

# Cooling buildings and growing food: performance evaluation of a hydroponic roof system in a Mediterranean climate

F. Nocera<sup>1</sup>, V. Costanzo<sup>2\*</sup>, G. Evola<sup>2</sup>, M. Detommaso<sup>2</sup>, A. Gagliano<sup>2</sup>, M. Cellura<sup>3</sup>, M. Mistretta<sup>4</sup>, S. Longo<sup>3</sup>

<sup>1</sup> Department of Civil Engineering and Architecture, University of Catania, via S. Sofia 64, 95123 Catania, Italy

<sup>2</sup> Department of Electrical, Electronic and Computer Engineering, University of Catania, viale A. Doria 6, 95125 Catania, Italy

<sup>3</sup> Department of Engineering, University of Palermo, Viale delle Scienze Bld. 9, 90128 Palermo, Italy

<sup>4</sup> Department of Information Engineering, Infrastructure and Sustainable Energy, University Mediterranean of Reggio Calabria, Via Graziella, Feo di Vito, Reggio Calabria 89122, Italy

\* Corresponding author [vincenzo.costanzo@unict.it](mailto:vincenzo.costanzo@unict.it)

**Abstract.** The aim of this research is to assess the thermal and agricultural benefits achievable with a novel deep water culture (DWC) and modular hydroponic system prototype developed in the framework of the Italian PRIN research project “Fud-Of-Sithy” (Favor the Urban Development OF Sustainable Agriculture Through Hydroponics). First, the experimental mock-up is characterized with its geometrical, thermal and plant cultivation features. Then, the results of an experimental campaign carried out during the 2024 summer season at the University of Catania campus (Italy) are presented and discussed in terms of water (i.e., nutrient) temperature, reduction in roof surface temperature compared to a traditional roof configuration and crops harvest for various vegetables. The results revealed that a well-insulated module of about 1 m<sup>2</sup> extension and 0.30 m water depth can guarantee a stable water temperature, in the range of 25-28 °C, when the outdoor air temperature is as high as 34-36°C and the peak solar irradiance is of about 800 W/m<sup>2</sup>. The first crops harvest included 0,125 kg of lettuce and 1,045 kg of basil, with growing cycles of about 25 days for the lettuce and 27 days for the basil.

## 1. Introduction

The building sector accounts for a large share of global energy consumption and consequently it is one of the main sources of environmental impact worldwide [1]. Moreover, the increasing frequency and severity of heat wave events has increased the focus on studies regarding innovative construction techniques that can help in cooling the outdoors while reducing the buildings’ cooling loads [2]. Concurrently, the need to reduce resource consumption for agriculture triggered an interest in building integrated agriculture (BIA) as a good compromise between buildings’ energy efficiency and sustainable cultivations [3].



Amongst the various BIA constructive techniques investigated over the past few years, the interest for hydroponic roof systems as an alternative to the traditional extensive green roofs has emerged [4]. The hydroponic system is based on soil-less cultivations that take place thanks to a nutrient solution dissolved in the water; this allows to overcome the issue of identifying the suitable substrate to grow the plants while reducing water consumption and chemical elements used for fertilization purposes [5]. In addition, it has the potential to increase food production and lower transportation demand, thus indirectly reducing atmospheric pollution [6, 7]. Amongst the different hydroponic system techniques, the deep water culture (DWC) is the most popular one because the water depth provides greater stability of the nutrient solution [8]. Many plant types can be grown with such systems, from ornamental plants to common vegetables such as lettuce and cabbage. From the thermal point of view, the hydroponic roof system acts as a roof pond because the water layer absorbs and dissipates the incoming heat and then lowers the surface temperature of the roof and the indoor air temperature [9, 10].

Most of the existing literature studies about hydroponic systems in buildings deal with experimental activities carried out in Asian and tropical countries focusing on roof surface temperature and heat flux trends [10, 11]. As an example, Huang et al. showed that a 10 cm-deep hydroponic roof system led to an average temperature decrease on the rooftop of about 11 °C and a heat amplitude decrease of 60% with respect to an extensive green roof [12].

