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Preliminary assessment of the thermal performance of a hydroponic green roof system in a Mediterranean climate

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Abstract. One of the main goals of building design is indoor comfort, regardless of its use (residential, educational, institutional, etc…).
However, to achieve indoor comfort, buildings require a significant amount of energy.
In the last decades, designers and researchers have been studying new strategies to improve buildings' energy efficiency, with the purpose of mitigating the negative environmental impact caused by heavy energy consumption.
Green roofs have been one of the most investigated solutions because of the many thermal benefits they can offer, and amongst these, hydroponic green roofs gained momentum.
This study aims to analyse the rooftop temperature reduction provided during the hot months by a hydroponic green roof, compared to a traditional roof slab and an extensive green roof, in order to assess the different performances of these systems.
In situ experiments were conducted to collect surface temperature of the roof slab during summer, with and without the hydroponic system, in order to assess the potential temperature reduction, which subsequently affects the heat flow through the roof and therefore the indoor air temperature.
The results show a significant decrease in the external surface temperature of the roof compared to the bare roof, but also slightly better performance compared to the extensive green roof.
Despite first promising results, the knowledge on hydroponic green roofs performance remains limited and some drawbacks need to be assessed. For these reasons, further in situ testing should be carried out, under different climatic conditions and experimental setups.

Key words. Hydroponic green roof systems, Heat mitigation, Passive cooling, Environmental impact mitigation.

1. Introduction

Over the years, building design has evolved to suit people's and cities' needs. Buildings' operation is one of the most resource demanding activity, mainly because of the great amount of energy necessary to pursue indoor comfort.
In Europe, not only buildings represent 40% of the total energy consumption but are also responsible for 36% of the overall CO_2 emissions. Due to these phenomena, in the last decades governments have pursued solutions for the increasing energy demand and the contextual decrease of available resources. European and national regulations, as well as strategies such as net zero energy buildings (NZEB) policy, have been issued as a mean for environmental protection and conservation of non-renewable resources.
In this perspective, designers and researchers have been investigating new strategies to improve buildings' energy efficiency in order to subsequently mitigate the negative environmental impact caused by heavy energy consumption.
As buildings' envelopes play a substantial role in buildings' energy performance, since they regulate inbound and outbound heat fluxes, they represent a key aspect in the assessment of energy efficiency strategies. In this regard, green roofs are one of the most investigated technologies.
The interest in green roof technology is intensified by the fact that it joins high energy performance with sustainable materials and reduced emissions, compared to traditional construction materials.
In fact, studies show that, thanks to their various layers (i.e., green canopy and substrate layer) they provide remarkable performances under several aspects, such as air temperature reduction, solar radiation shielding during hot seasons, water runoff management, and urban heat island (UHI) effect mitigation [1,2].
Despite them being widely known, the use of green roofs is limited due to few drawbacks that prevent these systems to become mainstream construction techniques, such as high maintenance and high installation costs.
In recent years, few studies [3-6] have hinted at the possibility of implementing hydroponic cultures in green roof systems. The idea arises from the consideration that most of the issues with green roofs are linked to the composition and mechanical characteristics of the substrate layer and root control, which require great attention both during the design phase and the subsequent maintenance. In fact, hydroponic cultivations are soil-les systems characterised by the absence of a solid substrate layer, replaced by a water based nutrient solution, which provides the nourishment for the plant growth.
Hydroponic practice arises as an alternative to traditional agriculture, due to the possibility to cultivate despite the

lack of land and regardless of the soil quality.
In regard to urban greenery implementation, the option of implementing hydroponic systems instead of traditional green coverings is encouraged by other peculiarities such as lower impact of parasites, less need for fertilizers, absence of weeds.
Hydroponic cultivations have mostly been studied as a more sustainable alternative to traditional agriculture in terms of water and soil consumption [7] and for their easy implementation in urban areas, determining an increase in crop production for the population, a reduction in food transportation and waste and the improvement of food safety [8] thanks to a production policy based on "controlled environment agriculture" [9]. Only few authors have focused on the thermal benefits [3-6] of hydroponic systems as green roofs technologies however, studies on building-integrated agriculture (BIA) [10] have investigated how these systems can contribute to optimizing their energy and resource consumption through the trade-off between the building and the cultivation system [11]. If studies report comparable thermal and energy performances to traditional green roofs, hydroponic systems can likely become their viable competitors due to their added potential in terms of reduced resource consumption and subsequent lower environmental impact.
This paper presents the results of an experimental campaign conducted on a hydroponic green roof prototype, to assess how this system affects the temperature trend of the roof cover. Also, measurements were conducted on an extensive green roof prototype, at the same time. The aim is to obtain a quantitative preliminary assessment of the temperature reduction, in order to compare the thermal behaviour of the two systems.

