conventional concrete structure, the temperature gradient usually occurs from the vegetation to the roof. There is a gradual temperature decrease due to the thermal resistance of the components [27] However, in a building designed by reusing containers, the walls and slabs are made of metallic material in direct contact. The thermal conductivity of this material is much higher than those of green roof materials. The study results have shown that there is a possibility of heat conduction from the lateral walls that receive direct solar radiation to the slab. This received heat was faster than the heat transfer through the green roof, whose materials had more thermal delays (Figure 9). The opposite was observed when the external temperature decreased due to rain or the nighttime period. In this case, heat conduction occurred from the slab to the walls, and the slab's temperature decreased faster than the substrate's temperature. It is worth mentioning that a drainage layer consisting of expanded clay and stagnant air established considerable thermal insulation between the substrate and the slab.

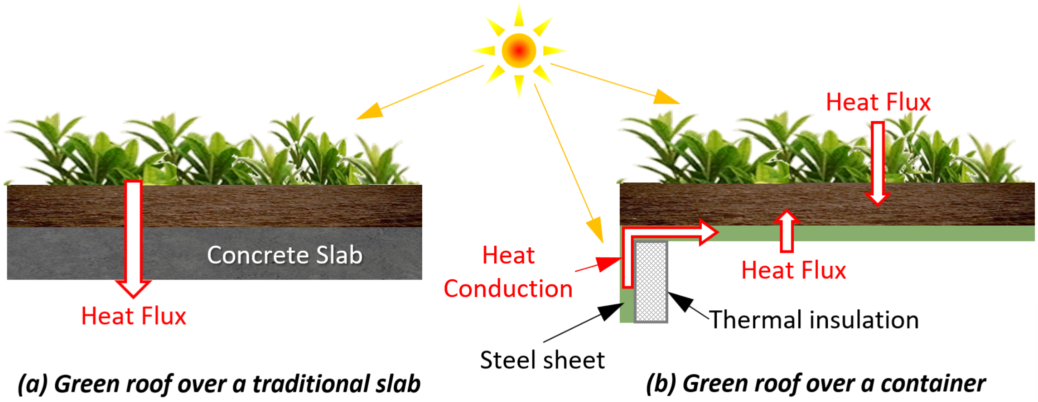


**Figure 9.** Heat fluxes on the green roof in a conventional structure and a container.

The time delay was not affected by the thickness of the substrate, despite the difference in the maximum temperatures. On the first day, the time variation ranged between 0.72 and 0.80 h for the four different thicknesses, while on the second day, it ranged between 1.62 and 1.67 h. These values were lower than those of a traditional green roof building, which takes more than 3 h [9,15]. This is intriguing since the substrate's mass variation was significant, and the heat transfer at its boundaries was similar. The distribution of heat through the metallic walls also seemed to affect the internal temperature of the module, with the maximum temperatures being reached at similar times.

The thickness of the substrate had a direct impact on the decrement factor, which was caused by a significant change in the internal air temperature. The roof with the lowest substrate thickness had the highest values (0.95 and 0.84) on the first and second day, respectively. However, the maximum and minimum temperatures of the module without a green roof had much greater differences, being around 2.5 times greater than the differences between the maximum and minimum temperatures of the external air. The decrement factor decreased significantly as the thickness increased, with values of 0.67 and 0.60 on the two days with the thickest substrate in the experiment. These values are higher than those found in traditional buildings with green roofs, which can be less than 0.2 [9,15], meaning that they are better at maintaining the internal temperature variation within a narrower range.

An increase in the external air and soil humidity followed the periods of rainfall, followed by a fast decrease in the roof temperature. The temperature decreased faster in the layers closer to the external air, such as the vegetation. The temperature of the vegetation was similar to that of the external air, while the internal air, slab, and substrate had slightly higher values that were close to each other. Running water greatly influenced the temperature of the green roof, making uniform the temperatures of its layers. The internal layers of the green roof took longer to reach the external temperatures due to their thermal inertia.

At night, without the incidence of solar radiation, the temperatures of the layers of the green roofs were close. It can be observed that the substrate's temperature was slightly higher, causing a gradual release of the substrate's internal energy to both the internal and external environment. The humidity in the air and substrate remained quite high during this period, and therefore the effect of evapotranspiration on energy exchange must be negligible.

