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Original Article

Green Roofs Thermal Analysis for Ébano, San Luis Potosí, Mexico

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Abstract - *This paper presents the results of an impact evaluation of green roofs on the environmental conditions of an urban module in Mexico by comparing temperature and relative humidity with and without this system. The experimental part was conducted through measurements taken at various times over a period from April to June 2024. Methodology was supported by data taken every hour (temperature and humidity sensors) within modules representing the green roof. By comparing the daily averages of temperature the data was analyzed, dew point, and relative humidity, the data were compared, showing the thermal advantages of green roofs with possibilities in reducing the urban heat island effect and improving comfort conditions. Results show that green roofs significantly influence the internal temperature of the modules, reducing it from 2 to 4°C compared to the modules without green roofs, particularly during peak solar radiation hours (2:00 p.m.). Green roofs increase relative humidity by 5-10%, which could be considered a positive effect on air quality and thermal comfort depending on the localization and context. The results help to support of the ability of green roofs to buffer temperature fluctuations, maintain more stable indoor climates, and contribute to better air quality. Valuable insights are shown for urban design and sustainable infrastructure planning, with the integration of green roofs as a strategy for enhancing urban sustainability.*

Keywords - *Sustainability Slab, Energy Efficiency, Component Selection in Green Roof.*

1. Introduction

Green roofs have emerged as a sustainable solution in urban design, particularly in densely urbanized areas where issues such as urban heat islands and poor air quality are pronounced [1]. These systems involve the installation of vegetation on building surfaces and offer a wide array of ecological, social, and economic benefits, including energy consumption reduction, air quality improvement, and enhanced biodiversity [2, 3]. Green roofs modify local microclimatic conditions by influencing temperature and relative humidity. References [4, 5] demonstrate that vegetative use contributes to improving thermal comfort, related to climate change, by using emissions for its development and growth.

A growing body of research on roofs in a house has demonstrated the ability to positively impact thermal conditions inside buildings [6], showing that green roofs can reduce internal temperatures by providing shade and promoting evapotranspiration. The main impact is the reduction in the use of artificial cooling systems, contributing to healthier and more comfortable indoor environments. Furthermore, green roofs can influence relative humidity through plant transpiration, changing comfort in dwellings [7]. The effectiveness of green roofs in modifying thermal conditions varies with several factors, i.e., plant composition, roof typology (intensive vs. extensive), material (as roof, concrete, steel, or a combination of two of them), and local climatic conditions. Green roofs in hot climates have been shown to significantly reduce internal temperatures, but in places with cooler or freezing temperatures, there is not much help in reducing internal temperatures. Additionally, green roofs contribute to improved air quality by filtering pollutants, such as fine particles and gases, including carbon dioxide, which has substantial implications for urban health [8].

Despite their numerous benefits, the widespread adoption of green roofs faces challenges, particularly in terms of high upfront costs and maintenance requirements. One important characteristic is that the weight added to the slabs increases the dimensions or structural parts in the roof.

However, [9] shows that the price cover for roof production is mitigated by the long-term advantages, i.e., reduced energy demand (for air conditioner use) and improved microclimatic conditions and use of other materials and energy. This paper evaluates the impact of green roofs on the environmental conditions at a San Luis Potosí place and applies it to an urban module. It compares temperature and relative humidity with and without the solution of a green roof, for a comprehensive understanding of how green roofs affect the internal microclimate.

1.1. Literature Review

Studies showed in [10] the benefits of green roof use, due to big data use, with thermal and environmental changes in indoor buildings at Hong Kong, with cooling effects (~0.15 °C), increasing benefits such as more green space and improved urban livability [10]. In subtropical China, application of green roofs with modifications in materials and structure in façades demonstrated improvements in thermal conditions with lower temperatures and carbon capture; in effect, plants reduce CO2 emissions and absorb this gas, reinforcing the multifunctional potential of vegetated systems [11].

