Comparative-experimental study of different roof types in a tropical climate

Estudio experimental-comparativo de diferentes techos en un clima tropical

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Abstract

Introduction— The implementation of green roofs in buildings has become increasingly common, because it is an ecological construction alternative that provides great benefits, which range from reducing air pollution to improving air conditioning inside of the buildings.

Objective— This article aims to evaluate whether extensive green roofs are an energy-valuable option in a tropical climate compared to a thermoacoustic, clay tile, and concrete roof.

Methodology— An experimental study was carried out in summer (December) in a tropical climate, where the internal temperature of two identical small buildings was compared except for the roof type. Both small buildings were built with a low construction standard according to buildings of families with low income in this region. Data of internal temperatures and other climatic conditions were analyzed to compare the influence of the roof type on the inner shelter temperature.

Results— In these experiments, the average inner shelter temperature of green roofs was lower than the same temperature for thermoacoustic, clay tile and concrete roof and resulted in average temperature differences of 1.8°C, 0.9°C and 1.5°C, respectively (depending on environmental conditions).

Conclusions— It was possible to show that the green roof has a greater thermal inertia compared to the others. However, the temperature difference between the green roof and the other roof types was in the same range as in studies conducted in other climatic regions, therefore no special benefit of the green roof has been derived in a warm-tropical climate in this study. However, the low building standard can be of great interest for a final evaluation and the authors recommend to conduct further studies.

Keywords— Green roof; temperature; tropical; experimental study; extensive

Resumen

Introducción— La implementación de techos verdes en las edificaciones se ha vuelto cada vez más común, debido a que es una alternativa de construcción ecológica que brinda grandes beneficios que van desde la reducción de la contaminación en el aire, hasta la mejora de la climatización dentro de los edificios.

Objetivo— Este artículo tiene como objetivo evaluar si los techos verdes extensivos son una opción energéticamente valiosa en un clima tropical en comparación con un techo termoacústico, de tejas de barro y concreto.

Metodología— Se realizó un estudio experimental en verano (diciembre) en clima tropical donde se comparó la temperatura interna de dos cubículos idénticos excepto del tipo de techo. Los cubículos fueron construidos de bajo estándar de construcción como se construyen casas unifamiliares de personas de bajos ingresos. Los datos de temperaturas internas y demás condiciones climáticas se analizaron para comparar la influencia del tipo de techo en la temperatura interna del cubículo.

Resultados— En los experimentos realizados, la temperatura interna promedio en los techos verdes fue menor que la misma temperatura de los techos termoacústicos, de tejas de barro y concreto, con diferencias de 1.8°C, 0.9°C y 1.5°C, respectivamente (dependiendo de las condiciones ambientales).

Conclusiones— Se pudo evidenciar que el techo verde presenta una mayor inercia térmica con respecto a los demás. Sin embargo, la diferencia de temperatura entre el techo verde y los otros tipos de techo estuvo en el mismo rango que en los estudios realizados en otras regiones climáticas, por lo tanto, no se ha derivado ningún beneficio especial del techo verde en un clima cálido tropical en este estudio. Sin embargo, el bajo estándar de construcción puede ser de gran interés para una evaluación final y los autores recomiendan realizar más estudios.

Palabras clave— Techo verde; temperatura; tropical; estudio experimental; extensivo

I. Introduction

Since cities are growing very fast, and plants, parks, and wood lands decrease, cities are heating up and animal and insect variation diminishes. Green roofs, also called vegetated roofs, eco roofs or living roofs, present a possible solution, as they present big benefits to environment and population. They are composed out of different layers like impermeable layer, drainage layer, filter layer and substrate, which allow growth of different types of vegetation on top of buildings.

Lots of research has been conducted in different climates, comparing different roof types with each other, evaluating the cost benefit and life cycle approaches. From an economical point of view, green roofs are considered a short-term investment with low risk. Thus, making profit is much more likely than a possible financial loss. Considering further advantages to society and nature this investment is even more worth of being made [1].

The mentioned further benefits are the moderation of heat island effect, better stormwater management and lifespan of the roof structure, noise reduction, among others. Besides, it can insulate a building efficiently [2], [3]. However, other researchers found out that the biggest challenges of green roofs are high initial construction costs, high maintenance costs and roof leakage problems [3].

From a technical point of view, lots of research was conducted in different climate. An overall review presented as parametric study, which compares the effect of different green-roof types on external/internal temperature and cooling demand under four different climates and three urban densities, uses a co-simulation approach with ENVI-met and Energy Plus and reveals an external and internal cooling effect between 0.05°C–0.6°C and 0.4°C–1.4°C, respectively depending on the green-roof type, urban density and time of the day [4].

In agreement with the above, the inner room and exterior roof temperature of a green roof and a common roof were compared in a humid subtropical climate in Shanghai. It was found that the inner room temperature of the green roof stayed constantly about 2°C cooler than the concrete roof [5]. The outer roof temperature of the green roof varied between 20 °C and 30°C, whereas the common roof temperature differs in amounts from 20°C to 65°C for one day. Additionally, in summer in Pennsylvania (humid continental climate) the same roof temperature difference was measured: where the maximum green roof inner temperature was about 40°C, the black roof on the same day was about 30°C hotter [2].