Parizotto et al. [6] found that in a house, the maximum external surface temperatures for ceramic, metal, and green roofs (14 cm substrate thickness) were 57.5, 51.7, and 39.4 °C, respectively. These values are similar to the results of this study, which found that the control module had a maximum temperature of 49.6 °C, while the green roof had a maximum temperature of 40.1 °C. Their study found that the temperature amplitudes for the averages of the days measured were 14.4, 6.3, and 7.9 °C for the vegetation, substrate, and drainage layers, respectively. These values are also similar to the average values found in this study, which were 14.7 °C and 19.5 °C for the vegetation layer with thicknesses of 12 and 16 cm, 5.7 and 3.7 °C for the substrate layer, and 7.1 and 6.3 °C for the slab layer, which was close to the drainage layer.

The effect of rain on the thermal performance can be seen in the study by Lin et al. [8] on green roofs (10 cm substrate thickness) in two urban areas, with measurements above and below a conventional slab. The temperatures of the bare slabs in summer, compared with the green roof slabs, were higher during the day without rain (22.5 and 25.1 °C for both sites). During a rainy afternoon, the bare roof had only slightly higher temperatures (0.8 and 3.0 °C), as well as during the night without rain (0.9 and 0.1 °C). The results of the present study showed similar behavior, with large temperature differences between the slab of the control module and the green roofs (between 16.5 and 18.2 °C for both days and with 8 and 12 cm substrate thicknesses). There was also a slight difference between those temperatures during the rainy afternoon and the night without rain, but the green roof slab reached higher values than the bare roof by between 2.0 and 3.5 °C.

The results found were similar to those of other authors regarding the impact of a green roof's substrate thickness on performance. Tam et al. [11] found no significant temperature variation at noon for vegetation with substrate thicknesses of 5, 10, and 15 cm, ranging from 22.5 to 22.8 °C. The vegetation temperatures of this study (average between 10:00 a.m. and 2:00 p.m.) for modules with substrate thicknesses from 4 to 16 cm were between 32.0 and 35.3 °C for the first day and 27.6 and 30.6 °C for the second day, with no evident correlation with the thickness. On the other hand, the authors' temperature measurements on the internal slab showed a clear correlation with the thickness of the substrate. The values were 21.1, 20.8, and 19.2 °C for 5, 10, and 15 cm, respectively. In this study, the slab temperature values (average between 10:00 a.m. and 2:00 p.m.) for thicknesses of 4, 8, 12, and 16 cm were 28.4, 25.6, 25.6, and 26.0 °C on the first day, and 27.7, 25.6, 25.5, and 26.0 °C on the second day, respectively. The values of the slabs only had a significant difference between the smaller thicknesses, which did not occur with the conventional slab. This effect may be due to heat conduction through the container's metal walls, transferring heat between the slab and the environment via the side walls.

During the summer, He et al. [10] observed a decrease in the temperature difference between modules with and without green roofs measured under the substrate. This decrease was 20.5, 21.2, and 21.7 °C for the substrates with 4, 8, and 12 cm thicknesses, respectively. The modules with green roofs had minimum temperatures 3.4, 4.7, and 5.3 °C higher than the control modules for all three thicknesses. These values are quite similar to those in this study, with the temperature differences increasing significantly with an increasing thickness. The maximum temperature difference between the control module and the substrate for substrate thicknesses of 4, 8, 12, and 16 cm were 21.5, 22.9, 23.2, and 24.5 °C, respectively. The minimum temperature differences between them were 1.4, 3.0, 3.3, and 4.0 °C for the four thicknesses, respectively.

In the study by Eksi et al. [12], a green roof with a 5 cm thick substrate and pre-vegetated sedum mats experienced significant temperature fluctuations throughout the day, reaching up to 32.8 °C, in contrast to a roof with a 20 cm thick substrate and a mixture of diverse herbaceous perennials and grasses that reached 21.2 °C. According to the authors, the main reason for this difference was the substrate's thickness and the shade created by the herbaceous plants. In the present study, the surface temperatures of the vegetation were similar between the substrate thicknesses, with no apparent correlation. Higher vegetation should bring advantages in terms of thermal insulation of the green roof, with more shade and higher evapotranspiration rates. They also found that the temperature amplitude was significantly greater on the thinner substrate than on the thicker roof (27.5 and 9.0 °C, respectively). In this study, the maximum temperature amplitude was 10.1 °C for the 4 cm-thick substrate and 3.7 °C for the 16 cm-thick substrate. Although these values are lower, there is a significant difference between the different substrate thicknesses.