A global study comparing urban green cooling effects in nearly 500 cities found significant disparities, with cities in the Global South experiencing about half the cooling benefits seen in the Global North. This finding underscores the importance of climate-adapted strategies in underrepresented regions [12]. Field research in Melbourne, Australia, confirmed that intensive green roofs help regulate rooftop microclimates by stabilizing temperature and improving humidity retention [13]. Researchers found in Berlin that on a heatwave day, a green roof produces a cooler temperature at night and increases human comfort during daytime, which also produces a change in environmental humidity with a better temperature perception [14]. On the other hand, a review of green roof performance for Mediterranean climates demonstrates regional disparities in research coverage and a lack of long-term empirical studies, where a better relevance is taken for low-income housing contexts [15]. It is important to consider tha there are some criteria to analyze components and every part of a green roof, as can be seen at [16-19].

1.2. The Urban Heat Island Problem

The phenomenon known as urban heat islands refers to the high temperatures found in specific areas within a city, typically due to the type of building materials used and the lack of vegetation [20, 21]. Since the 21st century and the increase in industrialization, this has become a significant urban and environmental challenge related to abnormal temperature changes. For example, while the average temperature in a city might be around 32°C, it can rise to 38°C or 39°C in a specific area, especially one with dark surfaces and an excessive use of massive materials like concrete. To carry out the modification of the temperature, the type of vegetation to be placed on the roof must be selected, mainly because the development of the plant is related to the surrounding climate. The temperature is modified since a layer of soil is placed on the roof, in which plants are cultivated or grown. For this, it is necessary to place a waterproof layer to prevent water from passing through the slab, which is generally made of concrete, or it can be done on a wooden structure.

The use of different colors, permeable materials, and the implementation of vegetation helps typically to dissipate heat; some solutions are explained at [22, 23]. However, this is often difficult in areas where trees have already been cleared and land is being prepared for new buildings. The creation of heat islands has several negative effects, from an environmental perspective, to the presence of pollutants caused by the high temperatures themselves, as well as successive increases in energy consumption.

1.3. Context in Mexico and San Luis Potosí

Globally, Mexico faces the urban heat island phenomenon, particularly in densely populated cities [24, 25]. In places like Ébano, where this study is being conducted, the climate is warm and sub-humid, which can promote the heat island effect if standard city construction practices are followed. For this state in Mexico, vegetation has also been produced for use in construction, increasing population density. It is necessary to reduce industrial materials, characterized by high heat transfer (i.e., concrete), and discomfort for residents. San Luis Potosí is home to a great diversity of plants, including native species such as peyote, mesquite, agave, and various types of barrel cactus, as well as agricultural species like chili peppers and corn, and ornamental trees such as jacarandas and palms. The Huasteca Potosina region, with its mild climate, is also an important center for the production of ornamental plants, coffee, and vanilla [26].

1.4. Justification for Green Roofs as a Sustainable Solution

Given the presence of heat islands in Mexico and the high possibility of new ones forming due to the construction of housing and buildings to support population growth, green roofs are presented as a potential solution for building design and urban regeneration. They offer an alternative to traditional materials, primarily by promoting evapotranspiration and providing thermal regulation. A green roof uses the properties of its components to enhance evaporation, which lowers temperature, as well as the insulation promoted by the substrates they are composed of. This thermal insulation can also improve comfort. However, more studies are needed to fully understand their impact, which is why this research proposes to evaluate both solutions in a specific, given area.

The architectural envelope receives the sun's rays throughout all hours of the day, regardless of the building's orientation, making it one of the most critical elements of a building. The building component that is most exposed to the sun throughout the year and for most of the day is the one in a horizontal position or on the roof. However, even though it is the element that receives the most heat, it is also the one that radiates the most heat back into space during the night. This characteristic, inherent to its position, can be used to dissipate the heat accumulated during the day in the cooler nighttime hours. It is also important to consider the finishes of these elements, which should have similar characteristics.

The materials with which the dwelling was built are currently inadequate to withstand present solar radiation. These materials must be reconsidered in terms of their thermophysical, radiative, and insulation properties. It has been shown that the roof is the element through which the most significant amount of heat enters the home, as it is typically exposed to 12 continuous hours of solar radiation, making it necessary to attend solutions to reduce the temperature in the horizontal structural parts in a building [27].