2. Materials and methods

The hydroponic green roof prototype was installed on the terrace roof of building 4 (Figure 1a) of the Department of Engineering and Architecture (DICAR) at the University of Catania, a metropolitan city in the Mediterranean coast of Southern Italy, characterized by warm and humid summer and moderately cool, wet winter, according to the Köppen-Geiger climate classification [12]. The site is a three-story concrete building with traditional concrete cast slabs, while the terrace floor is also covered with concrete tiles. The terrace was chosen because it is easily accessible and, at the same time, it has great sun exposure.

In fact, the portion of the terrace where the setup was installed faces South (Figure 1b) and it is fully exposed to sunlight from about 10:00 am to 5.30 pm.
The measurements were carried out over a two-months period, across the hottest summer days in Catania of year 2021 (from 21st July 2021 to 21st September 2021).

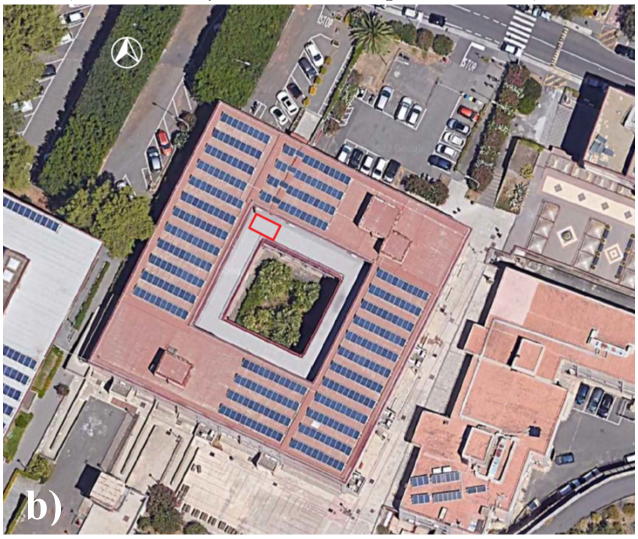

Fig. 1. Building n.4 of DICAR at University of Catania (a); placement of experimental set-up on the building terrace (b).

A. Design and installation of the experimental prototype

There are six variations of hydroponic cultivation systems: nutrient film technique (NFT) [13,14], deep water culture (DWC) [13-15], wick system, ebb and flow, drip system and aeroponic system. Amongst them, the NFT is the most widespread, however, all the types were analysed in order to assess which one is the most suitable alternative to a traditional extensive green roof.