In contrast, certain experiments conducted in the semi-warm climate of Mexico [6], where a green roof was compared to a concrete roof, the interior temperature of the green roof remained 20.5°C cooler than the temperature of the concrete roof, which reduced electricity consumption of an air-conditioning equipment about 1.3 kW/h, representing 10.3%. So, do green roofs outperform other roof types regarding lower inner shelter temperatures and is this effect higher in a tropical climate than in internationally conducted studies?

To respond to that hypothesis, the inner shelter temperature of a green roof has been compared against three other common roof types in the region: thermoacoustic, clay tile, and concrete roof.

The main objectives of this study are the following:

- Determine the influence of a green roof on the inner shelter temperature in a tropical climate.
- Compare different roof types under same meteorological conditions.
- Quantify the benefit of a green roof in a tropical climate.

First, the instruments of the experimental data are shown, the climatic conditions of Bucaramanga are highlighted, and the green roof is characterized. Afterwards, the methodology of the experiment is explained, and results and conclusions of this study follow.

II. Implementation of the experimental measurement equipment

A. *Climatic conditions*

Bucaramanga (6.99°N, 73°W, 959 m.a.s.l.) is a city located close to the equator and belongs to the tropical monsoon climate. It has no seasons and the average temperature is about 22°C with a maximum of 27.1°C and a minimum of 17.5°C. Due to close mountains, the average temperature in Bucaramanga is lower, than in cities with comparable geographic conditions. The relative humidity counts about 83% throughout the year and the total precipitation rate is about 1346 mm per year [7]. The experiments took place in "Parque Tecnológico Guatiguará", which belongs to "Universidad Industrial de Santanter".

B. *Experimental structure*

In this experimental study, Green Roofs (GR) systems have been compared to other roof type systems: Thermoacoustic Roof (TAR), Clay Tile Roof (CTR), and Concrete Roof (CR). The experiment was realized with two identical shelters (except roof type) of a volume of 29 m^3 [2.44 m × 4.88 m × 2.44 m (L × B × H)], whose geographic orientation is shown in Fig. 1. The roof area of each shelter is 12 m^2.

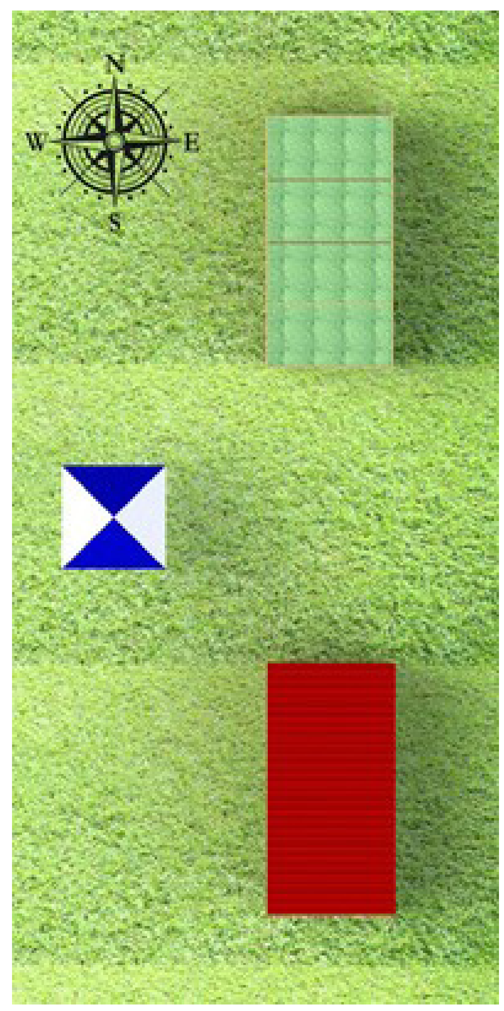


Fig. 1. Orientation of the shelters [9].
Source: [10].

The GR is made of various layers: vegetation layer, soil layer, drainage layer, and impermeable layer. *Arachis pintoi (Pinto peanut)* was used as vegetation and the GR is characterized as extensive green roof, since the soil substrate depth is less than 10 cm. The properties of the materials used can be found in Table 1. The irrigation event found place manually every morning until soil moisture saturation.

Table 1. Material properties of the green roof layers.

Material	ρ	Cp	k	δ
Vegetation	1000	2000	*	0.15
Soil	1500	1320	0.69	0.03
Stone	1600	880	1.15	0.015
Wooden batten	950	1600	0.29	0.01

Source: [8].

C. *Instrumentation and temperature measurements*

Meteorological data, as wind speed and direction, solar irradiation, and ambient temperature, were taken with a weather station that was installed close to both shelters to obtain local meteorological data, as seen in Fig. 1, marked with blue and white. Those were saved as average value every 10 min. In each shelter, five thermocouples of type K were installed to monitor the inner temperature, as demonstrated in Fig. 2. All thermocouples were connected to the data acquisition system Agilent 34972A, which scanned temperature data every 2 min from 8 am until 4 pm. For the analysis, the average value of all five thermocouples was calculated.