In some references, such as those mentioned above, it is proposed that green roofs not only mitigate heat in buildings but also serve as strategies to reduce flooding when used to retain specific amounts of water, allowing them to act as moisture absorbers as well-something that can occur in various areas within the Mexican Huasteca region [28]. It is important to note that this study is relevant for understanding temperature changes through a green roof compared to a material without one, or directly with traditional materials, allowing for its implementation in cities.

2. Method

Calculations were based on the model developed in [16, 17], tailored to the specific characteristics of the study area. Experimental evaluation was conducted in an outdoor location, exposed to weather and solar radiation. The experimental place has the coordinates 22.21051°N, 98.36615°W. This place was selected for its suitability for effective data collection, offering a large, accessible terrain free from any elements that could interfere with the study.

It is important to select ideal vegetation for the green roof, especially with those plants that must be part of the nature of the zone where it is used. For plant choice and species, considerations are outlined in [18] and further exemplified in [19]. Analysis of vegetation in the Huasteca region southeast of San Luis Potosí was produced utilizing the conabio. gob.mx platform. Vegetation and characteristics visually documented by photographs facilitated the classification based on physiognomic criteria of the possible species used in this paper. The characterization of the Soil used in this research was made using [20]. The area where the green roof was installed was characterized following the guidelines of NOM-021-RECNAT-2000. Every 24 kg soil sample was enriched with 2.5 kg of dried and crushed leaves obtained from Francis mango and Valencia orange trees; green material was taken from the same geographic location. Laboratory tests: Atterberg consistency limits, granulometry analysis, carbonates content, and chlorides in the soil were conducted for the material's suitability as a substrate for the green roof. The experimental part initiates with the groundwork preparation for two distinct modules. The second part is the site leveling and pouring a 10 cm thick concrete foundation for each. The construction of the walls was constructed using 12x20 cm cement blocks, and surface finishing with a plaster made from a mixture of cement/sand. An aspect of the roof's design is a deliberate 10% westward slope over the slab, ensuring efficient drainage. For roof structural integrity, a final coat was applied (white paint) and a waterproofing layer using PASA 405, erasing the possibility of water permeability to the inside of the slab.

For the module with the surface with the green roof, it was implemented a multi-layered system was implemented, designed for optimal insulation and drainage, as shown in Figure 1: a first layer of four layers of black polyethylene plastic (serving as an insulating base). Above this, a 2 cm layer of gravel facilitates drainage with homogeneous distribution, followed by four layers of felt for the moisture retention properties. The substrate for growing medium is spread to a cm thickness, culminating with the vegetative layer.

For Data collection, a digital humidity and temperature meter (model HT-86) is used, allowing for measurement of temperature and Relative Humidity (RH) every hour at three different times for alternating days. Comparison of temperature variation is made with this information, between the module with and without a green roof. Temperature (°C) and relative humidity (%) were monitored, assessing their impact on the thermal behavior of the modules. This research is important in Mexico for the possibility of using it in social housing in Ébano, San Luis Potosí, to evaluate the practical benefits.

3. Results and Discussion

Results obtained in the granulometry analysis for mesh sizes 4, 40, 200, and P200 were 0%, 1.87%, 0.93%, and 97.2%, respectively. Regarding the Atterberg consistency limits, the Liquid Limit is 29% and the Plastic Limit is 15%, classifying the soil as clay with low plasticity. Additionally, the determination of carbonates and chlorides in the soil showed concentrations of 483.2±001.3 ppm and <1 ppm, respectively. For the green roof, three species were selected for their adaptability to the local climate: Parthenium hysterophorus (false altamisa), Artemisia ludoviciana Nutt (a medicinal species), and Lysimachia nummularia (coin grass). These plants were chosen due to their ability to thrive in the area and to create a favorable microclimate on the roof, helping to reduce the internal temperature of the module during warmer days. Figure 1 shows the final diagram composition of the slab and the layers used to determine the heat transfer process. Table 1 shows the thermal properties of each layer.

