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Original Research Article

Enhancing Urban Sustainability: Water-Saving Bio-Solar Green Roofs in Mediterranean Climates

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ABSTRACT

Green roofs are expanding due to their advantages, but may face water deficits in the summer. However, bio-solar green roofs integrating renewable energy and green infrastructure could positively contribute to sustainable urban development and enhance environmental management. Therefore, the current study aims to experimentally investigate the benefits of bio-solar green roofs over conventional green roofs. The experiments were conducted in Rende, in southern Italy, which has a Mediterranean climate. Comparing soil temperature and relative humidity helps in understanding temperature, water reduction, and the irrigation cycle in both conventional green roofs and bio-solar green roofs. The analysis revealed that the soil surface temperature was higher in conventional green roofs than in bio-solar green roofs, with a difference of 4.8 °C to 9.8 °C, and exhibited the same trend in the case of bare soil. However, the bare soil humidity declined less than that of green roofs, possibly due to plant evapotranspiration. The analysis of the irrigation cycle in conventional green roofs and bio-solar green roofs shows a difference of 41.2%. While the relative humidity of conventional green roofs dropped from 97.7% to 32.5% at noon on the third day and fell below the 40% threshold required for succulent irrigation, the relative humidity in bio-solar green roofs was higher than 73.7%. According to the outcomes, bio-solar green roofs could have lower temperatures and reduced water consumption, thereby enhancing the cooling impact of green roofs. The results will improve knowledge on the subject and be useful for policymakers in sustainable urban development by presenting a solution to real-world problems through practical and innovative building technologies.

KEYWORDS

Green roof, Solar panel, Sustainable urban planning, Bio-solar, Nature-based solution, Climate adaptation.

INTRODUCTION

Cities face various social and environmental issues due to population growth, increased density, and climate change, including air, water, and noise pollution [1]. More green space could improve the quality of urban life, but the amount of green space that remains shrinks each year and is distributed unevenly, particularly in the city centres [2]. One potential solution

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to mitigate the issues above is the implementation of green or vegetated roof infrastructure strategies [3]. This strategy may also improve the quality of urban life and have positive economic impacts [4], in addition to the environmental benefits of reducing urban floods [5], [6], enhancing urban runoff quality [7], [8], reducing noise levels as insulation [9], and reducing urban air pollution [10].

Different vegetation or plant varieties can be utilised in designing green roofs, and the types of plants and amount of irrigation might vary based on the local climate [11]. Additionally, water content has a direct impact on the proper operation of the green roof system, as it influences plant survival and enhances plant performance, particularly in mitigating thermal impacts on the building [12], [13]. However, water scarcity is one of the world's most pressing issues, and it is likely to worsen over time due to population growth and climate change. Therefore, it is crucial to consider methods for reducing the water consumption of green roofs, and one approach could be to utilise the shade impact of PV panels [14], [15]. Meanwhile, because solar panels provide shade and cooling benefits, integrating them with green roofs can improve their efficacy and performance [16]. The potential synergistic relationship between PV panels and green roofs enables the optimal utilisation of roof space for energy production and stormwater management. The presence of solar PV systems can also reduce solar radiation and wind flow in green roofs. As a result, it may reduce the rate of evapotranspiration and water consumption of green roofs. Additionally, the shadowing effect of solar panels lowers the roof's ambient temperature [17]. In this case, a multipurpose irrigation system lowering water and energy usage could better fit green roof systems integrated with PV panels [18].

In terms of sustainability at the urban level and energy savings at the building level [19], green roofs are essential passive techniques [20]. Moreover, coupling building-integrated photovoltaic (BIPV) with green technologies is one of the most promising solutions for future building design and development [21]. Green roofs can reduce surface temperatures and positively impact a building's energy performance [22]. However, the reduction values in different climates, which can be as high as 33 °C, would directly depend on the water content and evapotranspiration rate [23].