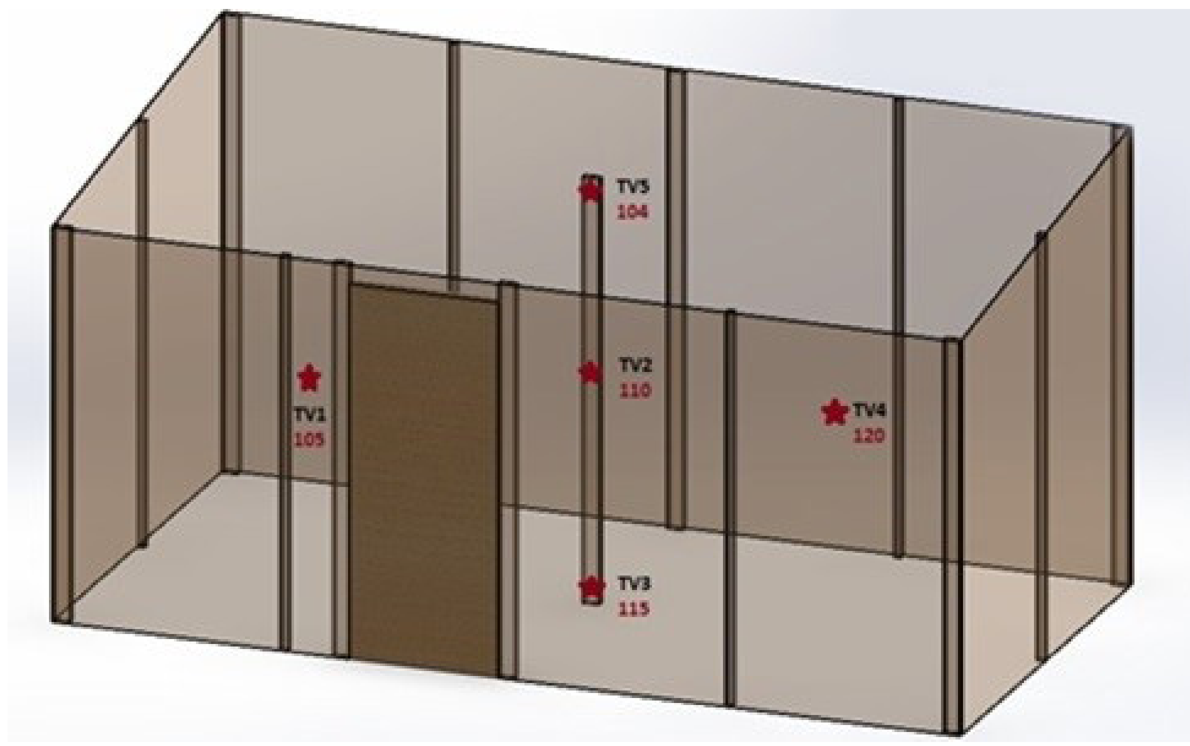


Fig. 2. Installation of thermocouples in the shelter in SolidWorks [9].
Source: [10].

In the following, the measuring equipment, as well as their resolution and accuracy values are listed.

TABLE 2. MEASUREMENT EQUIPMENT.

Equipment	Resolution	Nominal Accuracy (±)
Thermocouples type K		2°C
Data acquisition Agilent 34972A		
Weather station Davis Vantage Pro2:		
Outer temperature	0.1°C	0.5°C
Wind speed	0.5 ms^{-1}	1 ms^{-1}
Wind direction	1°	3°
Solar irradiaron	1W m^{-2}	5% of full- scale

Source: Authors.

III. RESULTS AND DISCUSSION

During the measuring period, a GR has been compared to a TAR, CTR, and CR, during summer on the 7th, 10th, 12th, 15th and 18th of December, respectively. To compare the temperature difference between both measured inner shelter temperatures of one day against other days, the solar irradiation has been modified polynomially. The data have been analyzed in MATLAB [11].

Firstly, the shelter with a GR is compared against a TAR. In Fig. 3 the temperature variation and the respective solar irradiation during both days are shown. On both days it can be noted that the temperature of the GR is lower than ambient temperature in the morning.

Also, the inner shelter temperature of the GR is for both days and at any time lower than of the TAR independent from solar irradiation heights and time of the day. The mean difference between both roof types is of 1.1°C and 2.5°C, on the 7th and the 10th of December, respectively, where the daily solar energy corresponds to 17.3 MJ m^{-2} and 17.66 MJ m^{-2}.

Afterwards, the TAR was changed to a CTR. Data were obtained on the 12th and 15th of December, as shown in Fig. 4, and the solar energy was summed up to 15.84 MJ m^{-2} and 13.34 MJ m^{-2}, respectively. On the 12th of December, again the inner shelter temperature with GR is lower than ambient temperature in the morning. the solar irradiation increased very fast and constantly in the morning, until reaching nearly 900 W m^{-2} at 10.30 am.