Fig. 1 Diagram of the green roof composition

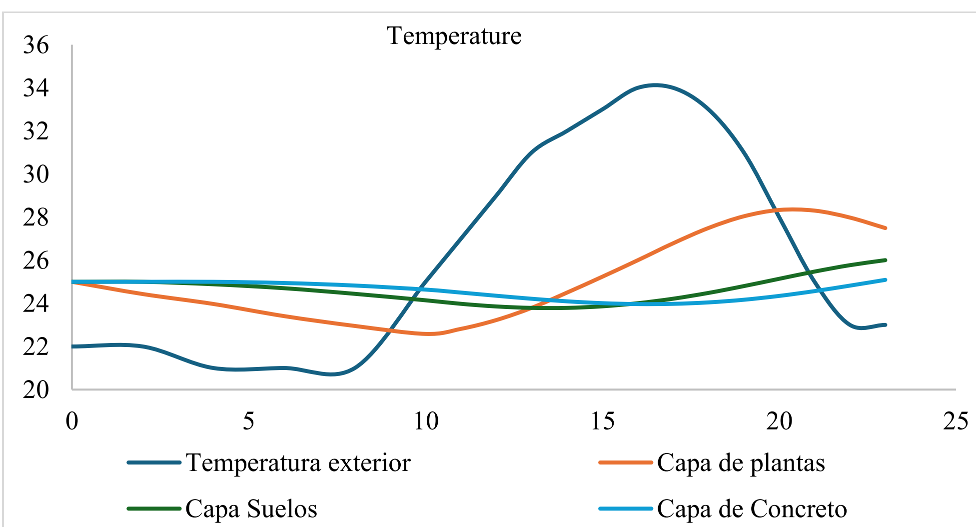
Table 1. Layer properties for the green roof composition

Material	Thermal Diffusivity (mm²/s)	Thermal Resistivity (°C·cm/W)	Thermal Conductivity (W/m·K)	Specific Heat (MJ/m³· K)
Concrete*	0.947	41.47	1.608	1.698
Soil	0.3171	182	0.5481	1.728
Vegetative Layer	0.2963	175	0.5712	1.928

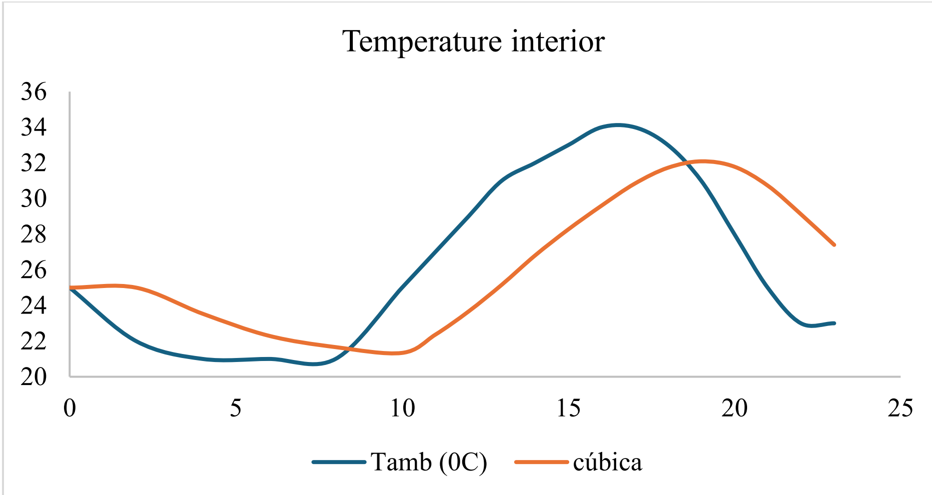
The thermal results of Table 1 were used for the heat transfer analysis using a differential equation system. Model applications used are reported in [10, 11]. The main temperature prediction is:

$$T_2(t) = \frac{(T_{2,0}-T_{1,0})}{\left(\frac{h^2}{\kappa_1}C_1-\frac{C_2V}{UA}\right)}\left(\frac{h^2}{\kappa_1}C_1\, exp\left(-\frac{t}{(\frac{h^2}{\kappa_1}C_1)}\right)-\frac{C_2V}{UA}exp\left(-\frac{t}{\frac{C_2V}{UA}}\right)\right)+T_{1,0}$$