### *3.2. Slabs*

It was observed that the temperature amplitude of the slabs increased with a decreasing substrate thickness. On average, the maximum temperature variation in the module with the thinnest substrate was 10.9 °C, while for the thickest substrate, it was 6.3 °C. The temperature amplitudes of the slabs in modules 2 and 3 were 7.9 °C and 7.1 °C, respectively. Hence, it can be concluded that the temperature amplitude of the metallic slab is inversely proportional to the thickness of the substrate.

The temperature variation in modules 1–4 showed decreases of 66.0%, 75.6%, 78.0%, and 80.4%, respectively, when compared with the control module. The average temperature amplitude of the control module was 32.2 °C. Green roofs can considerably reduce the temperature of container roofs, regardless of their configuration.

During the day, temperature variations are most significant, and solar irradiation strongly impacts the lateral walls of the chambers, which conduct heat toward the slabs. However, it is worth mentioning that the substrate's action minimizes this effect. Due to its lower surface temperature and higher thermal capacity, the substrate can remove heat from the slab while receiving it through the lateral walls by conduction.

During periods of heavy rainfall, the temperature profiles of the slabs in all modules with a green roof were similar when the soil was close to saturation. At the onset of precipitation (before the soil became saturated), the modules with less substrate experienced a faster decline in temperature. Over two days of measurement, the average temperature amplitudes for modules 1–5 were 6.7 °C, 3.5 °C, 3.2 °C, 2.9 °C, and 20.5 °C, with average surface temperatures for modules 1–5 equal to 26.5 °C, 26.1 °C, 25.6 °C, 25.7 °C, and 24.0 °C, respectively. The control module showed the most significant temperature variations and the lowest temperatures compared with the others. Based on the analysis, it can be concluded that during rainy periods (when the soil was saturated), the extensive green roof contributed to the cooling of the slab, causing a delay in this process. However, the thickness of the substrate did not play a significant role in this regard, as indicated by the similarity of temperature profiles.

During the night, the temperature fluctuations observed in modules 1–5 were smaller and closer to each other. These modules exhibited maximum variations of 5.6 °C, 5.4 °C, 5.1 °C, 4.3 °C, and 4.7 °C, respectively. Once again, module 4, which had the highest thermal capacity, had the lowest temperature amplitude, with an average slab temperature of 22.2 °C. On the other hand, module 5 (the control) exhibited the second-lowest variation, with an average temperature of 18.3 °C, which was quite close to the average outside air temperature of 19.3 °C. Modules 1, 2, and 3 recorded average temperatures of 20.5 °C, 21.6 °C, and 21.6 °C, respectively. Based on the data, it is evident that the installation of a green roof contributes to keeping the temperature of the slab higher during the night. This is because during this period, the substrate is at a higher temperature, providing heat downward. Furthermore, the green roof was more effective with greater substrate thicknesses.

### 3.3. Substrate

According to the data shown in Figure 8, it can be concluded that the soil in all modules remained moist, ranging from 78% to 100% saturation. An increase in soil moisture of 5.1% was observed from the first to the second day due to accumulation after a rainy period. Regarding the average daily variations, the average values obtained from modules 1–4 were 88.6%, 91.3%, 91.6%, and 95.3%, respectively, demonstrating that the substrate layers with lower thicknesses had less capacity to retain moisture.

The temperature curves of the lower surface of the substrate layers showed similar behavior to the slabs but with smaller temperature amplitudes (9.3 °C, 6.4 °C, 5.7 °C, and 3.7 °C from modules 1 to 4, respectively), indicating that a greater substrate thickness promoted thermal stability in the building.

During the day, an inversion process began in the temperature values in all modules when the sun's rays began to fall on the prototypes at around 7:00 a.m. After 9:00 a.m., the profiles acquired an almost linear behavior, with higher slopes for smaller substrate thicknesses, demonstrating greater thermal inertia for larger masses.

