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# EXPERIMENTAL EVALUATION OF THE THERMAL BEHAVIOR OF ROOFS: A COMPARISON BETWEEN GREEN AND CONVENTIONAL ROOFS

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## ABSTRACT

Urban densification and the consequent reduction of green areas intensify environmental variables, especially with regard to thermal conditions and air quality. Given this scenario, sustainable solutions, such as the implementation of green roofs, are presented as viable alternatives to mitigate these impacts. In this context, the present experiment statistically analyzed the effectiveness of green roofs, considering two types of roofing – ceramic tile and fiber cement tile – compared to conventional roofs. The research has an applied character and experimental approach, combining qualitative and quantitative methods of

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descriptive and explanatory nature, with the objective of evaluating the thermal performance of green roofs from the analysis of empirical data and literature review. The results showed that the green roofs presented a superior performance in all the variables analyzed, except for the rate of water evaporation in the models with ceramic tiles, which registered a higher water loss, possibly due to the thermal and hygroscopic properties of the material. Thus, this study contributes to reinforce the potential of green roof technologies as sustainable solutions for the mitigation of environmental impacts, notably with regard to the reduction of thermal discomfort and the adverse effects of accelerated urbanization. In addition, the findings highlight the relevance of incorporating mitigating measures, such as green roofs, in the adaptation of cities to global climate change.

**Keywords:** Green Roof. Thermal Behavior. Thermal Performance. Urban Sustainability.

## INTRODUCTION

Due to the increasing urban density and direct reduction of green areas, the worsening of environmental variables becomes increasingly present, especially in thermal and air quality conditions (Manso *et al*, 2021). Land occupation and changes in topography not only affect the landscape, but also terrestrial and aquatic ecosystems, modifying the climate in cities (Mendonça, 2019). The replacement of more and more green areas with surfaces, such as concrete and asphalt, waterproofs the soil and increases the chances of flooding, while amplifying the so-called urban heat island effect. This context promotes a greater demand for cooling and consequent consumption of electricity to maintain thermal comfort inside and outside homes (Kader *et al.*, 2022).

In the face of these challenges, there are environmentally healthier constructive alternatives, which can contribute to the improvement of variables that are harmful to ecological and, consequently, environmental health. One of them is encompassed by Low *Impact Development (LID*) techniques, characterized by effective alternatives to mitigate the effects of urbanization to the extent that optimal materials are used to reduce environmental impact (Liu *et al.*, 2021). In addition, Dietz (2007) also agrees that sustainable urban drainage techniques, integrated in LID, seek to preserve natural landscapes and reduce impermeable areas. Examples of these techniques include bio-retention of water, rain gardens, the use of permeable pavements, and the installation of green roofs.

The green roof, also known as green roof or hanging garden, may or may not be installed directly on the roof and is a possible sustainable solution to alleviate the aforementioned circumstances in Brazilian urban areas, including the benefits of increasing the green area related to the improvement of air quality, by absorbing carbon dioxide and particulate matter (Kwon *et al.*,2020). However, although it has great benefits, installation costs tend to be higher compared to conventional roofs, due to the need for qualified labor to avoid poor installation, preventing greater risks of infiltration and fires, in addition to the constant need for care and maintenance (Sanches *et al*., 2019).

Therefore, to contribute to the theoretical construction in practice, this study aimed to build an experiment to evaluate the effectiveness of the installation of the green roof in fiber cement and colonial ceramic tiles compared to roofs without this structure, in the local climatic context. Thus, the following variables were used: external temperature of the roof and the internal temperature of the water in the prototype, in order to statistically measure the results.

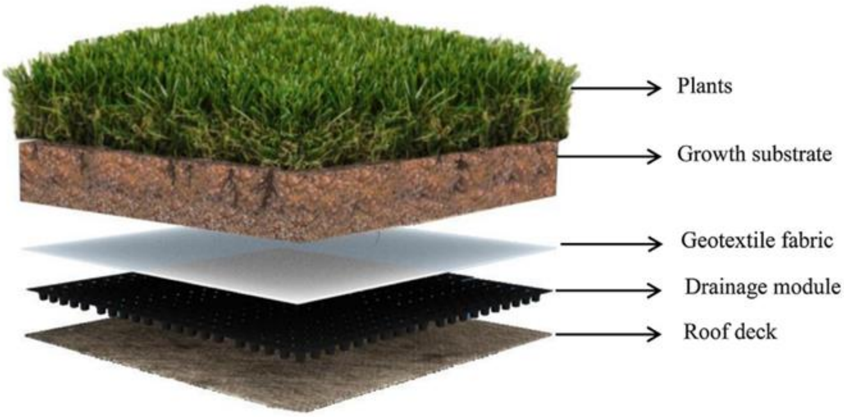
For this, prototypes of a masonry residence were created, with conventional and green roofs of the extensive type, with the base of colonial ceramics and fiber cement respectively, within an ordered place and with homogeneous sunlight. All specimens had their thermal behavior examined by monitoring and recording the variations in roof temperatures, water and water level over a period of 5 days. Finally, with the compilation of the data obtained, the results were analyzed and the implications and conclusions about the thermal performance and effectiveness of the different types of built roofs were discussed.

## THEORETICAL FRAMEWORK

### STRUCTURE AND CLASSIFICATION BY VEGETATION TYPE OF THE GREEN ROOF

According to Vijayaraghavan and Joshi (2015), the construction of a green roof requires a minimum structure of five layers, as represented in Figure 1, containing only the vegetation, and must be appropriate to the local climatic conditions, with a substrate appropriate to the type of vegetation chosen, a textile layer to prevent the migration of particles from the substrate to the drainage layer and a drainage layer,  All this on top of the waterproofed roof. The model represented in Figure 1 was used for this experiment.