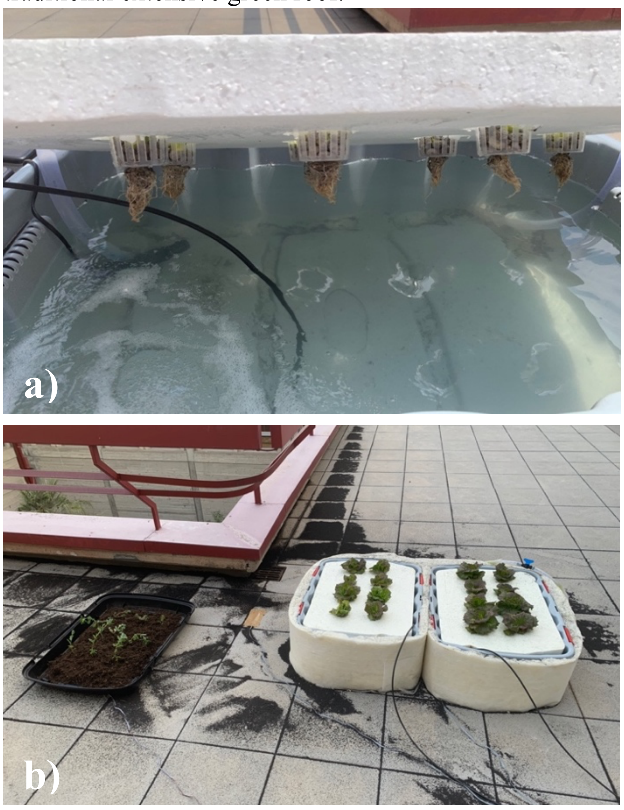

Fig. 2. Hydroponic green roof based on deep water culture system (a); Experimental set-up (b).

For the purpose of this study, the hydroponic variant chosen for our experimental setup is based on the DWC system, where the plants are lodged in a perforated polystyrene board that keeps them in place on top of a tank filled with a water based nutrient solution, where the roots are submerged (Figure 2a).
The grow beds – made with two 80 cm × 55 cm plastic tanks, filled with 18 cm-deep water – were located in an area of the roof where they were exposed at the direct sunlight at all times (Figure 1b). The hydroponic system prototype covered an overall area of 2.00 m^2.
The design of the experimental set-up is show in figure 3.
Eight lettuce plants, appropriately spaced, were used for each container. Hydroponic cultivations are versatile in terms of plant choice, since a variety of greens are suitable for this technique [16], however, lettuce plants were chosen because of their reduced growing period, which combined to their high leaf area index (LAI) guarantees a full coverage in short time period. The LAI represents the leaf area of the plant canopy per unit of ground area, and it is significative because it is an indication of the area subjected to transpiration, which contributes to passive cooling [17,18,19].
The nutrient solution was formed adding tap water with a fertilizer obtained by mixing equal parts of nitrogen, phosphorous and potassium.

In order to guarantee a constant layer of water, subject to daily evaporation, especially in hot weather condition, the regular refill of the tanks was automatized by connecting a timer to a hose inserted in the tanks.
An extensive green roof set-up was also installed to compare the insulation contribution of a traditional green roof substrate layer. The green roof was placed next to the hydroponic system in order to guarantee the same physical and exposure characteristics of the roof slab, but appropriately spaced (1.00 m apart) in order to prevent each system from affecting the performance of the other.
The extensive green roof setup was built with a layer of culture substrate and a purslane vegetated layer. The substrate is characterized by a weight at saturated volume of 1050 kg · m^{-3}.
The aim of building the extensive green roof prototype was to compare the thermal mitigation of the terrace surface provided by the two different substrates that characterise the two green roofs (respectively soil and water).
Commonly the two main layers of an extensive green roof, in terms of thickness, are the growing media and the drainage, however, for this study the extensive green roof design was simplified in order to have only the substrate and not the drainage layer, considering its contribution neglectable for the purpose of thermal assessment.