Scolaro and Ghisi [24] investigated the life cycle assessment (LCA) of green roofs. Based on their findings, green roofs have lower costs over their life cycle when their entire lifespan and benefits are taken into account. Pirouz *et al.* [25] performed a case study analysis in a Mediterranean climate to investigate the water consumption of green roofs and the corresponding thermal reduction in the water footprint. According to their findings, utilising water directly on green roofs could reduce building energy consumption. Due to the water footprint of energy, less water would be required in power plants to achieve the same thermal reduction. Zhang *et al.* [26] studied the sustainability of green roofs in Beijing's moderate monsoonal environment. Their findings demonstrated that using stress-tolerant species and appropriate substrate moisture content is crucial for plant survival. Moreover, for unirrigated green roofs, the substrate depth must be a minimum of 15 cm. Pirouz *et al.* [27] investigated the average water consumption of green roofs in Mediterranean climate regions during the hot season, which is approximately 4.5 L/(m^2 day). Additionally, efficiency could increase through the utilisation of atmospheric water harvesting systems. The benefits of combining PV panels with green roofs (GR-PV) were examined by Ramshani *et al.* [28], and their findings indicated that combining them with green roofs could result in increased energy generation.

However, in any climate zone, calibration of elements is strictly necessary. Research by Heusinger *et al.* [29] demonstrated that irrigation is crucial for enhancing the performance and efficiency of solar green roofs, thereby reducing the heat generated by photovoltaic panels and achieving higher efficiency. Fleck *et al.* [30] conducted a case study analysis of bio-solar green roof energy generation in Sydney, Australia. The analysis revealed that, on average, throughout all seasons, the production of a bio-solar green roof was 4.5% higher than that of a conventional solar roof. Jahanfar *et al.* [31] investigated the hydrological performance of green roof photovoltaics in comparison to a traditional green roof module at the University of

Toronto, Canada, with a particular emphasis on the lower capacity of GR-PV to mitigate stormwater runoff and peak flow. Their research showed that while the vertical distance between the PV panel and the green roof improves hydrological efficiency, the height of the panels had no noticeable impact on peak flow reduction or rainwater retention. Wang *et al.* [21] analysed the potential of building-integrated photovoltaics (BIPV) and the knowledge gap in this field. They highlighted that more in-depth research is required regarding the interaction of solar panels with green roofs, noting that many factors, such as solar module types, installation patterns, operating temperatures, and greenery, including plant types, water management, and substrate materials, require further investigation.

Combining solar panels with green roofs is a remarkable alternative for buildings, particularly those in urban areas that lack green spaces and are transitioning to PV systems for energy supply. The BS-GR approach combines PV energy generation with the benefits of having a green roof for buildings. In previous studies, the water consumption of green roofs in various climates, the reduction of temperature, and water consumption in shaded areas of agrivoltaic systems have been investigated. However, there is a significant knowledge gap regarding the irrigation cycle, water consumption, and soil temperature of bio-solar green roofs, particularly in Mediterranean climates. This study aims to enhance knowledge on the subject by investigating the fundamental advantages of bio-solar green roofs (BS-GRs) over conventional green roofs (CGRs) through experimental analysis. Moreover, enhancing urban sustainability in Mediterranean climates through water-saving bio-solar green roofs is another goal of the study. The results can be beneficial for policymakers in sustainable urban development strategies, presenting a solution to real-world problems. Moreover, innovative building technologies such as BS-GRs can be considered promising solutions for future building design and development, where the interaction of energy and water plays an important role.

MATERIALS AND METHODS

This study compares the temperatures and relative humidity (RH) of bare soil and green roofs under solar panel shadow and direct sunlight to better understand the performance of bio-solar green roofs (BS-GRs). This comparison will demonstrate the reduction of water usage in BS-GRs and aid in understanding the irrigation cycle of CGRs and BS-GRs in a Mediterranean environment. The experimental analysis conducted through pilot studies can demonstrate the advantages of BS-GRs and highlight their positive contribution to sustainable urban development and future building technologies, particularly in Mediterranean climates.

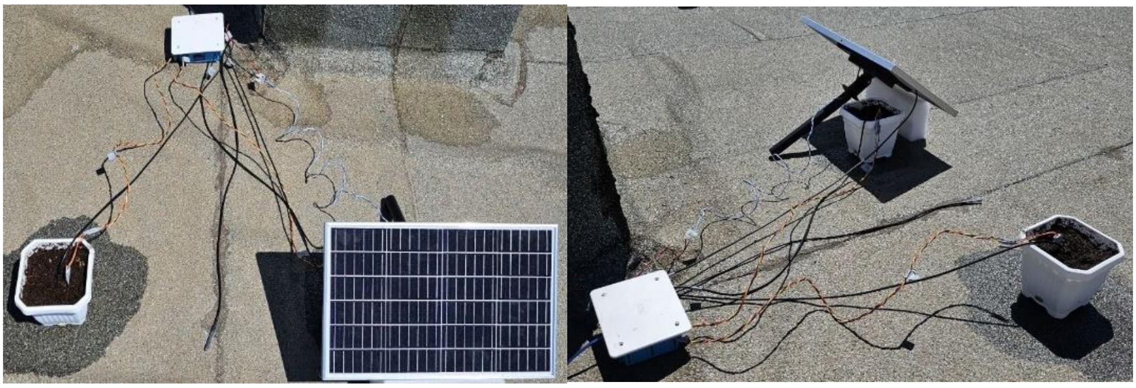
Case Study Definition and Analysis Procedures