During rainfall, a significant temperature change was observed in the thinner substrate. The average amplitudes recorded from prototypes 1 to 4 were 5.1 °C, 2.0 °C, 2.0 °C, and 1.0 °C, with the average temperatures being 26.0 °C, 26.1 °C, 25.8 °C, and 24.8 °C, respectively. When the soil was saturated, the temperatures of the substrate layers of modules 2, 3, and 4 were quite similar, while module 1 had lower values.

During the night, modules 1, 2, and 3 showed similar fluctuations, with temperature amplitudes of 6.0 °C, 5.7 °C, and 5.4 °C, respectively, while module 4 showed a maximum variation of 3.9 °C, indicating greater stability at night. Although module 1 had the highest temperature range, it had the lowest temperatures, with an average of 20.5 °C, while modules 2, 3, and 4 recorded averages of 22.3 °C, 22.4 °C, and 22.8 °C, respectively, showing the influence of the substrate thickness on heat exchange during the night.

### 3.4. Vegetation

The thermal behavior of the vegetation layers in the experimental modules showed significant variability, with no apparent influence from the substrate thickness, especially during the daytime.

The average temperature amplitudes for modules 1–4 were 18.2 °C, 16.8 °C, 14.4 °C, and 19.4 °C, with average temperatures of 23.0 °C, 23.5 °C, 22.9 °C, and 23.7 °C, respectively. Module 4 had the highest daily variation and surface temperature averages compared with the other modules. There was a significant drop in the maximum temperatures recorded on the second day, even though the global solar radiation rates were higher than those on the first day. This behavior may be attributed to the accumulation of soil moisture.

During periods of rainfall, the temperature curves of the four vegetated modules became similar, as the vegetation was in direct contact with the external environment. The average temperature amplitudes recorded during this period for modules 1–4 were 15.6 °C, 13.5 °C, 10.5 °C, and 17.5 °C, and the average surface temperatures for the modules were 24.2 °C, 24.4 °C, 23.4 °C, and 24.1 °C, respectively. Thus, in rainy periods, the thickness of the substrate does not significantly affect the surface temperatures of the vegetation layer.

At night, the thermal behavior of the vegetation layers on green roofs was quite similar across all modules. The maximum variations from modules 1 to 4 were 3.9 °C, 3.5 °C, 3.2 °C, and 3.3 °C, with average surface temperatures equal to 19.1 °C, 20.0 °C, 19.9 °C, and 19.6 °C, respectively. These temperatures were rather close to the average outdoor air temperature for the night, which was 19.3 °C.

### 3.5. Indoor Air

This topic is significant for discussion, as it aims to analyze the internal environmental conditions that directly affect the thermal comfort of potential building occupants, considering the solutions studied here. The prototypes did not establish ideal housing conditions due to the lack of openings and air circulation. However, these conditions allow a more complete analysis of the effect of green roofs with minimal influence from other energy exchange mechanisms.

The results indicate that there was a significant difference in the average temperature amplitudes among the experimental modules on both measured days. Module 1, which had a thinner substrate, showed the highest average daily variations at 12.8 °C. On the other hand, module 4, which had the thickest substrate, exhibited the smallest variations, with an average of 9.1 °C, a reduction of 3.7 °C or 29.0% when compared with module 1.

Modules 2 and 3 had average amplitudes of 10.9 °C and 10.7 °C and 4.6% and 14.5% reduction compared with prototype 1, respectively. These values showed a negligible difference between both modules. Compared with the control (prototype 5), which had an average daily temperature variation of 36.5 °C, modules 1–4 had reductions of 64.9%, 70.0%, 70.7%, and 75.1%, respectively. The estimated relative humidity of the indoor air showed average variations of 36.1%, 30.0%, 27.4%, 26.5%, and 67.3% from modules 1 to 5, respectively.

On the first day, the maximum temperature variations occurred, with module 5 registering the highest variation of 35.3 °C. The maximum outside air temperature was 32.5 °C at 11:14 a.m. At this time, module 4 exhibited the lowest temperature of 27.9 °C, a reduction of 4.6 °C or 14.2% compared with the outside temperature. The relative humidities for modules 1–5 were 65.1%, 72.3%, 72.1%, 73.4%, and 40.9%, respectively. The thicker substrates (like in module 4) had a more significant impact on the thermal behavior of the indoor air, exhibiting smaller temperature amplitudes and keeping the air with lower energy levels.