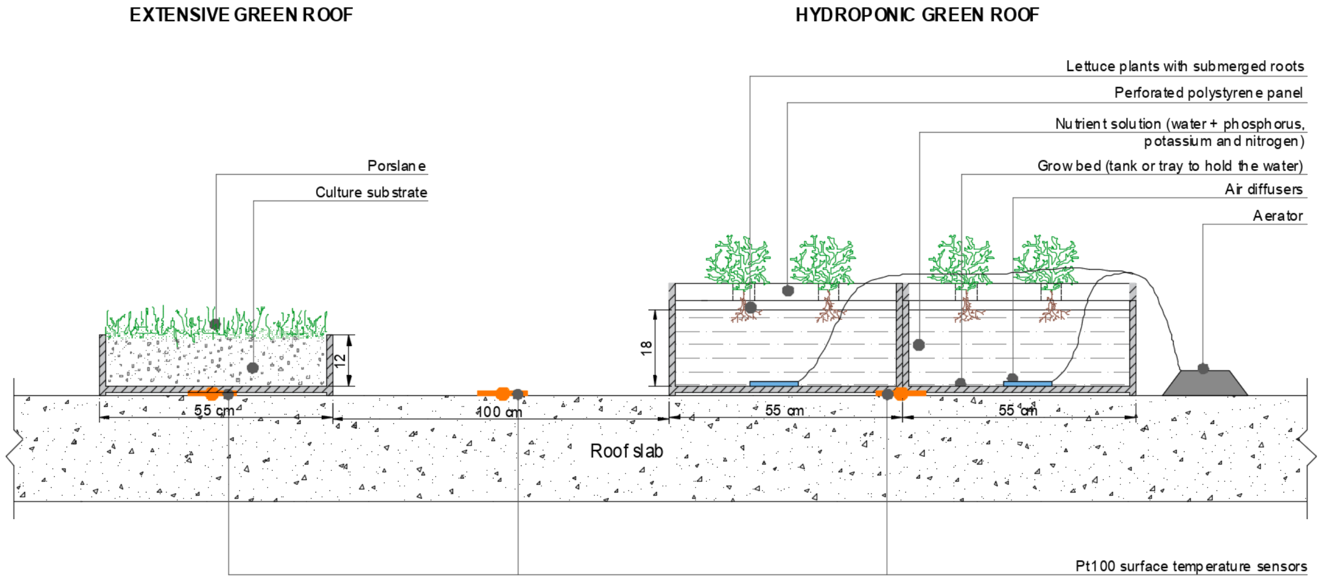

Fig. 3. Experimental set-up design and sensors placement

For the correct plant growth, two diffusers connected to an aerator were inserted inside the tanks, in order to keep the roots oxygenated, necessary when using non-aquatic plants. Due to the small size of the prototype and therefore the reduced water volume, compared to a potential real-size HGR, the water in the tanks was likely to suffer sudden temperature increase. The risk was that, with the heat of the summer months, the water could easily reach 30-35°C or more, suffocating the roots of the plants. In order to avoid this inconvenience, a layer of glass wool was wrapped around the tanks, to compensate for the thermal behaviour delivered by a greater volume of water. However, the glass wool was not placed underneath the tanks, so that only the insulation contribution of the water was considered in the measurements.

Nevertheless, the thickness of the EGR was chosen considering that a traditional green roof design would always include a drainage layer and therefore its weight contribution needs to be taken into account.
This evaluation led to set the thickness of the substrate layer of the extensive green roof at 12 cm (and not 18 cm alike the water layer in the hydroponic green roof).
The weight per unit area of the HGR with a water layer of 18 cm is 180 kg · m^{-2}. It was therefore considered that by adding a generic gravel drainage layer with a thickness of 3 cm to the 12 cm substrate layer, the total weight of the extensive green roof would match that of the hydroponic system.

B. Equipment and Monitoring

The experimental measurements were carried out using three Pt100 surface temperature sensors, to assess and compare the outer surface temperature of the slab, respectively underneath the hydroponic system, underneath the extensive green roof and on the bare roof, as base value.

Fig. 4. M-Log data logger and Pt100 surface temperature sensor LSI Lastem

Table I shows the features of the sensors used for the set-up monitoring.

Table I. – Equipment features

Equipment	M-Log	Pt100
n.	1	3
Scale	-	-50 ÷ 125 °C
Resolution	18/16 bit	0.003 °C
Accuracy	-	±0.05 °C
n. analog inputs	4	-

The temperature sensors were connected to a M-Log ELO009 data logger LSI Lastem through a connector terminal block.
The data logger is set to automatically collect minute-by-minute measurements of the surface temperature from the three sensors.
The collected data was then downloaded and exported in text files on digital support, running the 3DOM tool, through which the sensors are also configured.
The state of the hydroponic systems was also monitored collecting daily measurements, at the same time of the day, of the water temperature and its concentration of the nitrogen, phosphorous and potassium compound, using a TDS meter.
The shading provided by the plants and the polystyrene board above the grow bed allowed the water temperature to remain constant within the range 25 °C – 27 °C, with isolated peaks of 28 °C during the warmest days.
The water concentration was kept at around 1015 µS/cm (or 650 ppm), suitable for lettuce growth, by adding the fertilizer when the concentration dropped lower the optimal value, due to the nutrient absorption by the plants and the dilution of the solution after refilling the evaporated water, in order to keep the layer at a constant depth.
Daily measurements of the water depth were taken in order to assess the water evaporation rate. It was observed that the evaporation per unit area, calculated from the measurements of the water depth, kept increasing at a constant rate from the beginning of the study (21st July) until 4th August, going from 11,35 mm $\cdot$ m^{-2} to 45,40 mm $\cdot$ m^{-2}, then it kept constant throughout the following two weeks, and finally started decreasing.