**Figure 1** - Simplified structure of the green roof




**Source:** Vijayaraghavan; Joshi, 2015.

According to Cascone (2019), these roofs can be divided into intensive, extensive, and semi-intensive, based on the objective and costs associated with the amount of materials, the need for care, and the intensity of maintenance required. Regarding the structure, there is some divergence among authors.

However, in general, the consensus revolves around the intensive roof being characterized by the substrate with a thickness greater than 15cm, having support for larger vegetation, such as small trees and shrubs, greater weight, maintenance and cost, however, greater environmental benefits; the extensive having the thickness of the substrate below 15cm, supporting only small vegetation,  such as grasses and succulents, have lower weight, maintenance and cost, but also lower benefits; and the semi-intensive is a hybrid between the two (Cascone, 2019; Manso *et al*., 2021; Kader *et al*., 2022).

## THERMAL BEHAVIOR OF THE ROOF

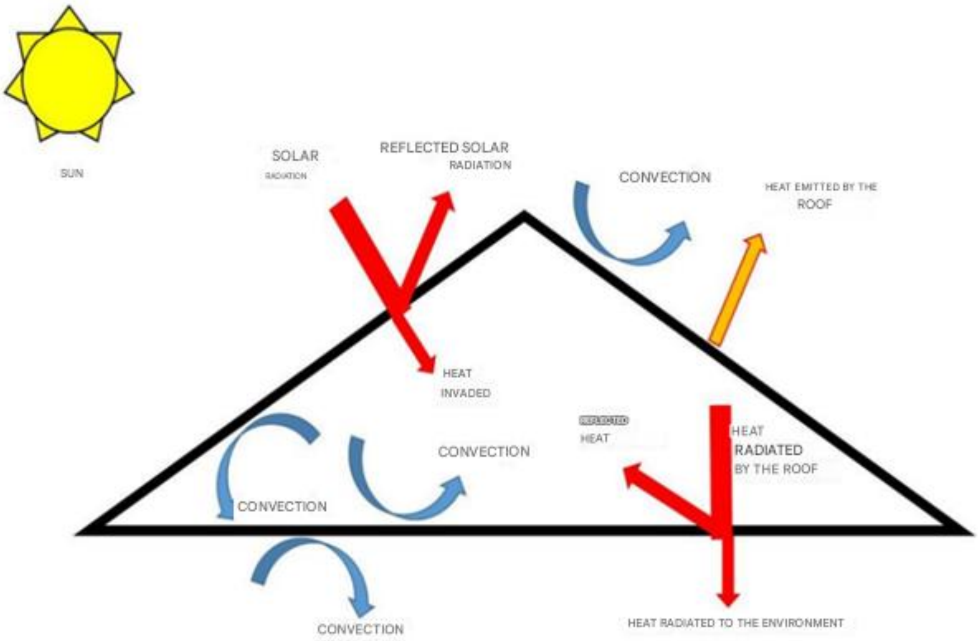
According to the *United States Environmental Protection Agency* (2024), urbanized areas that have higher temperatures than peripheral areas, reaching a difference of up to 7ºC during the day and 5ºC at night, are called Heat Islands. However, environments with a high density of materials containing high thermal conductivity and low dispersion capacity, coupled with low evapotranspiration, tend to be the main points where this occurs, mainly due to the replacement of vegetation cover.

This replacement by exposed soil or buildings, even in small fragments of urban forest, but especially large ones and with connections to other forests, alters the radiation, thermal, moisture retention balances, wind speed, soil and air pollution levels, rainfall regime and evaporative processes, altering the local microclimate (Wanderley; Miguel, 2019)

In addition, the conventional roof, as shown in Figure 2, maintains a complex heat exchange between the external and internal environments, retaining a part of it from permeating and remaining in its internal space. Due to the lack of a system to block and disperse solar irradiation, it provides conditions in which they can cause thermal discomfort, since the usual materials used tend to absorb heat easily, heat up quickly during the day and have a sudden drop in temperature at night.

In contrast, the green roof, as a fragment of green area, by absorbing solar radiation with vegetation, minimizes temperature fluctuations and prolongs its durability by up to twice that of a traditional roof (Teemusk; Mander, 2009). In addition, green roofs help reduce the effects of urban heat islands through evapotranspiration (Jusić,Hadžić; Milišić, 2019) and bring benefits in mitigating various variables, with varying intensity with the size adopted and the local concentration of specimens.

**Figure 2** - Exemplification of the energy flows present on a roof




**Source: Santos** *et al.*, 2020.

## ATMOSPHERIC CLEARANCE

Another variable that the green roof can help to mitigate is air pollution, due to the ability of plants to filter the air based on leaf density, especially carbon dioxide, which any tree species used will contribute to its reduction in concentration.

Johnston and Newton (2004) wrote about the possibility of the technique reducing pollution by up to 85% in park environments. In addition, the shading provided by the green roof decreases the photochemical reaction, helping to reduce the formation of pollutants. Pendiuk, Moisés and Pereira (2017) also point out that 1.0 m² of grass, without cuts, can provide enough oxygen for a human being for more than a year, in addition to arguing that the capacity of 2000 m² of uncut grass can remove 4000 kg of particulate agents.