Under this condition, the difference between the GR and the CTR stays constantly between 2.5°C and 3°C, as presented in Fig. 7.

In the afternoon, the solar irradiation varied a lot, however frequently reaching values of about 900 W m^{-2}. Throughout the day, the temperature of the GR was around 2.3°C cooler than the CTR. On the 15th of December, the incident solar irradiation was very low, which caused a similar behavior of the GR and the CTR, thus nearly no benefit was found. The average temperature difference between both roof types was 0.5°C.

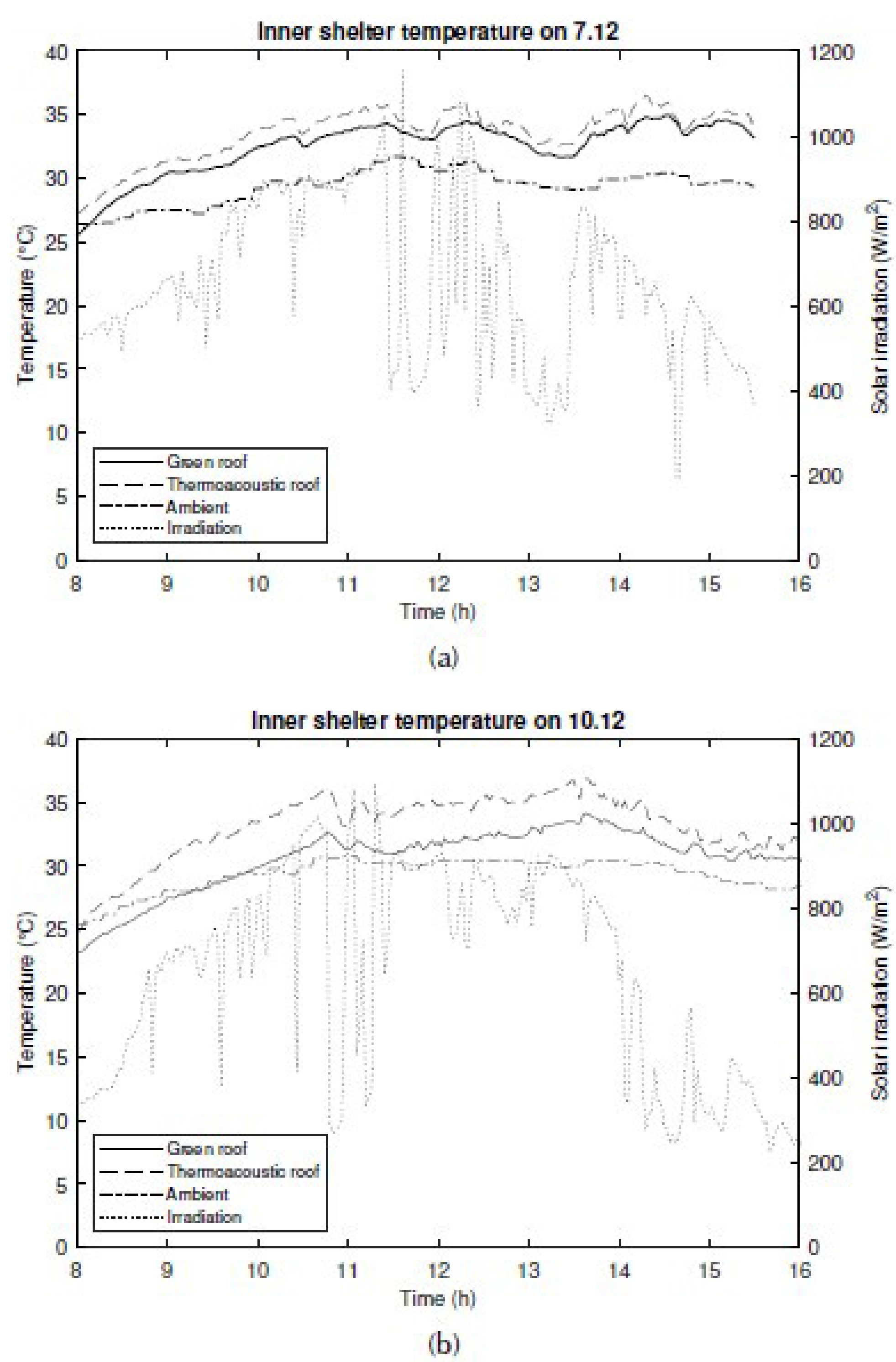


Fig. 3. Inner temperature of GR and TAR plotted against solar irradiation on a) 7th and b) 10th of December.
Source: Authors.

Data from the 18th of December show the difference between the GR and a CR, as demonstrated in Fig. 5, with a solar energy amount of 14.46 MJ m^{-2} during the day. The maximum temperature difference was about 2.1°C and its average difference about 1.5°C. All in all, the inner temperature of the shelter with GR was lower, than with CR.

TABLE 3. COMPARISON OF THE ROOF TYPES.