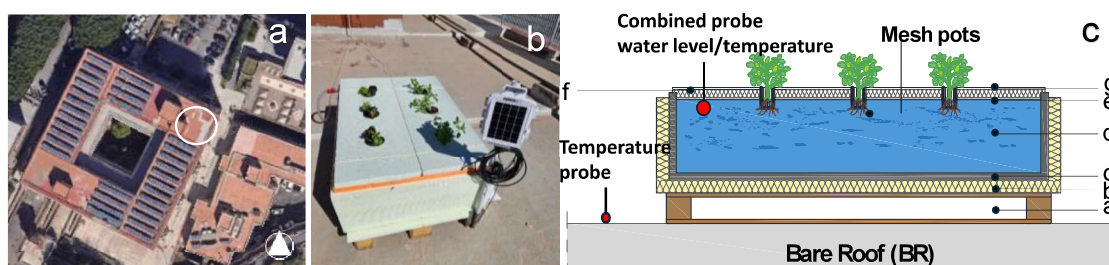
This research paper aims to expand the current knowledge by assessing the combined thermal and agronomic benefits of a DWC hydroponic roof system prototype installed on the rooftop of a building located in the Mediterranean climate of Catania (Italy). Experimental measurements of roof surface temperature and heat flux were conducted during the 2024 summer period, along with the first crops harvest of different vegetables.

## 2. Material and methods

### 2.1. Description of the experimental mock-up

The prototype of the hydroponic roof system has been installed on the existing roof of a building at the Civil Engineering Department, University of Catania, Italy (Latitude 37°30' N, Longitude 15°04' E), a location classified as Csa according to the international Köppen-Geiger climate classification.

The existing roof structure is made of 16 cm hollow clay blocks and 6 cm reinforced concrete layer, covered with clay tiles. Figure 1a shows the aerial view of the building where the hydroponic roof prototype was installed, while Figure 1b depicts the experimental setup and Figure 1c shows a schematic of the different materials used. The thermo-physical features of each layer in the hydroponic module (HR) and the existing bare roof (BR) are instead reported in Table 1. The letters (a-g) indicate all the layers of hydroponic module whose thermal properties are reported in Table 1. The thermo-physical properties of the various layers in the existing bare roof are taken from the Italian Standard UNI EN 10361:1994.



**Figure 1.** DWC hydroponic roof prototype: a) aerial view of the rooftop where the hydroponic module is installed; b) Experimental mock-up of the hydroponic system; c) Vertical section of the mock-up with the various materials indicated

**Table 1.** Layers and thermal features of the hydroponic module (HR) and the bare roof (BR).

	Layer	t (m)	$\lambda$ (W/m·K)	$\rho$ (kg/m <sup>3</sup> )	Cp (J/kg·K)
HR	g Polycarbonate top lid shell	0.001	0.20	0.593	1200
	f Extruded polystyrene	0.03	0.032	33	1450
	e Polycarbonate bottom lid shell	0.001	0.20	1200	1200
	d Water solution	0.30	0.56	1000	4186
	c Polycarbonate floor	0.003	0.20	1200	1200
	b Extruded polystyrene	0.05	0.032	33	1450
	a Lightly ventilated air gap*	0.04	0.20	1.2	1000
BR	Clay tiles	0.02	1.50	1700	1000
	Mortar cement	0.02	1.40	1500	2000
	- Light cement screed	0.06	1.35	1800	1000
	Reinforced concrete	0.06	1.40	2000	1000
	Hollow clay blocks	0.16	0.70	1280	840
	Inner plaster	0.02	0.90	1800	1000

\*The value refers to an equivalent thermal resistance for a lightly ventilated horizontal air gap according to the National standard UNI EN ISO 6946:2008.

The size of the innovative DWC hydroponic module is 124 x 85 x 35 cm<sup>3</sup>, with a 30 cm deep water plastic tray that is raised from the existing roof surface by means of a wood support structure. The tray support realizes a lightly ventilated air gap of slightly less than 4 cm.

The plastic tray has a volume of 240 litres, and it is thermally insulated by means of a layer of extruded polystyrene with a thickness of 4 cm in the vertical sides and in the bottom, respectively. On top of the tray, a perforated polystyrene container includes six empty spaces that host mesh pots with the crops to grow. The roots of seedlings are dipped in a water and nutrient solution thanks to the mesh pots. The thermo-physical features of the various materials making up the hydroponic module are certified by the manufacturer according to Italian standards UNI 10456:2008 and UNI 10361:1994, respectively.

The experimental setup is equipped with a recirculation pump, a water reintegration system and an oxygenator: the pump allows the movement of the water and the nourishment of the plants, while the oxygenator is used to deliver pure oxygen into the tray water providing an optimal source of oxygen for the seedling roots. The recirculation pump and oxygenator are both activated by means of a remote Wi-Fi control system.