## RETENTION AND USE OF RAINWATER

The hydrological cycle, as well as the other variables mentioned, has been negatively affected by the large population increase and consequent urbanization process, since the soils are increasingly being impermeable and the volume of rainwater in the cities ends up being directed, almost entirely, to the drainage systems. This results in more frequent flooding, destabilization of stream ravines, continuous destruction of aquatic habitats, and degradation of water quality in the oceans (Keeler; Burke, 2010).

Green architecture emerges as a sustainable solution that contributes to the reduction of surface runoff and the management of rainwater. Among the technologies used, vegetated structures such as the green roof dampen, capture and take advantage of rainwater, reducing the impact on the urban drainage system, retaining up to 90% of the water in the system, depending on the roof structure and vegetation size (Sa *et al.*, 2022; Azis and Zulkifli, 2021).

Being for non-potable uses, it can also be used as a toilet flush, car wash and garden watering, as they are used as a rainwater reuse system. These systems also take advantage of natural processes, such as phytoremediation for water treatment, sequestering contaminants that are normally redirected to drainage by the conventional roof, such as heavy metals, nitrogen, and phosphorus (Sa *et al*., 2022; Xu *et al*., 2020).

## METHODOLOGY

This applied research, containing characteristics of a mixed approach of the explanatory sequential design type, of an experimental nature, sought to describe and explain the performance of extensive green roofs in the built prototypes, compared to their peers without the green structure, from the results found and bibliographic research. For this, in the first stage, research was carried out to understand the technology and build hypotheses, based on bibliographic references and documents available on platforms such as SciELO, ScienceDirect, Google Scholar and government websites. Then, the prototypes were assembled and the primary data were obtained, through measurements carried out between October 1, 2024 and October 5, 2024, using the thermometer and school ruler in a measuring cup, for the preparation of this work.

### CHARACTERIZATION OF THE STUDY AREA

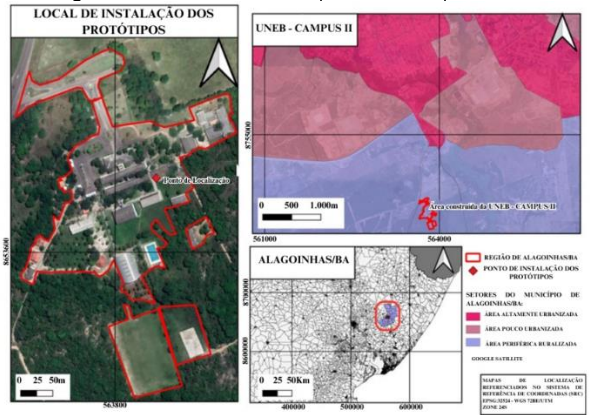
The work was developed in the municipality of Alagoinhas, state of Bahia, located at latitude 12° 07' 13'' South and longitude 38° 24' 35'' West. The experiment was implemented at the State University of Bahia (UNEB), Campus II, through the construction of four prototypes (Image 1), identified as Green Ceramic Roof (TCV), Green Fiber Cement Roof (TFV), Ceramic Roof (TC) and Fiber Cement Roof (TF).

**Image 1** - Experiments installed on Campus II

**Source:** Authors, 2024.

The site is located between the part with undergrowth and the building near the built area of the Campus, arranged in Figure 3, with a direction of 97º East, seeking continuous and homogeneous sun exposure. The experiment was conducted during the first five days of October 2024.

**Figure 3** - Location map of the experiment




**Source**: Authors, 2024.

The area occupied by the prototypes, after closing and assembly, was exactly the same, measuring 0.1089 m², while the distance between the units was set at 1.11m, when using a Polyvinyl Chloride (PVC) tube to assist in the manual marking of the prototypes.

## SPECIFICATION OF MATERIALS

The materials used to build the base of the specimens were 16 ceramic blocks (measures of 9cm x 19cm x 24cm), mortar with a 1:2:0.5 ratio, 4 ceramic tiles, 2 cut fiber cement tiles, measuring 0.1804 m² per unit, and 2 wooden molds, measuring 0.1156m² per unit. For the green roof, PVC plastic tarpaulins were added, measuring 0.16m² per unit (replacing the bidim blanket), felt, measuring 0.1936m² per unit (replaces the geotextile), gravel 1 (for drainage), vegetable soil and grass boards, measuring 0.24m² per unit.

Rischioto measuring cups were used for a precise visual delimitation of the volume of 200mL of water, a VMP crystal ruler to measure the decreased amount of water, and a Multilaser infrared thermometer, model HC260.