During rainfall, the indoor air temperatures of the vegetated modules displayed quite similar temperature profiles. These profiles indicated nearly identical temperatures when the substrate remained saturated. At the start of the rainfall, module 5 displayed a rapid temperature drop due to the fast heat exchange between the air and the wet slab. The other prototypes followed with the thinnest ones first until all of them converged to similar profiles in terms of saturation. The average temperature amplitudes recorded during the rainy periods for the two days of measurement were as follows: 8.6 °C, 7.0 °C, 7.1 °C, 6.0 °C, and 23.4 °C for modules 1–5, with average temperatures of 25.8 °C, 25.4 °C, 25.2 °C, 24.9 °C, and 25.5 °C, respectively. The estimates for the average indoor relative humidity provided similar results of 81.1%, 83.5%, 85.0%, 84.8%, and 84.5% for modules 1–5, respectively. These findings suggest that extensive green roofs, regardless of substrate thickness, do not significantly impact indoor air behavior during rainy periods, especially when there is soil saturation.

At night, when the external air temperature was at its lowest value, the roofs with thicker substrates influenced the internal air temperature more. However, this subtle influence resulted in a difference of less than 1 °C for the vegetated roofs. The average temperature variations for modules 1 to 5 were 4.3 °C, 4.1 °C, 4.2 °C, 3.6 °C, and 5.6 °C, and the average temperatures recorded were 19.9 °C, 20.3 °C, 20.5 °C, 20.8 °C, and 18.5 °C, respectively. The estimated average relative humidities for modules 1–5 were 94.7%, 94.8%, 93.4%, 93.0%, and 97.9%, respectively.

### *3.6. Outside Air*

Regarding the external air, which was measured at a vertical distance of 10 cm from the vegetation layer, the experimental modules exhibited only minor changes in temperature variation. Establishing any relationship with the substrate thicknesses under investigation was not possible. However, the relative humidity did slightly decrease across all experimental modules. Although there was a reduction in the daily temperature variations in all prototypes, the difference was less than 1 °C, indicating only a slight interference without any apparent relationship to the thickness of the substrate.

During the daytime without rain, module 5 had an average temperature of 27.8 °C, with a maximum temperature of 32.5 °C and a maximum variation of 12.5 °C. The relative humidity was 69.2%. For modules 1–4, the average temperatures were 26.8 °C, 27.3 °C, 26.9 °C, and 26.6 °C; the temperature amplitudes for each module were 11.7 °C, 12.7 °C, 12.2 °C, and 12.5 °C; the maximum temperatures for each module were 32.0 °C, 32.7 °C, 32.5 °C, and 32.2 °C; and the average relative humidities for each module were 65.0%, 62.2%, 68.9%, and 65.5%, respectively.

There seemed to be a slight difference in the temperature recordings between module 1 and the other modules. Module 1 showed slightly lower averages, amplitudes, and maximum values, decreasing under 1 °C. According to research by Eksi et al. [12], this slight difference might be due to evapotranspiration caused by the thinner substrate. The average relative humidity showed a significant increase in module 3 compared with the other modules, particularly on the first day of measurement. These results may be associated with the soil moisture, which showed lower values in this prototype than the others.

At night, the average temperature recorded for modules 1–4 were 19.7 °C, 19.7 °C, 19.7 °C, and 19.3 °C; the maximum temperature variations recorded were 4.1 °C, 3.5 °C, 3.8 °C, and 3.3 °C; the highest temperatures recorded for each module were 22.2 °C, 21.7 °C, 21.9 °C, and 21.3 °C; and the average relative humidities recorded for each module were 88.9%, 87.4%, 89.6%, and 90.5%, respectively. It was confirmed that all modules displayed similar thermal performance, with only minor differences. This can be attributed to the higher levels of relative humidity typically found in the external air, which helped minimize evapotranspiration's influence on the results.