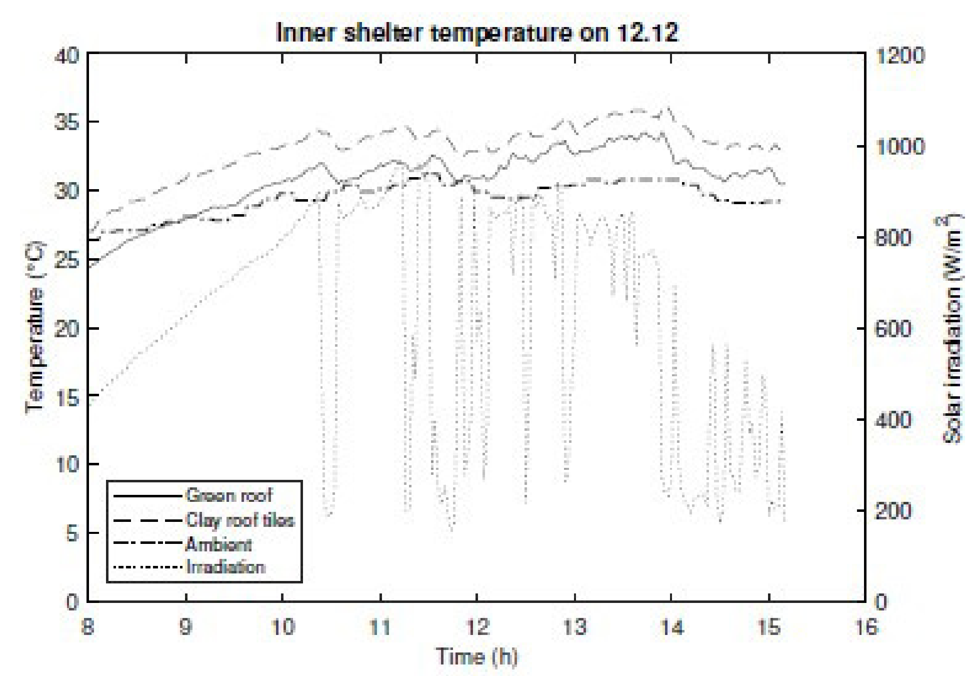
	GR-TAR		GR-CTR		GR-CR
date	07.12.	10.12.	15.12.	17.12.	18.12.
Solar energy [MJ m⁻²]	17.30	17.66	15.84	13.34	14.46
ΔT_{max} [°C]	1.6	4.0	3.5	1.6	2.1
ΔT_{avg} [°C]	1.0	2.5	2.3	0.5	1.5

Source: Authors.

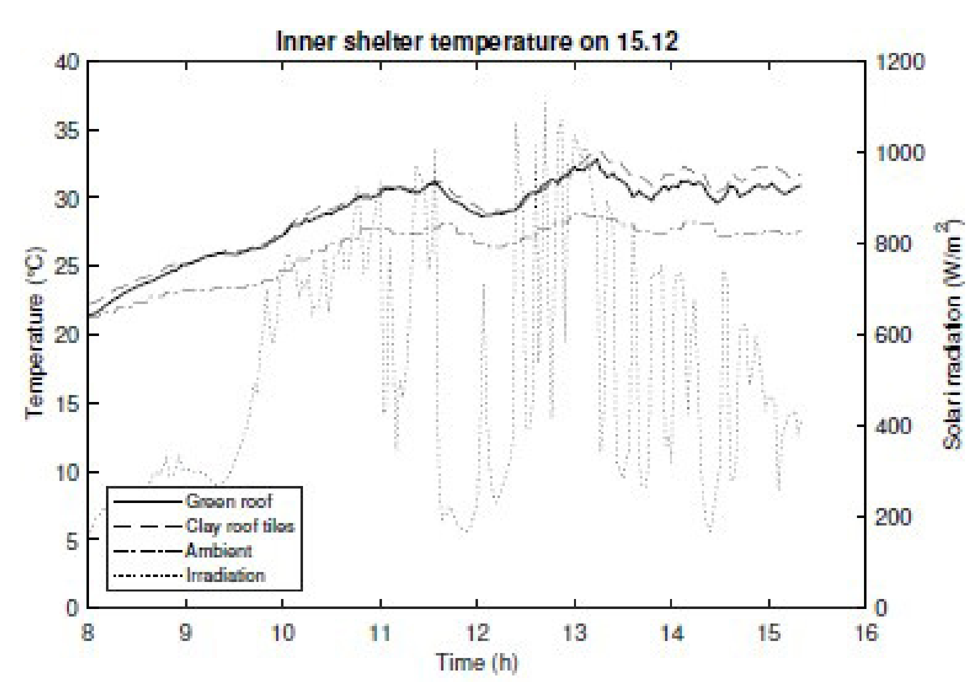
The most important values for a comparison of the different roof types and dates have been concluded in Table 3.

Unfortunately, the solar energy per day varied a lot, complicating the comparison but comparing the 7th and the 10th of December (GR-TAR), which had similar solar energy values, the maximum and average temperature differences between both roof types vary a lot, indicating that the irradiance at midday enables a higher benefit of the GR.

This is not surprising due to the nearly vertical solar incident angle but the maximum temperature difference of 4°C is still important especially for locations near the equator.