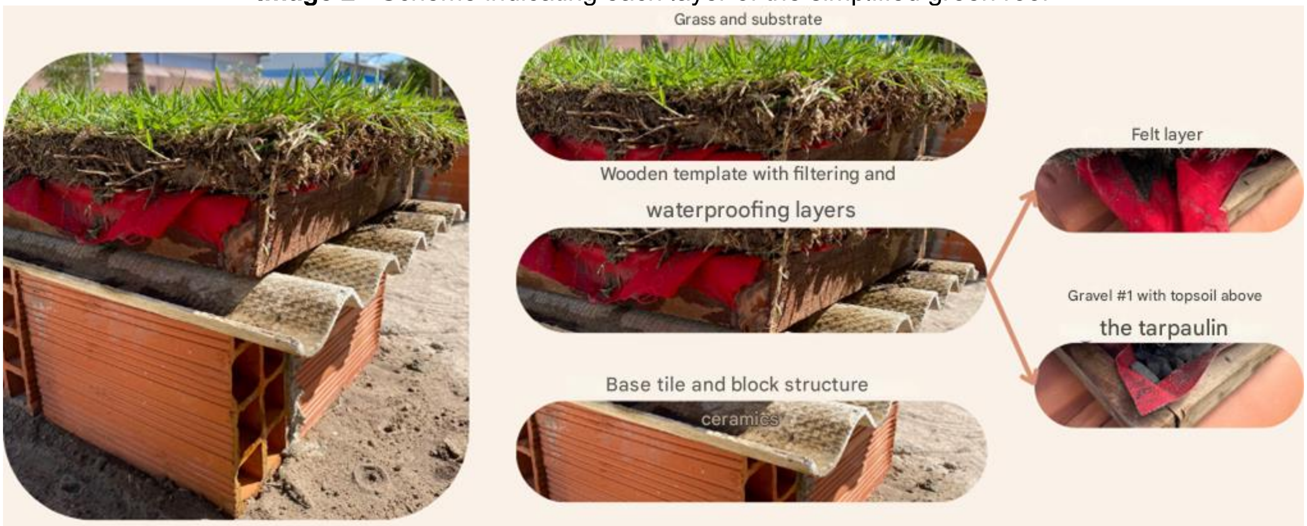
## CONSTRUCTION OF PROTOTYPES

The first step in the construction of the prototypes consisted of separating the ceramic blocks to form four uniform structures. Each set of blocks was arranged on the ground in a rectangular shape, leveled and laid manually with the help of the spirit and plumb level, and then mortar was applied on the sides to ensure the stability and solidity of the structures. After this stage, the roofs were installed, and in two of the prototypes ceramic tiles were adopted on the structure of the blocks while in the other two fiber cement tiles were installed, adjusted to perfectly cover the bases.

Before starting the monitoring of the green roofs, the amount of water from a 200mL disposable cup was added, with the help of a beaker, to each of the measuring cups that were inside the prototypes. This measure aims to monitor and evaluate how the water temperature behaves and the decrease in the amount of water in the internal environment of the prototypes until the end of the experiment.

The installation of green roofs with a simplified structure (Image 2), similar to the one schematized by Vijayaraghavan and Joshi, (2015) begins with the placement of the rimmed containers, which were made from wooden molds, measuring 34cm x 34cm, for the two prototypes with fiber cement tiles. Then, a waterproofing layer was applied, using a 40cm x 40cm plastic tarpaulin, adjusted according to the initial modeling. After that, a drainage layer composed of coarse aggregate (gravel 1) was added over the tarpaulin. Next, a layer of felt (used from old fabric) measuring 43cm x 44cm was placed. Finally, vegetable soil was applied, and the final stage consisted of planting the grass. It is worth noting that the fiber cement roof tiles were cut with a measure of 41cm x 44cm, while the colonial ceramic was used without alterations, maintaining the dimensions of 50cm x 15.5cm.

**Image 2** - Scheme indicating each layer of the simplified green roof




**Source:** Authors, 2024.

## EXPERIMENT PREPARATION, STANDARDIZATION, AND DATA ANALYSIS

The types of roofs were organized into two pairs, one consisting of ceramic and fiber-cement roofs as a control, and the other of green roofs, allowing for a later comparison.

The data acquisition strategy was standardized to minimize the interference of external variables, such as variations in manual measurements and differences between the measurement instruments. Thus, the cups, the ruler and the thermometer used were always the same and the order of the measurements followed a specific sequence, starting at the roof with colonial ceramic tile and proceeding to the fiber-cement roof, ceramic green roof and green fiber-cement roof, respectively. In addition, measurements were carried out at specific times, and the location and arrangement of the prototypes were arranged to ensure homogeneous insolation.

The guidelines for the measurements followed a determined pattern to reduce the error associated with manual measurement, intensified when performed by different people. The measurement periods were defined to occur at approximately 8, 13 and 17 hours, with the precise recording of the start and end times of each measurement.

Thus, when measuring the height of the water in the glass, the meniscus generated in the container was considered, using the first line of the water surface for visual measurement. For the height measurements on the measuring cup, it was stipulated that they were all made in the same place, level at level 0, as indicated by the iPhone's "level" function, one at a time. In addition, the experiment recorded the air temperature and weather conditions during the measurements, ensuring that the temperature of the prototypes was always measured under the same circumstances, whether on rainy days, under sunshine or in cloudy skies.

In addition, in the measurement process, a one-minute wait was performed after turning on the thermometer to start the measurement. The temperature considered was the one at which the thermometer stabilized, even after other attempts at the same positioning and aiming point. The thermometer was kept at a distance of 2 to 5 cm from the surface, using the "surface" option of the device. All water measurements in the cups were carried out inside the prototype.