Which includes the temperature in the layer (T_1), the time (t), the distance measured taking as a reference the outer side of the solid (x), and C_1 κ_1 the heat capacity and the coefficient of thermal conductivity of every material. The temporal behavior of the air temperature in the room is given from$T_2$the volume V and the area$A$ in the room (sum of the areas of the walls), h the thickness of the solid, while and are the heat capacity and the coefficient of heat transport by natural convection of the air. The application of the model had the results shown in Figure 2. In the case of the green roof, it is observed that the temperature in the different layers (floor, soil, concrete) is initially lower than in the solid concrete slab during the first hours (0-10 hours). In the time, green roof temperature increases more gradually compared to a concrete slab, demonstrating that green roof has a greater ability to buffer the temperature rise. At the time of maximum temperature (from 12:00 to 18:00 hours), the layers of the green roof remain in relatively moderate temperature ranges, while in the concrete slab, the temperatures rise much more abruptly.



(a)



(b)

Fig. 2 (a) Results for the temperature outside and inside every layer in the green roof, and (b)The concrete one-layer-roof.

Measurements show thermal differences within the green roof's layers, with lower temperatures compared to an exposed concrete slab. The plant layer, in this case, maintains a temperature range of 22 to 27°C during the day. When it is considered a concrete layer beneath, temperature can exceed 25°C, reaching a temperature of more than 45ºC for the inner part of a slab exposed to the sun. In this work, vegetation and soil provide a significant buffering effect (and offer thermal insulation).

3.1. Thermal Behavior of Green Roof

Temperatures in the Plant Layer fluctuated between 22°C and 28°C. This indicates the vegetation's capacity for moderate heat absorption, effectively serving as a barrier that prevents direct heat transfer to the underlying concrete. It is observed that relatively stable temperatures within the soil range from 23°C to 26°C. This stability points to the soil's role in moderating temperature variations, contributing significantly to the overall thermal equilibrium of the green roof system. Protected by the layers above, the concrete layer maintained more consistent temperatures, specifically between 23.5°C and 25°C. This confirms that when shielded by a green roof, concrete does not experience the same extreme heating as a solid concrete slab directly exposed to ambient conditions.

3.2. Thermal Behavior of Solid Concrete Slab

In the solid concrete slab (without vegetation or soil), temperatures rise widely. Heat in the slab reaches up to 32°C during the hours of maximum solar radiation (12:00 to 18:00 hours), a much faster increase compared to the green roof layers. This is characteristic of opaque materials such as concrete, which quickly absorb heat and release it slowly. Temperatures of the pyramidal and cubic configurations (two variations of concrete) follow a similar trend. At 10:00 a.m., the slab already reaches 21°C, while at 4:00 p.m. temperatures exceed 29°C. This acceleration of heat can generate a greater thermal load within the space covered by the roof, affecting the energy efficiency of buildings. Finally, concrete has higher temperature peaks (reaching up to 32°C) compared to green roof layers, where temperatures do not exceed 28°C. The comparative thermal analysis between a module with an extensive green roof and one without this roof was carried out during the spring and summer seasons, with relative temperature and humidity measurements at 9:00 a.m., 2:00 p.m., and 8:00 p.m. between April and June. The data are presented in Table 1, which facilitates the comparison between both modules and their behavior in the face of outdoor conditions.

As for the maximum temperature, the module with a green roof showed, in general, a slight decrease in temperature during the morning and afternoon, except in the hottest hours. For the green roof, at 9:00 a.m., the difference was 0.41°C, changing at 8:00 p.m. to 0.78°C lower. On the other hand, at 2:00 p.m., the module with a green roof registered a temperature of 0.65°C higher than the module without a green roof for the extreme case, but with a significant reduction of 5.34°C in the minimum temperature. This underscores the ability of the green roof to moderate extreme temperatures in the afternoon.