## 2.2. Crop features

The experimental hydroponic cultivation focused on two plant species: lettuce (*Lactuca sativa*) and basil (*Ocimum basilicum*). These crops were selected because of their fast growth cycle, their high adaptability to hydroponic systems and the sensitivity to environmental conditions. Both crops have shallow root systems that allow them to efficiently absorb nutrients from the oxygenated water solution while requiring minimal maintenance. The lettuce variety used in this study has a relatively short growth cycle of approximately 25 days from seedling transplantation to harvest. It requires moderate light exposure and a nutrient-rich solution to support rapid leaf development.

On the other hand, the selected basil variety – known for its aromatic properties and commercial value – has a slightly longer cycle of about 27 days. Basil thrives in warm environments with stable water temperatures, making it an ideal candidate for assessing the buffering effect of the hydroponic system on temperature fluctuations. The seedlings were transplanted into the hydroponic module at an early growth stage (approximately 10 days after germination), placed in mesh pots containing an inert support material, and suspended in the nutrient solution. The system was designed to maintain optimal growth conditions through continuous aeration and a controlled nutrient supply.

### 2.3. Experimental measurements campaign

The experimental measurements of the water temperature in the hydroponic module and external surface temperature of the bare roof have been conducted by means of a wireless node that includes:

- a multi-functional probe for measuring water depth, temperature and conductivity in the tray (Water depth: range = 0-11 m, accuracy  $\pm 0.05\%$ ; Temperature: resolution = 0.01 °C, accuracy =  $\pm 0.1$  °C; conductivity: range = 5-100000  $\mu\text{S/cm}$ , resolution = 0.1  $\mu\text{S}$ );
- a probe to measure the surface temperature on the existing bare roof (resolution = 0.1 °C, accuracy =  $\pm 0.1$  °C).

The weather data were taken from a stationary weather station placed in a building in front of the experimental site, recording temperature and relative humidity of outdoor air, wind speed and direction, and precipitations. The main technical features are summarized as follows:

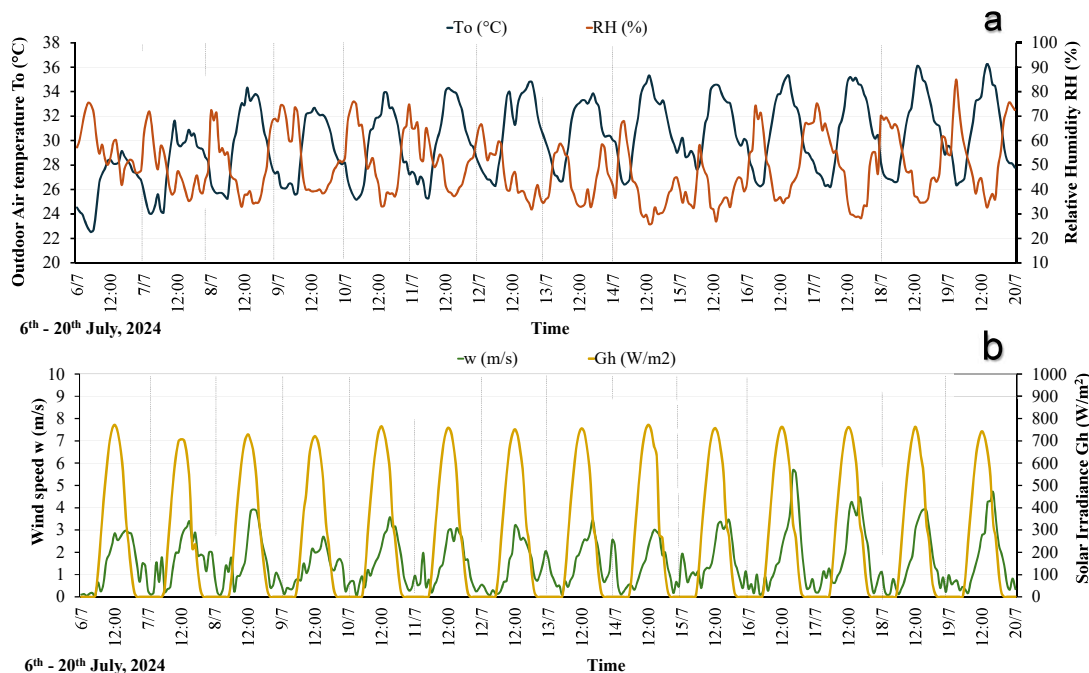
- Temperature sensor: measurement range =  $-40\div 65$  °C; accuracy =  $\pm 0.3$  °C; resolution = 0.1 °C.
- Humidity sensor: measurement range =  $1\div 100\%$ ; accuracy =  $\pm 2\%$ ; resolution = 1%.
- Anemometer: measurements range =  $0\div 89$  m/s for wind velocity and  $1\div 360^\circ$  for wind direction; accuracy =  $\pm 0.9$  m/s for wind velocity and  $\pm 3^\circ$  for wind direction; resolution = 0.4 m/s for wind velocity and  $1^\circ$  for wind direction.
- Rain collector: range =  $1\div 762$  mm/hr; accuracy =  $\pm 5\%$  up to 250 mm/h; resolution = 0.1 mm.