(a)



(b)

Fig. 4. Inner temperature of GR and CTR, as well as solar radiation on a) 12th of December and b) 15th of December.
Source: Authors.

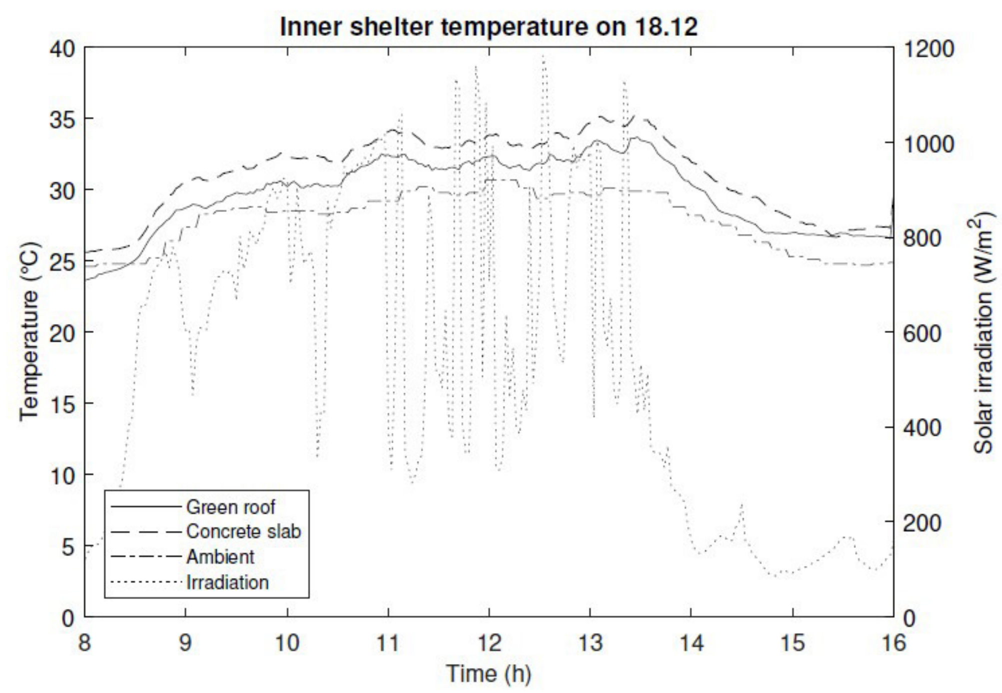


Fig. 5. Inner temperature of GR and CR, as well as solar radiation on 18th of December.
Source: Authors.

For further analysis, the temperature difference between the compared roof types per day has been plotted against the corresponding irradiance in the trajectory of the day, since the irradiance data have been modified polynomically.

On the 7th of December (*continuous line*), the temperature difference is very low, and the benefit of GR is nearly insignificant. The temperature difference does not vary from morning to evening, thus both roof heat up and cool down equally.

On the 10th of December (*dashed line*) a higher temperature difference in the morning, than in the afternoon can be observed, indicating a higher thermal inertia of the GR system, than the TAR system.

Comparing the GR and the CTR, lower solar irradiation was measured in the morning than in the evening. Fig indicates a higher temperature difference in the morning than in the evening, thus also indicating that the GR has a higher thermal inertia than the CTR for the 12th of December (*continuous line*). However, for the low irradiation values of the 15th of December the benefit of the GR especially at midday is nearly negligible.