Figure 3 summarizes differences in temperature and demonstrates that the green roof has a significant impact on thermal stabilization by the use of the green roof in the module. Although the maximum temperature at 2:00 p.m. was slightly higher in the green-roofed module, it mitigated temperatures (during the hottest hours), reducing minimum temperatures significantly. This is consistent with previous studies such as [20], suggesting that roofs have the ability to improve indoor thermal comfort by reducing the amplitude of exterior thermal fluctuations. Modules with green roofs contribute to greater thermal stability, regulating and attenuating excessive heat. It creates a cooler temperature and a more comfortable microclimate within the modules, especially in hot climates. Implications in social housing are: Lower cost in energy, major efficiency in thermal use for air conditioning. In addition, reducing the temperature by up to 3°C allows for demonstrating the implications of changes in these modules.

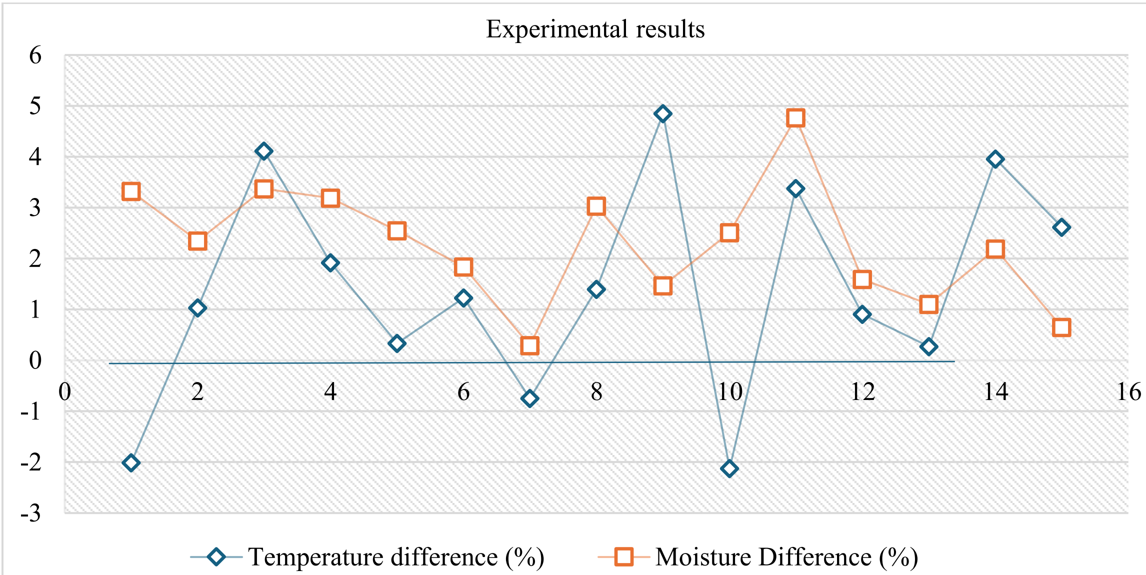


Fig. 3 Comparison of temperature and relative humidity between the module without a green roof and the module with a green roof. The "y-axis" is % differences between

In Figure 3, several key trends and differences between green-roofed and non-green-roofed modules can be highlighted. It shows an average temperature difference ranging from -0.5°C to +1.33°C. Relative humidity in the green-roofed module was typically higher than in the non-green-roofed module, with differences ranging from +0.29% to +4.77%. Temperature changes found in this work can be explained by evapotranspiration, increasing by the release of water vapor, raising humidity levels inside the module, and decreasing temperature. The most significant increase in relative humidity was observed at 2:00 p.m.: The Green roof's higher moisture retention capacity as heat and humidity increased during the day. The green roof helped to moderate both temperature and humidity levels inside the module. Although it did not consistently lead to large temperature drops, it played an important role in regulating humidity, creating a cooler and more comfortable indoor environment. The most significant differences were noted around 2:00 p.m., during peak solar radiation, when the green roof effectively reduced temperature spikes and maintained higher humidity levels.