All the weather data were collected with a sample time of 15 minutes and transmitted remotely through a wireless/LAN IP Gateway to a server collecting all the data coming from the weather station and the measuring node.

## 3. Results and discussion

### 3.1. Thermal analysis

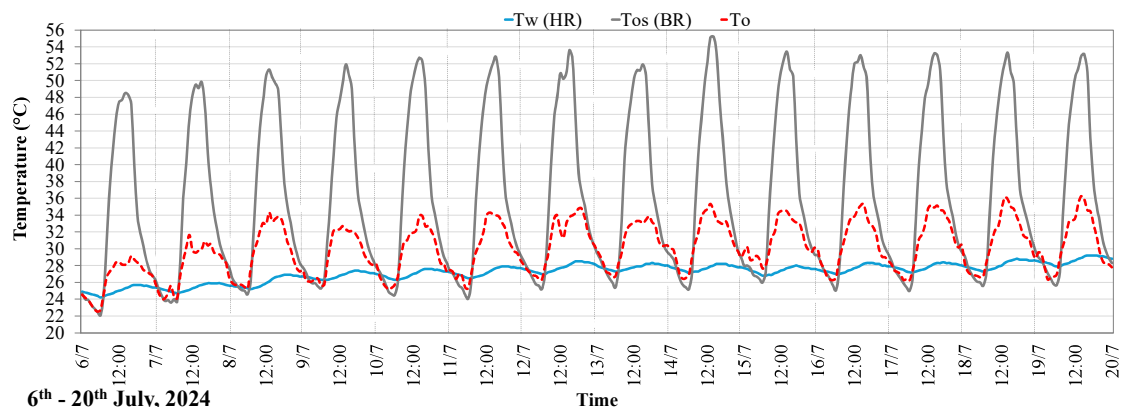
Figure 2a depicts the hourly values of temperature ( $T_o$ ) and relative humidity (RH) of outdoor air while Figure 2b represents the hourly trend of wind speed ( $w$ ) and solar irradiance ( $G_H$ ) during the investigated period (6<sup>th</sup>-20<sup>th</sup> July 2024).



**Figure 2.** Weather data collected between 6<sup>th</sup> and 20<sup>th</sup> July; a) Hourly trend of outdoor air temperature and relative humidity; b) Hourly trend of solar irradiance and wind speed.

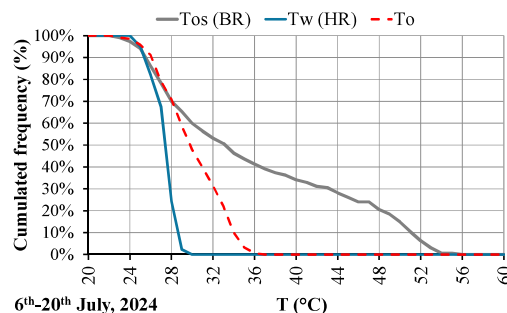
The maximum value of global solar irradiance is about 800 W/m<sup>2</sup> and it occurs at around 12.00 am, while the outdoor air temperature varies from a minimum of 22.0 °C to a maximum of 36.0 °C during the investigated period. The wind speed is on average about 2.0 m/s and the prevalent wind direction is east.