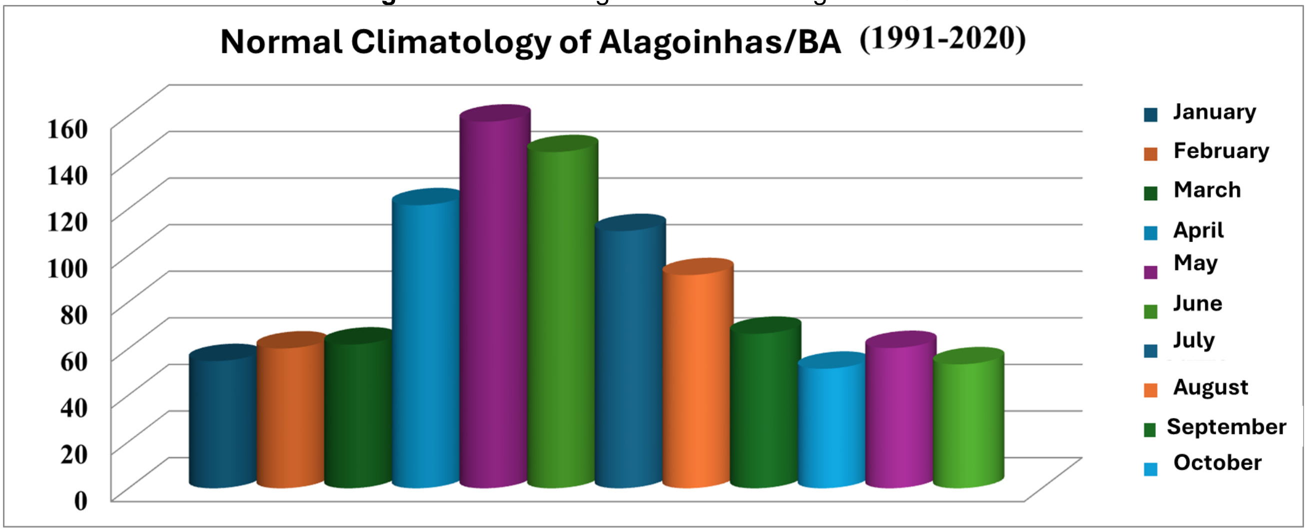
During the initial preparation of the experiment, the grass of the green roofs was irrigated with 200 mL of water each, at 4 pm the previous day. After the measurements, the same amount was applied to each green roof, except at 8 am on the first day of measurement, to avoid excess humidity. For the analysis of the results, the Excel spreadsheet software was used  as a support tool, allowing the development of graphs and facilitating the interpretation of data related to temperatures and the quantification of excess rainwater.

## CONDITIONS EVALUATED DURING THE EXPERIMENT PERIOD

### Weather conditions

All measurements were carried out in October, a period characterized by water deficit (Figure 4) and the fifth lowest relative humidity of the year, compared to the climatological normal from 1991 to 2020, which was approximately 77.5% (INMET: Tempo, 2024b).

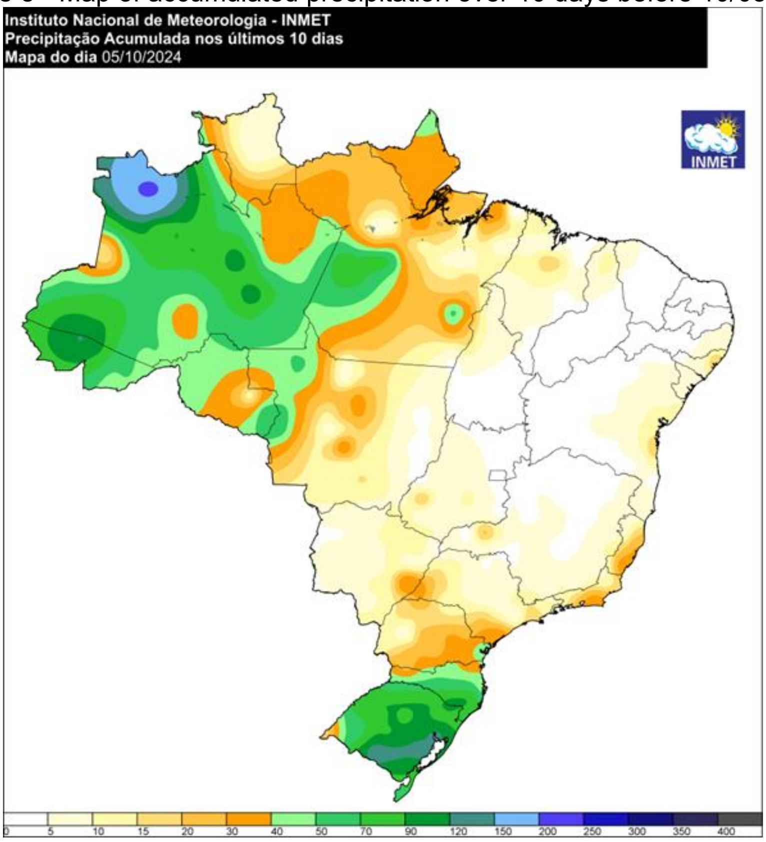
**Figure 4** - Climatological normal of Alagoinhas/BA




**Source:** Adapted from INMET: Tempo, 2024a.

In addition, a rainfall of about 10 mm was estimated in the five days before and during the experiment, as shown in Figure 5 (INMET: Tempo, 2024a).

**Figure 5** - Map of accumulated precipitation over 10 days before 10/05/2024




**Source:** INMET: Tempo, 2024b.

Considering the normative climate and the conditions mentioned above as a reference to infer conclusions about the data, the weather conditions (Chart 1) and the air temperature in Alagoinhas/BA, recorded at the time of measurement by Apple's native weather application, were taken into account.