As described previously, the results show a notable difference between modules with and without a green roof, especially concerning temperature and relative humidity. Figure 2 shows the curves where the green-roofed modules stayed much cooler, reaching up to 3°C less during peak heat (around 2:00 p.m.), reinforcing the hypothesis that the green roof acts as a thermal insulator. It's also worth noting that there was higher relative humidity inside these modules. This means they retain more moisture, which translates into a more pleasant and comfortable environment.

3.3. Impact on Thermal Comfort and Energy Efficiency

Green roofs offer substantial advantages in thermal comfort and energy efficiency. The plants and soil help attenuate temperature increases, while the insulating properties of the concrete beneath the vegetation reduce the need for cooling on hot days. This, in turn, lowers energy consumption and contributes to cost savings for buildings.

Vegetation enhances indoor air quality and stormwater management, usually related to the drainage system, too, allowing rainwater to be absorbed. Conversely, solid concrete slabs, lacking insulating layers, experience greater temperature increases, leading to heat accumulation during the day and slower cooling at night. This can affect thermal comfort and increase energy consumption to maintain a comfortable indoor temperature.

3.4. Identified Research Gap

A vast number of papers explore green roof thermal performance; some of them, particularly those on a larger scale or in diverse climates, often rely on simulation models, remote sensing, or aggregated city-level data (e.g., as seen in studies by [10, 11] for broader urban assessments, or [12] for global comparisons). For instance, some simulation-based studies in Mexico have projected significant temperature reductions (e.g., up to 4.7°C, [Source 1, 2]), yet direct validation in specific social housing contexts remains less explored. Approaches are valuable for macro-level insights or predicting hypothetical scenarios that may be generated in further work. Architectural design and civil engineering are some areas that benefit from this work, and bring the necessary elements to create spaces that are functional and also capable of evoking emotions and sensations. Comfort in a house design is valuable because in Mexico, families live a significant part of the day inside their homes.

This study directly addresses this gap by employing a controlled, field-based experimental setup involving paired social housing modules-one with a green roof and one as a control-in Ébano, San Luis Potosí. Unlike studies primarily using theoretical models or broader geographical data, our methodology provides localized, empirical measurements of temperature and relative humidity. This comparative, real-world approach offers concrete evidence of green roof performance in a specific, underrepresented context, contributing valuable data for sustainable infrastructure planning where empirical results for social housing are scarce.

4. Conclusion

This paper shows that green roofs have a notable ability to reduce internal temperatures (for the case of modules exposed in this work). Compared to modules without green roofs, those with green roofs exhibited a temperature reduction of 2 to 4°C, particularly during peak solar radiation hours (2:00 p.m.).

It highlights the effectiveness of the use of multilayer material over a slab in green roofs in moderating indoor microclimates. It is important to relate this to the urban heat island effect, forming heat islands, which may reduce temperature in a wide zone if this technique is supported, making them a valuable tool for improving urban resilience to heat stress. Furthermore, modules with green roofs increase the relative humidity, ranging from 5 to 10%. This enhancement in humidity not only contributes to better air quality but also creates a more comfortable environment, particularly during hot days, thereby promoting occupant well-being. The regulation of both temperature and humidity by green roofs significantly improves thermal comfort, an essential factor in urban areas characterized by high temperatures and air pollution.

The results of this study show that green roofs at the selected place can mitigate the adverse effects of climate change in cities. Findings suggest that green roofs offer significant environmental benefits, including the moderation of internal temperatures and regulation of humidity, by reducing ambient temperatures, improving air quality, and enhancing building energy efficiency.

A green roof can be a multi-faceted solution to sustainability in cities with a cost-effective and accessible strategy for urban planning, reducing energy consumption, and fostering climate adaptation. Thus, the adoption of green roofs should be promoted as part of broader urban strategies aimed at creating healthier, more sustainable urban environments.

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