## 4. Conclusions

An experimental analysis of the thermal performance of a green roof was conducted in representative modules of shipping containers with varying substrate thicknesses. The study found that using extensive vegetated roofs on buildings made from reused containers is a viable thermal solution. The main findings are as follows:

- Installing a green roof effectively decreased the difference between the highest and lowest indoor air temperatures over a day. In the absence of a green roof, the internal air temperatures varied by 38.7 °C, whereas for the smallest substrate thickness (4 cm), the variation was 13.8 °C, and for the largest thickness, it was 9.7 °C. Even with a thin substrate layer, the green roof had a significant impact, but a greater substrate thickness provided fewer temperature fluctuations throughout the day.
- The time delay for the green roofs was found to be similar regardless of the thickness of the substrate used. On the first day, the time delay was between 0.72 and 0.80 h, while on the second day, it was between 1.62 and 1.67 h. The decrement factor had a significant reduction with an increasing substrate thickness, decreasing from 0.95 to 0.67 between the thinnest and thickest substrate on the first day and between 0.84 and 0.60 on the second day.
- In contrast to a green roof over a conventional slab, the metallic walls of the container conducted heat, and the increase in the substrate thickness contributed to the removal of heat from the slab, promoting lower internal surface temperatures. This phenomenon alters the temperature gradient of the roof layers, modifying the heat flow directions. During the day, the substrate absorbed energy from the slab and vegetation and, at night, returned the energy.
- During rainy periods, the roof's influence the general thermal performance of this type of building was similar to that at nighttime, tending to maintain higher internal temperatures. However, when the soil was saturated with water, the substrate's thickness did not significantly affect the thermal behavior.

It was observed that the installation of a green roof, regardless of its thickness, can significantly enhance the thermal comfort of container occupants. However, based on the results, the thinnest substrate thickness tested may result in considerable temperature fluctuations and should be used only if necessary due to the building's structure. Opting for thicknesses starting at 8 cm and above is recommended, with a preference for larger options, which can effectively reduce internal temperature fluctuations and enhance overall thermal comfort.

One way to improve the performance of green roofs in containers is by using insulating materials on the outside of the metal walls to prevent heating. This can be achieved by using insulating materials, green walls, or a special covering such as ceramic painting. Another option would be to replace part of the metal sheet with insulating material or openings to avoid direct contact between the side walls and the slab.

This study has some limitations: tests were carried out on scaled modules and not in real situations; ventilation of the internal environment was not considered; and only typical summer days were analyzed.

In order to contribute to the topic, the following topics could be addressed to continue this work: studying solutions to reduce heat conduction from the walls to the slab; examining different types of vegetation in green covers used for containers suitable for cultivation; analyzing the influence of soil moisture on the thermal performance of green roofs applied in containers; measuring the energy performance of green roofs applied to containers using air conditioning systems; comparing the energy performance of buildings constructed with containers using conventional insulation and green roofing; observing seasonal thermal performance in green roofs applied to containers; and modeling and simulating green roofs applied to containers.

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## References

1. Besir, A.B.; Cuce, E. Green roofs and facades: A comprehensive review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 915–939. [CrossRef]
2. Cascone, S. Green roof design: State of the art on technology and materials. *Sustainability* **2019**, *11*, 3020. [CrossRef]
3. Berardi, U.; GhaffarianHoseini, A.; GhaffarianHoseini, A. State-of-the-art analysis of the environmental benefits of green roofs. *Appl. Energy* **2014**, *115*, 411–428. [CrossRef]
4. Saadatian, O.; Sopian, K.; Salleh, E.; Lim, C.; Riffat, S.; Saadatian, E.; Toudeshki, A.; Sulaiman, M. A review of energy aspects of green roofs. *Renew. Sustain. Energy Rev.* **2013**, *23*, 155–168. [CrossRef]
5. Shafique, M.; Kim, R.; Rafiq, M. Green roof benefits, opportunities and challenges—A review. *Renew. Sustain. Energy Rev.* **2018**, *90*, 757–773. [CrossRef]
6. Parizotto, S.; Lamberts, R. Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianópolis city, Southern Brazil. *Energy Build.* **2011**, *43*, 1712–1722. [CrossRef]
7. Kostadinović, D.; Jovanović, M.; Bakić, V.; Stepanić, N.; Todorović, M. Experimental investigation of summer thermal performance of the green roof system with mineral wool substrate. *Build. Environ.* **2022**, *217*, 109061. [CrossRef]
8. Lin, B.S.; Yu, C.C.; Su, A.T.; Lin, Y.J. Impact of climatic conditions on the thermal effectiveness of an extensive green roof. *Build. Environ.* **2013**, *67*, 26–33. [CrossRef]
9. Bevilacqua, P.; Mazzeo, D.; Bruno, R.; Arcuri, N. Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area. *Energy Build.* **2016**, *122*, 63–79. [CrossRef]
10. He, Y.; Yu, H.; Ozaki, A.; Dong, N. Thermal and energy performance of green roof and cool roof: A comparison study in Shanghai area. *J. Clean. Prod.* **2020**, *267*, 122205. [CrossRef]
11. Tam, V.W.; Wang, J.; Le, K.N. Thermal insulation and cost effectiveness of green-roof systems: An empirical study in Hong Kong. *Build. Environ.* **2016**, *110*, 46–54. [CrossRef]
12. Eksi, M.; Rowe, D.B.; Wichman, I.S.; Andresen, J.A. Effect of substrate depth, vegetation type, and season on green roof thermal properties. *Energy Build.* **2017**, *145*, 174–187. [CrossRef]
13. Zhang, K.; Garg, A.; Mei, G.; Jiang, M.; Wang, H.; Huang, S.; Gan, L. Thermal performance and energy consumption analysis of eight types of extensive green roofs in subtropical monsoon climate. *Build. Environ.* **2022**, *216*, 108982. [CrossRef]
14. Yang, W.; Wang, Z.; Cui, J.; Zhu, Z.; Zhao, X. Comparative study of the thermal performance of the novel green (planting) roofs against other existing roofs. *Sustain. Cities Soc.* **2015**, *16*, 1–12. [CrossRef]