C. Data processing

The raw data exported from the 3DOM tool in text files were then imported into spreadsheets and processed, selecting the significant values and excluding the anomalies.
Environmental parameters values referred to the monitoring period were provided by the weather station Catania Fontanarossa. The data files from the weather station reports consisted of hourly values of outdoor air temperature and solar irradiation.
In order to normalize all values, experimental measurements of the surface temperatures, collected by the data logger at one minute sampling time, were averaged to obtain hourly data.
Over the two-months monitoring period, the week from 4th August 2021 to 10th August 2021 showed the highest solar irradiation and air temperature peaks, with values reaching respectively I = 916,41 Wh $\cdot$ m^{-2}, on the 7th August, and T_{air} = 40,9 °C, on the 10th August.
This data is also consistent with the water evaporation rate observed by the experimental measurements, which shows the highest evaporation values during the same week.
Figure 5 shows the air temperature and global solar irradiation trends from the hourly values, for the above mentioned week.
Normalized surface temperature values measured in situ were also graphed, as shown if figure 5, in order to compare the different trends of the three roofs solution.

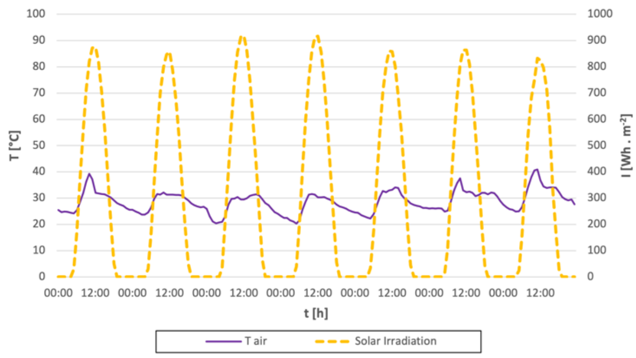

Fig. 5. Hourly values of outdoor air temperature (T_{air}) and global solar irradiation (Solar Irradiation), collected by the Catania Fontanarossa weather station in the week from 4th August to 10th August 2021.

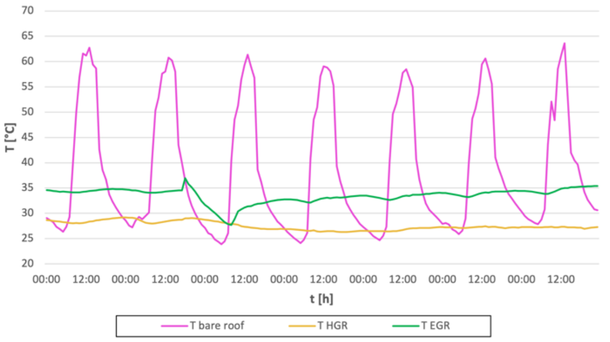

Fig. 6. Hourly values of terrace surface temperature ($T_{bare\ roof}$), roof temperature underneath the hydroponic green roof (T_{HGR}) and roof temperature underneath the extensive green roof (T_{EGR}), averaged from the direct measurements at one minute sampling time, in the week from 4th August to 10th August 2021.