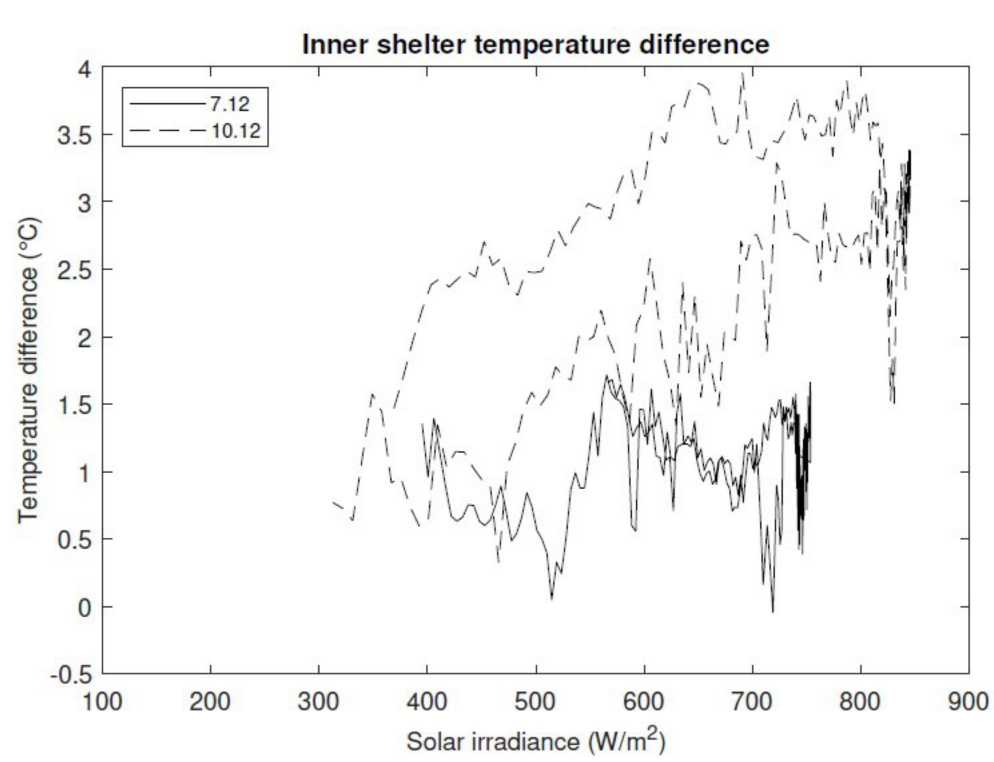


Fig. 6. Absolute temperature difference between GR and TAR.
Source: Authors.

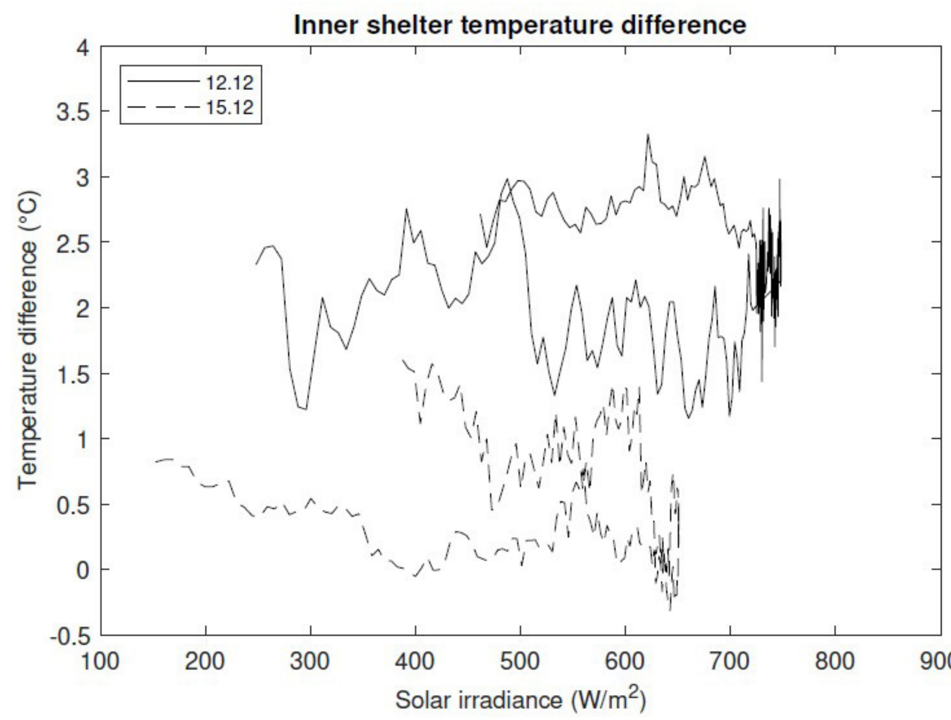


Fig. 7. Absolute temperature difference between GR and CTR.
Source: Authors.

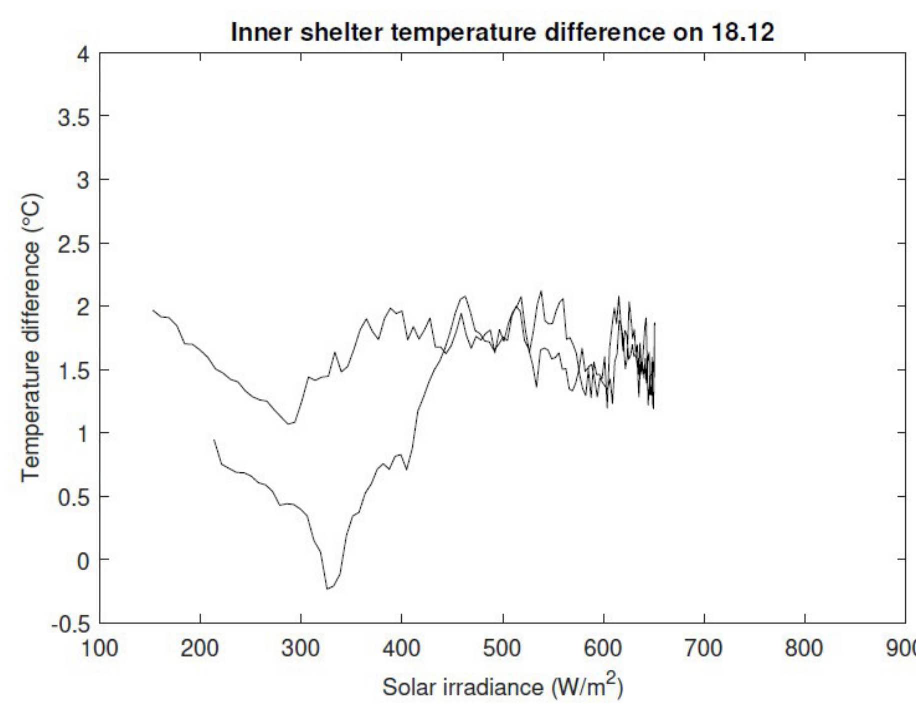


Fig. 8. Absolute temperature difference between GR and CR.
Source: Authors.