15. Porcaro, M.; de Adana, M.R.; Comino, F.; Peña, A.; Martín-Consuegra, E.; Vanwalleghem, T. Long term experimental analysis of thermal performance of extensive green roofs with different substrates in Mediterranean climate. *Energy Build.* **2019**, *197*, 18–33. [CrossRef]
16. Yıldırım, S.; Özburak, Ç.; Özden, Ö. Green roofs, vegetation types, impact on the thermal effectiveness: An experimental study in Cyprus. *Sustainability* **2023**, *15*, 2870. [CrossRef]
17. Chen, P.Y. Effects of meteorological variables and substrate moisture on evapotranspiration and thermal performance of a green roof in a subtropical climate. *Ecol. Eng.* **2022**, *180*, 106663. [CrossRef]
18. Jim, C.Y.; Peng, L.L. Substrate moisture effect on water balance and thermal regime of a tropical extensive green roof. *Ecol. Eng.* **2012**, *47*, 9–23. [CrossRef]
19. Zheng, X.; Yang, Z.; Yang, J.; Tang, M.; Feng, C. An experimental study on the thermal and energy performance of self-sustaining green roofs under severe drought conditions in summer. *Energy Build.* **2022**, *261*, 111953. [CrossRef]
20. Coma, J.; Pérez, G.; Solé, C.; Castell, A.; Cabeza, L.F. Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renew. Energy* **2016**, *85*, 1106–1115. [CrossRef]
21. Collins, S.; Kuoppamäki, K.; Kotze, D.J.; Lü, X. Thermal behavior of green roofs under Nordic winter conditions. *Build. Environ.* **2017**, *122*, 206–214. [CrossRef]
22. Wang, J.; Mei, G.; Garg, A.; Liu, N. A coupled heat and mass transfer model of green roof with water storage layer. *Build. Environ.* **2023**, *235*, 110245. [CrossRef]
23. Alonso-Marroquin, F.; Qadir, G. Synergy between photovoltaic panels and green roofs. *Energies* **2023**, *16*, 5184. [CrossRef]
24. Abdalazeem, M.E.; Hassan, H.; Asawa, T.; Mahmoud, H. Enhancing energy efficiency in hot climate buildings through integrated photovoltaic panels and green roofs: An experimental study. *Sol. Energy* **2024**, *270*, 112419. [CrossRef]
25. Radwan, A.H. Containers architecture: Reusing shipping containers in making creative architectural spaces. *Int. J. Sci. Eng. Res.* **2015**, *6*, 1562–1577. [CrossRef]
26. Islam, H.; Zhang, G.; Setunge, S.; Bhuiyan, M.A. Life cycle assessment of shipping container home: A sustainable construction. *Energy Build.* **2016**, *128*, 673–685. [CrossRef]
27. Jim, C.Y. Building thermal-insulation effect on ambient and indoor thermal performance of green roofs. *Ecol. Eng.* **2014**, *69*, 265–275. [CrossRef]