**Chart 1** - Weather conditions on the days of data collection

| Weather conditions | | | |
|---|---|---|---|
| **01/10/2024** | | | |
| Timetable | 08 | 13 | 17 |
| Climate | Cloudy | Sunny | Clear skies |
| **02/10/2024** | | | |
| Timetable | 08 | 13 | 17 |
| Climate | Sunny | Sunny | Shady |
| **03/10/2024** | | | |
| Timetable | 08 | 13 | 17 |
| Climate | Sunny | Sunny | Clear skies |
| **04/10/2024** | | | |
| Timetable | 08 | 13 | 17 |
| Climate | Sunny | Sunny | Shady |
| **05/10/2024** | | | |
| Timetable | 08 | 13 | 17 |
| Climate | Sunny with clouds | Sunny | Clear skies |

**Source:** Authors, 2024.

## Property and behavior of roofs

The thermal properties described in Table 1, especially thermal conductivity and specific heat, indicate a better thermal performance of the ceramic tile in relation to fiber cement.

**Table 1 -** Thermal properties of the tiles used

| Material | Bulk Density (ρ) in [Kg/m³] | Thermal Conductivity (λ) in [W/(m.K)] | Specific heat (c) in [J/(Kg.K)] |
|---|---|---|---|
| **Ceramics** | 2000 | 1,05 | 0,92 |
| **Asbestos** | 1900 | 0,95 | 0,84 |

**Source:** Adapted from ABNT, 2005.

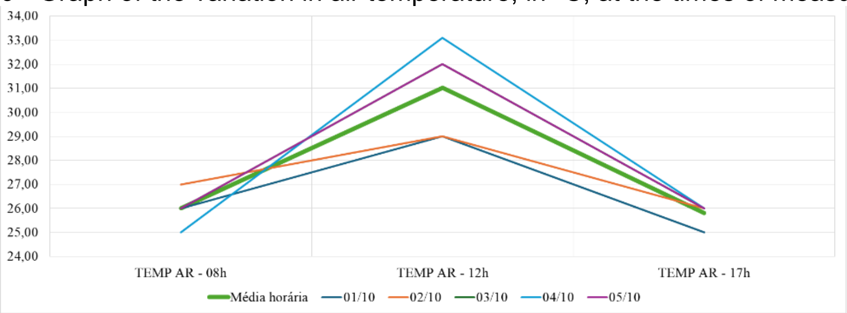
In addition, like Michels; Lamberts; Güths (2008) and Castellano *et al.* (2023) indicated, in general, ceramic tiles have porosity and the consequent possibility of fluid infiltration through the tile spaces. This characteristic gives the ability to create a protective film of water against irradiation, due to the absorption of water on its surface. This last effect happens with the material removing when moisture is removed from the environment, that is, dehumidifying the environment (Castellano *et al.*, 2023). In this way, the water adhered to the tile will protect it from the increase in temperature until it is volatilized. These constant adsorptions and desorptions of water vapor occur on a larger scale, as the presence of mesospores in ceramic tiles is additional to the larger area (Castellano *et al.,* 2023).

In addition, still related to table 2, it is expected that the fiber cement will heat up with some speed and remain hotter until the capacity of the ceramic roof exceeds it, as the middle of the day approaches.

## RESULTS AND DISCUSSION

From the data available in the *Weather* application, it was evident, as shown in figure 6, the average amplitude of more than 5 ºC in the air temperature at the times of the measurements, between peaks and depressions in Alagoinhas/BA, however, it reached 08ºC of amplitude between 8 am and 1 pm on October 4th. At this same time of 1 pm, as expected, there were the highest values of roof temperature, water temperature and decrease in the water level.

**Figure 6** - Graph of the variation in air temperature, in ºC, at the times of measurement

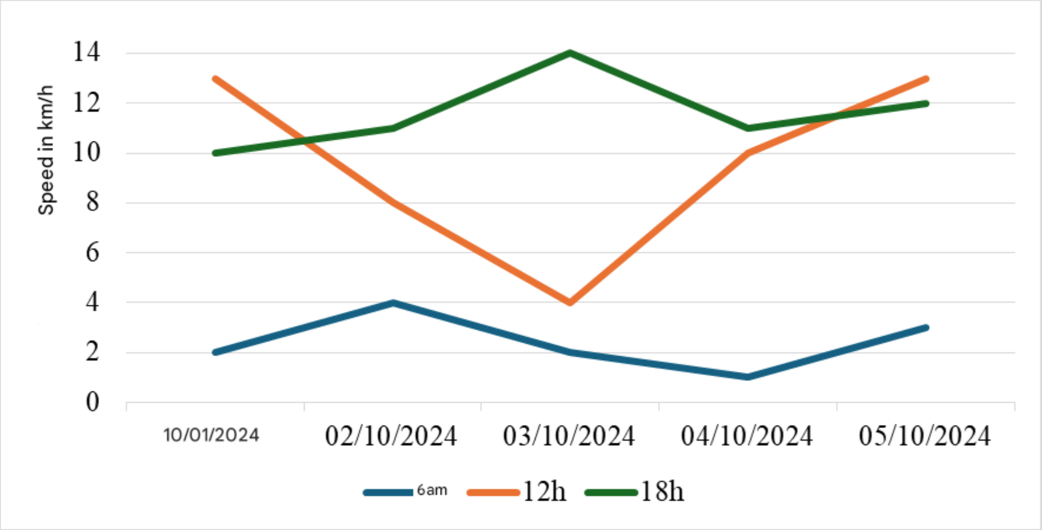



**Source:** Authors, 2024.

However, although day 05 had the highest water temperature values at all times (Figures 8, 9 and 10) and the second highest air temperature value, there was a lot of proximity between the peaks of the other prototypes on the other days. Even so, there was not the same behavior of maximums on the same days for the roof temperature, alternating between the days of maximum measurement between them, with a possible greater relationship with the time of greatest solar incidence only.