The case studies were conducted in southern Italy, specifically at Rende. The city is situated approximately 165 metres above sea level and has a Mediterranean climate characterised by cold, wet winters and hot, dry summers. Although Rende receives about 976 millimetres of precipitation annually, rainfall is less than 100 millimetres throughout the summer and almost zero in July. The installed systems and measuring sensors are shown in **Figure 1**.

Case Study 1 examined the irrigation cycle, temperature, and soil humidity in conventional green roofs (CGRs) and bio-solar green roofs (BS-GRs). The two bare soil (flowerpot) samples are placed at the same level and roof condition, and the same for the two green roof samples. The panels' tilt angle has been set to 33 degrees, which is an optimised slope according to the PVGIS tool [32] in the case study location.

Furthermore, the temperature and humidity of bare soil under the shade of solar panels and in direct sunlight have been investigated in Case Study 2. Measurements were made on cloudless, sunny days to analyse the effect of solar panels on the temperature of the green roof and the water content of the soil. These conditions were representative of the high-temperature conditions of the Mediterranean climate in summer.

(c) (d)



(c) (d)

Figure 1. Details of the installed systems and measurement of temperature and humidity: Case Study 1: bio-solar test boxes (a); Case Study 2: bio-solar test boxes (b); Case Study 1: measuring sensors (c); and Case Study 2: measuring sensors (d)

The details of the experimental configuration and measurements are as follows:

- Case Study 1 (bio-solar test box): L: 45 cm, W: 35 cm, H: 15 cm; Case Study 2 (bare soil test): L: 10 cm, W: 10 cm, H: 12 cm;
- Solar panel: monocrystalline, 20 W, sized 45 cm × 25 cm; panel tilt angle: 33 degrees;
- Soil type: soil for flowers and green plants: 36% superfine peat (0–10 mm), 27% Irish peat (0–5 mm), 23% coconut granules (0-5 mm), and 14% volcanic pumice (3–8 mm);
- Soil height: 10 cm in both case studies; drainage layer: gravel, 2 cm;
- Plant type: *Crassula ovata* (succulent), which offers drought tolerance, adaptability to shallow substrate environments such as extensive green roofs, and low maintenance requirements. Moreover, its consistent physiological behaviour under water stress allows for a focus on the comparative thermal and hydrological performance of the green roof systems themselves, rather than the variability introduced by different plant species. These characteristics make *Crassula ovata* particularly suitable for Mediterranean regions, where prolonged dry periods and high solar radiation are common.
- Sensors and devices: air and soil temperature sensors, air and soil humidity sensors, and a thermal camera;
- Measurement days and period: July 6, 2024, for thermal camera images of both bare soil and green roof, July 14, 2024, for measurements of soil temperature and humidity in sunlight and under PV panel shade for both bare soils and green roofs, and July 19–21, 2024, for temperature and humidity measurements in two types of green roofs.

Plant Behaviour and Green Roofs' Water Consumption in Shade and Sunlight

The differences in plant behaviour in shade and sunlight are listed in **Table 1**, showing that increased photosynthesis may contribute to higher water consumption under sunlight. Moreover, the size and orientation of the leaves in direct sunlight may reduce the percentage of green area on the roof, having an adverse effect on the thermal insulation provided by the green roof.

A study on green roofs and the shadows of photovoltaic panels in a Mediterranean climate in Haifa, Israel, revealed that the combination enhances plant growth conditions and promotes higher plant diversity. In the case of sedum, the presence of PV prolonged flowering but caused an increase in growth and enhanced vegetation cover during the summer **[33]**. Therefore, it appears that solar panels may be beneficial for a green roof, particularly when shade-loving plants are chosen.