3. Results and discussion

Figures 5 and 6 were overlapped in order to assess the consistency of the weather parameters and the roofs thermal behaviour.
As it was expected, the terrace temperature is in phase with the solar irradiation, with consistent peaks. In general, as opposed to the bare roof, both green roofs show a temperature oscillation within a much smaller range.
The same trends were observed for the entire duration of the study. Results referred to the week from 4th August to 10th August are presented as a significative sample of the experimental monitoring.
The analysis of the data collected from the measurements over the entire monitoring period shows a consistent trend: the outer surface of the roof below the hydroponic system has a significantly lower temperature than that of the bare roof during daytime, with a temperature difference in the range of 20 °C - 30 °C on average, in the hours between 9:00 am and 3:00 pm. In the evening hours, the temperatures of the two roofs tend to converge to similar values, until the bare roof temperature drops by 3 °C - 4 °C lower than that of the hydroponic roof at night-time, in the hours between 10:00 pm and 5:00 am.
The observed phenomenon is due to the high thermal mass of the water, which at night-time releases the heat stored during the daily hours. This result was consistent with the expected behaviour.
Likewise, it was also observed that the surface temperature of the roof underneath the hydroponic systems was lower than the air temperature during the same daily hours, but slightly higher during the night hours. This shows that the hydroponic system maintained the temperature consistent throughout the day, without sudden variations that determine thermal shocks, which can negatively affect the roof durability.
The external surface temperature of the hydroponic green roof and the green roof show a similar trend, likely due to the presence of the vegetation.
Nonetheless, it is observed that the hydroponic roof maintains a more constant surface temperature compared to the green roof, whose temperature shows greater fluctuations.
The surface temperatures determined by the green roof are observed to be on average 5°C to 8°C higher than those determined by the hydroponic system, and in general increase more with air temperature increase.
This phenomenon is accentuated when the outdoor air temperature is higher, while the temperature difference is lower for milder days.
However, the biggest difference is noticed between the hydroponic roof and the bare roof, with the maximum temperature difference exceeding 30°C.
The results obtained with the experimental phase of the study encourage the further investigation on the topic of hydroponic green roof systems, also considering the benefits of hydroponic cultures that have been brought to light by the research in the fields of building-integrated agriculture (BIA), food quality of hydroponic crops and resources consumption.

4. Conclusion

The study carried out in this paper presents the experimental results of the in-situ testing on a hydroponic green roof and an extensive green roof, carried out through the temperature monitoring of the roof surface.
This analysis represents the preliminary phase within the study of the potential thermal performance of hydroponic as an alternative to traditional extensive green roofs, therefore the first step was to assess if the temperature decrease determined by the presence of the hydroponic green roof was comparable (equal or higher) to that offered by a traditional extensive green roof.
Results have shown a significant decrease in the external surface temperature of the hydroponic green roof compared to the bare roof, but also consistent better performance compared to the extensive green roof, in the order of 5 °C – 8 °C during daytime.
An important phenomenon that was observed is the more consistent temperature of the HGR, as opposed to the extensive green roof, whose surface temperature is characterized by greater fluctuations.
Alongside the quantitative thermal assessment of a hydroponic green roof thermal behaviour, other aspects were evaluated as potential benefits provided by these systems, as mentioned in the first section of this paper.
The choice of studying the potential implementation of HGR comes primarily from the fact that these systems are relatively easy to build and maintain, as opposed to traditional green roofs. Their feature of being based on soil-les cultures cuts down the quantity of materials needed, and the problems connected to their availability.
The experimental campaign also showed the ease of setting up and maintaining a hydroponic system.
At the current state of the art, the limit of hydroponic green roof systems is the lack of extensive testing, both in different climatic conditions and in different seasons, in order to evaluate the overall performance as passive insulation system all year around.
Currently, further experimental testing on a prototype of hydroponic green roof is being carried out under different conditions, in order to assess its performance in combination with different climatic conditions and with different building features than that included in this study.
Since the ultimate goal of the investigation is to evaluate the overall potential advantages provided by the

implementation of HGR, under all the aspects involved, a further development of this study will be the definition of a model for thermal dynamic simulation of a building with a hydroponic green roof as the tested prototype, in order to assess the effect of the temperature reduction of the external surface of the rooftop on the overall indoor thermal comfort. The experimental data gathered through the testing will be used to validate the model [20].
Subsequently, an LCA analysis for a quantitative assessment of the resources consumption and environmental impacts determined by the construction and operation of these systems will be carried out.

Acknowledgement

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Nomenclature

HGR	Hydroponic green roofs
EGR	Extensive green roofs
UHI	Urban heat island
NTF	Nutrient film technique
DWC	Deep water culture
LAI	Leaf area index
TDR	Temperature difference ratio