Another complement to the analysis of the results was the obtaining of approximate data on wind speed in Alagoinhas/BA at the approximate times available for the measurements, using the Ventusky meteorological information visualization service platform (2024). It uses data available from international organizations to generate the interactive map.

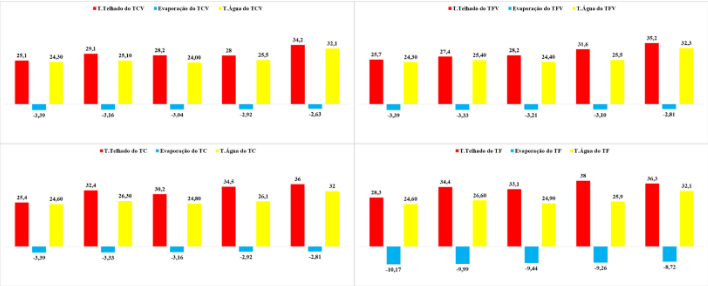
**Figure 7 -** Wind speed during the experiment estimates




**Source:** Adapted from Ventusky, 2025.

When observing the graph in Figure 7 and comparing the air temperature and the behavior of the prototypes, it is also not possible to infer an apparent correlation with any of the variations in the data collected from the roofs and water, since there is no direct or inversely proportional apparent correlation between the variables.

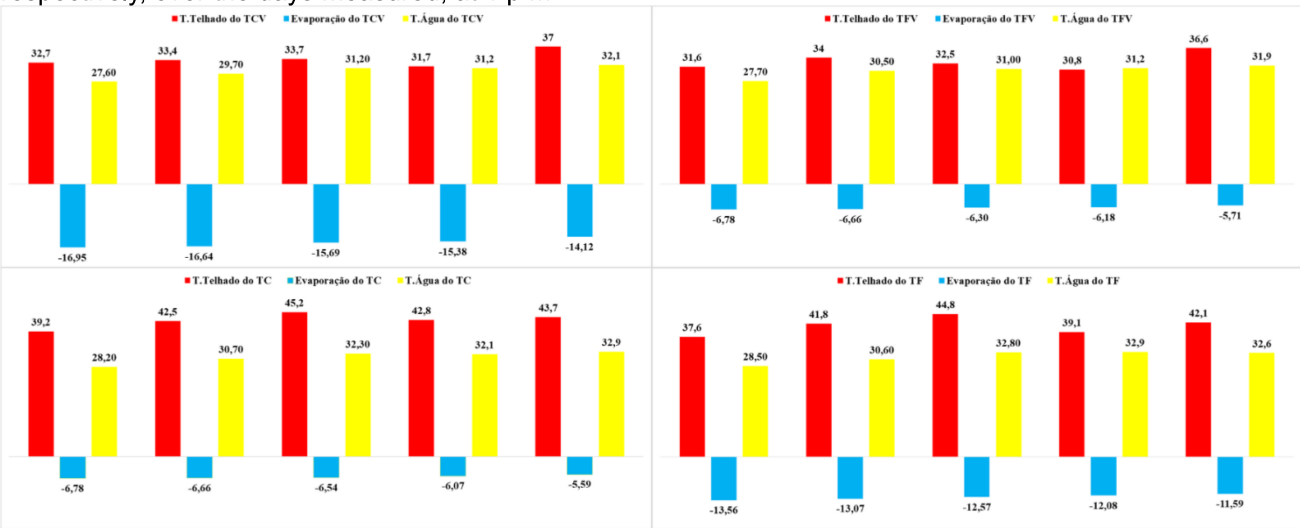
**Figure 8 -** Variation in roof temperatures, decrease in water level and water temperature in each prototype, respectively, over the days measured, at 8 am



**Source:** Authors, 2024.

In the examination of the data observed in the prototypes over the days, that is, in order of days one to five (October 1st to 5th and 2024), in the interval of 08 am (Figure 8), it is possible to notice the great difference in the decrease in the water level between the prototype with fiber cement and the others,  despite the small difference between the other variables. Although there is the consideration of the distinction of October 4th, where there was noticeably greater increase in roof temperature, and evaporation did not increase equivalently.

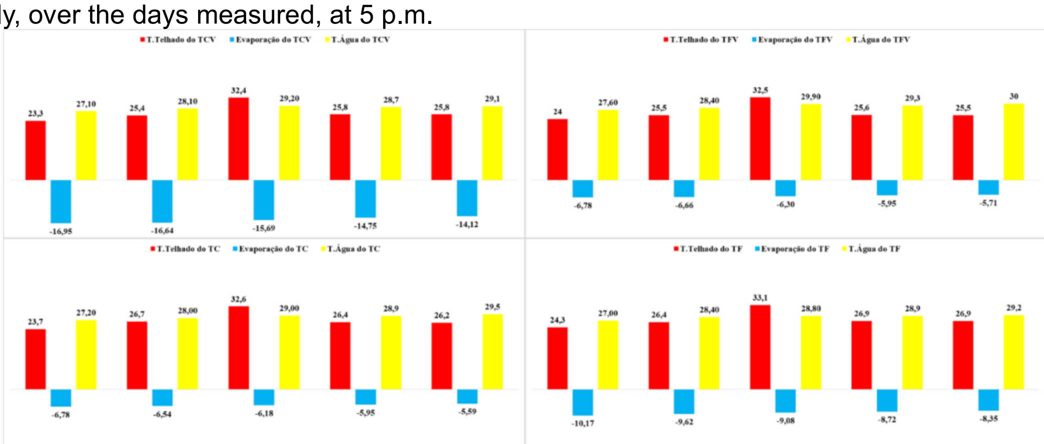
**Figure 9** - Variation in roof temperatures, decrease in water level and water temperature in each prototype, respectively, over the days measured, at 1 p.m.