Figure 3 shows instead the recorded trends for the water temperature inside the tray of the DWC Hydroponic prototype  $T_w$  (HR), for the external surface temperature on the existing bare roof,  $T_{os}$  (BR), and for outdoor air temperature  $T_o$ , from 6<sup>th</sup> to 20<sup>th</sup> July 2024. Here, it is possible to see how the hydroponic module allows a strong reduction in the peak temperature and provides a noticeable cooling effect: indeed, the maximum value for the water temperature in the tray is 29.2 °C, whereas the peak of external surface temperature for the existing roof is 55.2 °C and the outdoor air peaks at around 34°C at the same time.



**Figure 3.** Trend of water temperature in the tray of DWC hydroponic roof (light blue line), external surface temperature of existing roof (grey line) and outdoor air (red line) during the investigated period.

It is worth highlighting that the hydroponic module remarkably reduces the daily swing in the surface rooftop temperature, as can be seen in Figure 3: the roof equipped with the hydroponic module has lower temperature fluctuations if compared to the existing roof. Indeed, the maximum daily amplitude in the hydroponic roof was 1.7 °C, whereas in the existing roof it was of about 30 °C. These results reveal the role played by water in dampening the effect of the solar radiation and acting as an insulating material.



**Figure 4.** Cumulative frequency distribution of water temperature in the tray (light blue line) and of the external surface temperature of existing roof (grey line) during the investigated period.

This is further rebated in Figure 4, where the cumulative frequency distribution of the water temperature in the tray, the roof external surface temperature and the outdoor air are plotted altogether. It is important to underline that in the current configuration of the prototype, i.e. a DWC module on a lightly-ventilated air gap, the surface temperature of the roof area beneath the tray (not measured in the

study because of the small dimensions of the prototype) would be included between that of the water in the tray and that of the outdoor air. A configuration where the tray is directly in contact with the roof would thus bring an additional cooling effect to the building.

### 3.2. *Crops analysis*

The experimental campaign provided valuable insights into the growth performance and yield of lettuce and basil cultivated in the hydroponic roof module. The first harvest produced 0.125 kg of lettuce and 1.045 kg of basil from six individual plant spaces within the module. The DWC technique proved also to be efficient in sustaining plant growth with minimal water consumption: the average daily water replenishment required by the system was less than 1 cm, significantly lower than traditional soil-based cultivation methods. This reduction in water use can be attributed to the closed-loop nature of the hydroponic system, which minimizes losses due to percolation and surface evaporation. Additionally, the recirculating nutrient solution ensured a continuous supply of essential minerals, reducing the need for frequent fertilization and improving overall resource efficiency. One of the key advantages observed was the system's ability to maintain stable root-zone temperatures, which is critical for plant growth, especially during extreme summer conditions. This thermal buffering effect is particularly important for mitigating heat stress in plants and preventing excessive water loss due to transpiration. A comparison with conventional soil-based cultivation methods suggests that the hydroponic system can enhance yield efficiency while reducing the space required for cultivation. In particular, basil demonstrated higher productivity compared to field-grown counterparts due to the continuous nutrient availability and optimized growing conditions.

## 4. Conclusion

The experimental study conducted on a prototypical hydroponic roof system based on the Deep Water Culture (DWC) technique has demonstrated significant thermal and agricultural benefits. The data collected during the summer 2024 highlighted the ability of the hydroponic module to stabilize water temperature within the optimal range of 25 °C to 28 °C, even under peak external air temperatures of 36 °C and solar irradiance levels of approximately 800 W/m<sup>2</sup>. This temperature regulation capability not only ensures suitable conditions for plant growth, but also contributes to reducing the building cooling load by significantly reducing the roof surface temperature beneath the hydroponic module (values between those achieved by the water and those recorded from the outdoor air are expected in the lightly-ventilated configuration analysed in this study). From an agricultural perspective, the first experimental harvest resulted in 0.125 kg of lettuce and 1.045 kg of basil over an average growth cycle of 25 and 27 days, respectively. The deep-water culture system proved highly efficient also in water management, requiring a daily replenishment of less than 10 L of water, which significantly reduces water consumption compared to traditional soil-based agriculture. The continuous nutrient availability and stable root-zone temperature ensured optimal plant development with no signs of stress or deficiencies. The basil plants exhibited a high leaf-to-stem ratio, while lettuce achieved uniform vegetative growth, reinforcing the potential of hydroponic systems for urban agriculture applications. Ongoing research is assessing the thermal behavior of the system under winter conditions to determine whether additional insulation or heating mechanisms are necessary to sustain year-round crop production, while also investigating the growth and yield of different plant species, including high-value crops with longer growth cycles, to explore the versatility of the system.

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