Table 1. Differences in shade- and sun-loving plants **[34]**

Parameter	Sun-loving plants	Shade-loving plants
Maintenance	High	Low
Water demands	High	Low
Leaves size	Small thick	Large thin keeves (smaller leaves near the top (light levels are high), and larger leaves near the base)
Leaves angle/orientation	Vertical 	Horizontal 
Photosynthesis capacity	High	Low
Light absorbs	High	Maximum light for photosynthesis
Leaf reflectance	High	Low

The investigation of Schweitzer and Erell showed that the water demands of green roofs in a Mediterranean environment ranged from 2.6 to 9.0 L/(m^2 day) **[35]**. The results of another study by Peng and Jim in a humid-subtropical climate showed a water requirement of 5 L/(m^2 day) in the summer **[36]**. The experimental results in Germany, with a warm summer and humid continental climate, showed a daily mean evapotranspiration of 4.77 to 4.88 mm/day in the summer months **[37]**. However, water consumption by plants in shaded and sunny areas differs, and the percentage of water reduction varies depending on the type of plant, climate, and other factors, including soil type and depth.

The results of a study for a Mediterranean climate in Montpellier, France, determined that evapotranspiration (ET) reduces in agrivoltaics systems (photovoltaic systems on land) by 14-29% compared to conventional systems **[38]**. Analyses of cultivated lettuces at this location revealed that the shading effect of solar panels resulted in a 20% reduction in water consumption **[39]**. Another study conducted in the temperate semi-humid climate of Fuyang, China, revealed a decrease in soil surface water evaporation of about 21 to 33% **[40]**. Moreover, agrivoltaics permitted a 328% increase in water efficiency in Oregon (US), a state with warm summers and a Mediterranean environment **[41]**. Furthermore, the study conducted in Berlin, Germany, a humid continental environment, showed a 50% ET reduction in shade area **[42]**. The primary cause of differences in water consumption is the temperature variation between areas with direct sunlight and those in shade.

Table 2 presents such temperature changes in several case studies and illustrates that the temperature differential can range from a few degrees to 24.69 °C (the surface soil layer) and from 9 to 16 °C in a Mediterranean climate.

Table 2. Variations in temperature between sunlight and shaded areas

Case study	Location	Climate type	Type of analysis	Difference in temp. in sunlight and shade [°C]	Ref.
Photovoltaic rooftop	San Diego, US	Mediterranean	Thermography	2.5 °C (ceiling temp. difference with a bare roof)	[43]
Solar-shaded roof vs bare roof	Agrinio, Greece	Mediterranean	Experimental/Theoretical using thermocouples during the summer	9-13 °C (surface temperature)	[44]
Urban textile shading	Cordoba, Spain	Hot Mediterranean	Thermography on one summer day	Up to16 °C pavements and up to 6 °C facades	[45]
Façade surface temperature	Madrid, Spain	Warm-temperate subtropical	Thermography	7.4 °C summer, 1.2 °C winter	[46]
Multilayer GR	Seoul, Korea	Hot and very humid	Sensors for surface temperature measurement	5-9 °C (surrounding surface)	[47]
Shadow under hanging aluminium fins	Hong Kong, China	Humid subtropical	Sensors at 1.1 m height	0.8 °C (air temperature)	[48]
Under artificial shelter	Hong Kong, China	humid subtropical	Experimental data in June, July, and August	0.2-0.5 °C (at a height of 1.1 m)	[49]
Building shading effect	Harbin, China	Monsoon-influenced humid continental	Biometeorological measurement units	28.8 °C (surface around building shade), 1.2 °C (air temperature)	[50]
Building shading effect on soil layer temp. in green plot	Beijing, China	Warm temperate zone	Sensors	0.29-24.69 °C (surface soil layer temperature in summer)	[51]
Air temp. under solar panel canopy	Tempe, Arizona, US	Desert	Sensors 2.6 m from the ground and 3.5 m under panels between June 1, 2014 and May 31, 2015	2 °C (air temperature at a height of 2.6 m)	[52]

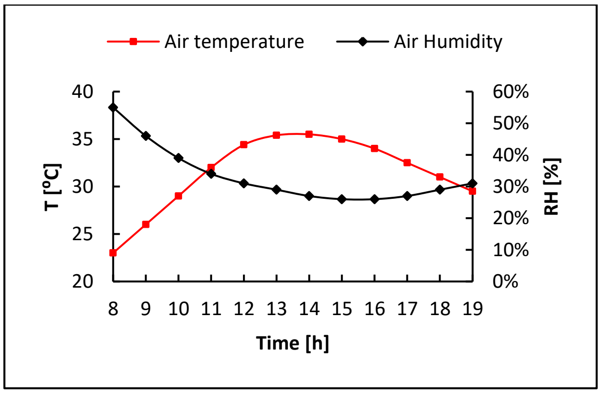
Study Limitations and Potential Weaknesses