**Source:** Authors, 2024.

At 1 p.m. (Figure 9) there was a divergent behavior from the 08. The green ceramic roof stood out in the decrease in the water level, even though the rest of the variables had relatively low values, with all other values similar to the GFR being lower than the TF at the time and in almost all values, with the sole exception of the water temperature in the TC of the 4th, when compared to CT. The latter has maintained its more directly proportional pattern of emptying with increasing temperature.

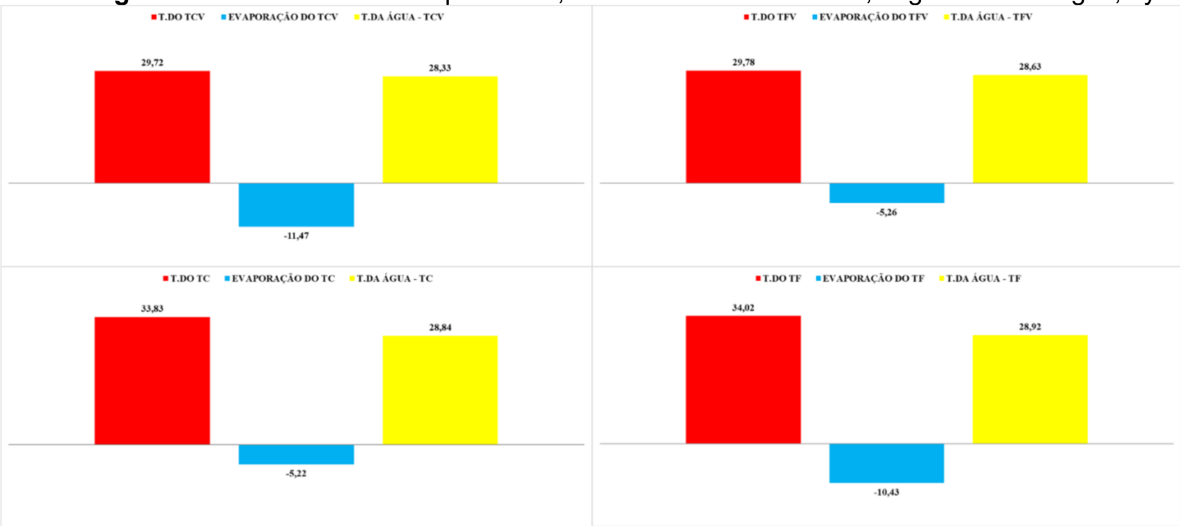
**Figure 10 -** Variation in roof temperatures, decrease in water level and water temperature in each prototype, respectively, over the days measured, at 5 p.m.




**Source:** Authors, 2024.

When we arrive at 5 p.m. (Figure 10), it is possible to verify a behavior of the TCV also of great emptying of the glass, but, despite the temperature below or similar to the others, on all days, different from the time of 1 p.m., all values, except for the decrease in water, are quite close.

Figure 11 - Values of roof temperatures, water and their decrease, in general averages, by roof




**Source:** Authors, 2024.

When comparing the measured variables organized in a general way, in the graph shown in Figure 11, in simple arithmetic mean, there were no significant differences between them, except for the decrease in water, which was quite intense in the green ceramic roof and in medium intensity in the fiber cement roof. However, when comparing only the general average temperatures of normal and green roofs, there is an average of at least 4 ºC.

## FINAL CONSIDERATIONS

The present study aimed to analyze the effectiveness of green roofs as a sustainable alternative to mitigate thermal impacts in urban environments, comparing their thermal performance in relation to conventional roofs. The results showed that the adoption of vegetation cover significantly influences the temperatures recorded on the roof surface and in the internal environment, reducing the temperature of green roofs by an average of 4.27°C compared to conventional roofs.

Although the green roofs had better thermal performance in all the variables analyzed, an atypical behavior was observed in the green roof with ceramic tile (TCV), which registered a higher evaporation rate than the other prototypes. This phenomenon may be associated with the hygroscopic capacity of the ceramic material, which absorbs and releases moisture according to thermal variations and environmental conditions, as described by Bueno (1993). This effect, intensified by the presence of the green roof, suggests that the ceramic tile interacts more dynamically with the internal microclimate, favoring a continuous flow of humidity.

The temporal analysis revealed that the greatest evaporation occurred on the first day of the experiment, which may be related to factors such as the thermal stabilization of the prototypes or the influence of the initial humidity of the plant substrate. In addition, a trend of reduced evaporation was observed over the days, even without a significant variation in air temperature, which reinforces the hypothesis that the interaction between the constituent materials of the green roof and the thermal dynamics of the environment are determinants for the observed behavior.

Despite the methodological robustness, some limitations of the study should be highlighted. The prototypes used had a simplified structure in relation to real buildings, which may have influenced thermal exchanges and moisture retention. In addition, variables such as relative humidity, wind speed and solar incidence were not directly measured, which could improve the analysis of the internal microclimate of green roofs.

Thus, this study reinforces the feasibility of green roofs as a strategy to mitigate urban thermal discomfort, highlighting its relevance for environmental sustainability and the adaptation of cities to climate change. It is recommended that future research deepen the investigation into the interaction between different structural materials and green roof layers, as well as their influence on other environmental variables, such as air quality and water efficiency.

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