Comparing the gradients of both roof types for the 18th of December in Fig. 5, it can be noticed, that the temperature difference in the morning is higher than in the evening. At midday and in the afternoon (*lower half of the line*), solar irradiation was very unsteady, but the temperature difference stayed constantly at around 1.5 °C. At 1.30 pm, solar irradiation diminished rapidly, causing an approximation of GR and CR temperature. Therefore, it can also be derived from the data, that also the CR system has a lower thermal inertia, than the GR system.

All in all, the average temperature difference of 0.5°C–1.6°C, is close to the temperature differences of different climates, where they compared mostly GR and CR and obtained temperature differences of between 0.05°C–0.6°C and 0.4 °C–1.4°C, depending on the green-roof type, urban density and time of the day [4]. So, this study did not reveal an especially high benefit of GR for a warm tropical climate. However, it needs to be taken in mind that the shelters of this study do not have the same building standard regarding materials, insulation or green roof installation, as buildings of low income in the tropics were considered.

Finally, the authors recommend a more extensive study of the green roof by measuring the volumetric water content throughout the measuring period in order to be able to analyze the evapotranspiration rate throughout the experiments and thus, determine the cooling effect of the green roof [6]. Besides, temperature measurements at night should be made, to analyze the thermal behavior of the GR and compare it to other roof types, when the ambient temperature is lower.

IV. Conclusions

The following conclusions have been derived:

- The temperature of the GR is lower than the ambient temperature in the early morning hours and most probably at night.
- The higher the solar irradiation, the bigger the green roof benefits regarding a lower inner shelter temperature.
- For the measured climatic conditions and the low building standard of the shelters, the green roof outperformed the thermoacoustic, clay tile and concrete roof, and the average temperature difference was 1°C to 2.5°C, 0.5°C to 2.3°C and 1.5°C, respectively.
- GR help to avoid high peak temperatures at midday, especially when the irradiation is high.
- The thermal inertia of green roofs is higher than of the other roof types that were analyzed during this study, which helps to maintain the temperature steadier throughout the day.
- No special benefit of green roofs for tropical warm climate has been derived in this study (with the low building standard buildings) comparing the results to [4].

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References

[1] F. Bianchini & K. Hewage, "Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach," *Build Environ*, vol. 58, no. 1, pp. 152–162, Dec. 2012. https://doi.org/10.1016/j.buildenv.2012.07.005

[2] K. L. Getter & D. B. Rowe, "The role of extensive green roofs in sustainable development," *HortSci*, vol. 41, no. 5, pp. 1276–1285, 2006. https://doi.org/10.21273/HORTSCI.41.5.1276

[3] M. Shafique, R. Kim & M. Rafiq, "Green roof benefits, opportunities and challenges – A review," *RSER*, vol. 90, no. 1, pp. 757–773, Jul. 2018. https://doi.org/10.1016/j.rser.2018.04.006

[4] T. E. Morakinyo, K. Dahanayake, E. Ng & C. L. Chow, "Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study," *En Build*, vol. 145, no. 1, pp. 226–237, Jun. 2017. https://doi.org/10.1016/j.enbuild.2017.03.066

[5] Y. He, H. Yu, N. Dong & H. Ye, "Thermal and energy performance assessment of extensive green roof in summer: A case study of a lightweight building in Shanghai," *En Build*, vol. 127, no. 1, pp. 762–773, Sep. 2016. https://doi.org/10.1016/j.enbuild.2016.06.016

[6] M. A. Chagolla-Aranda, E. Simá, J. Xamán, G. Álvarez, I. Hernández-Pérez & E. Téllez-Velázquez, "Effect of irrigation on the experimental thermal performance of a green roof in a semi-warm climate in Mexico," *En Build*, vol. 154, no. 1, pp. 232–243, Nov. 2017. https://doi.org/10.1016/j.enbuild.2017.08.082

[7] IDEAM, "IDEAM," *ideam.gov.co*, [online], 2014. Available: http://www.ideam.gov.co

[8] T. C. ASHRAE, "," *ASHRAE Handbook Fundamentals*, ATL., GA.: Ashrae Bookstore, 2017. Disponible en https://www.ashrae.org

[9] J. Hirschtick, "Solidworks CAD," *Software*. Ma., USA.: Dassault Systèmes, 2017. Disponible en https://www.solidworks.com/es

[10] R. Reyes & J. Sánchez, "Estudio de las ventajas térmicas de los techos verdes en Bucaramanga," *Thesis*UIS, Bga., San., Col., 2013.

[11] The Mathworks Inc., "MATLAB," *Natick*Massachusetts: The MathWork Inc., 2014. Available: https://www.mathworks.com/search.html?c%5B%5D=entire_site&q=matlab&page=1