The current study was conducted on cloudless, sunny days and investigated the role of a single solar panel in measuring the temperature and humidity of bare soil and a green roof. However, it might be confronted with some limits that mainly are:

- The influence of the solar panel location on the green roof was not considered;
- The global irradiance that has been used for analysis of thermal images was based on the July average [53] and not measured;
- The impact of solar panels on the samples in winter was not analysed in this study, as the aim was to focus on water saving, which is an issue in summer;
- This study did not take into account the type of plants or solar panels;
- The long-term impact of BS-GRs was not investigated in this study.

RESULTS & DISCUSSIONS

The subsequent sections will assess and explore the key findings on the shading effect of PV systems on green roofs, particularly regarding their impact on lowering temperature and water requirements. The experiments were conducted on July 6, from 8 AM to 7 PM, July 14, from 8 AM to 7 PM, and July 19–21, each day from 8 AM to 10 PM. Figure 2 shows the humidity and air temperature during the measurement days. The temperature ranged from 23 °C on July 6 to a maximum of 39 °C on July 14. The humidity ranged during the same period from 15.4% in the evening of July 20, 2024, to 65.5% in the morning of July 21, 2024.



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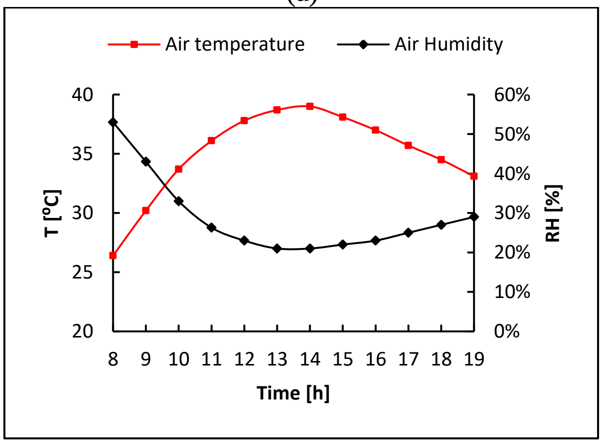

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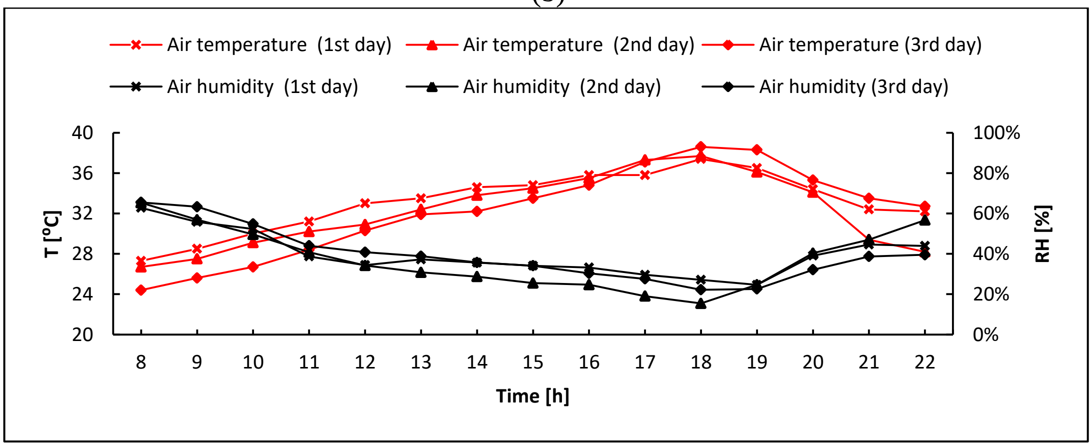

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Figure 2. Air temperature and humidity at various hours during the measurement days: July 6, 2024 (a); July 14, 2024 (b); and July 19 21, 2024 (c)

Temperature Variations of the Soil Surface in Sunlight and Shade

Figure 3 and Figure 4 illustrate the soil surface temperatures captured using a thermal camera at various hours of the day for both bare soil cases and green roofs exposed to sunlight and the shadow of solar panels. Moreover, the temperature variations of the soil surface in sunlight and shade, recorded in both case studies, are presented in Figure 5.

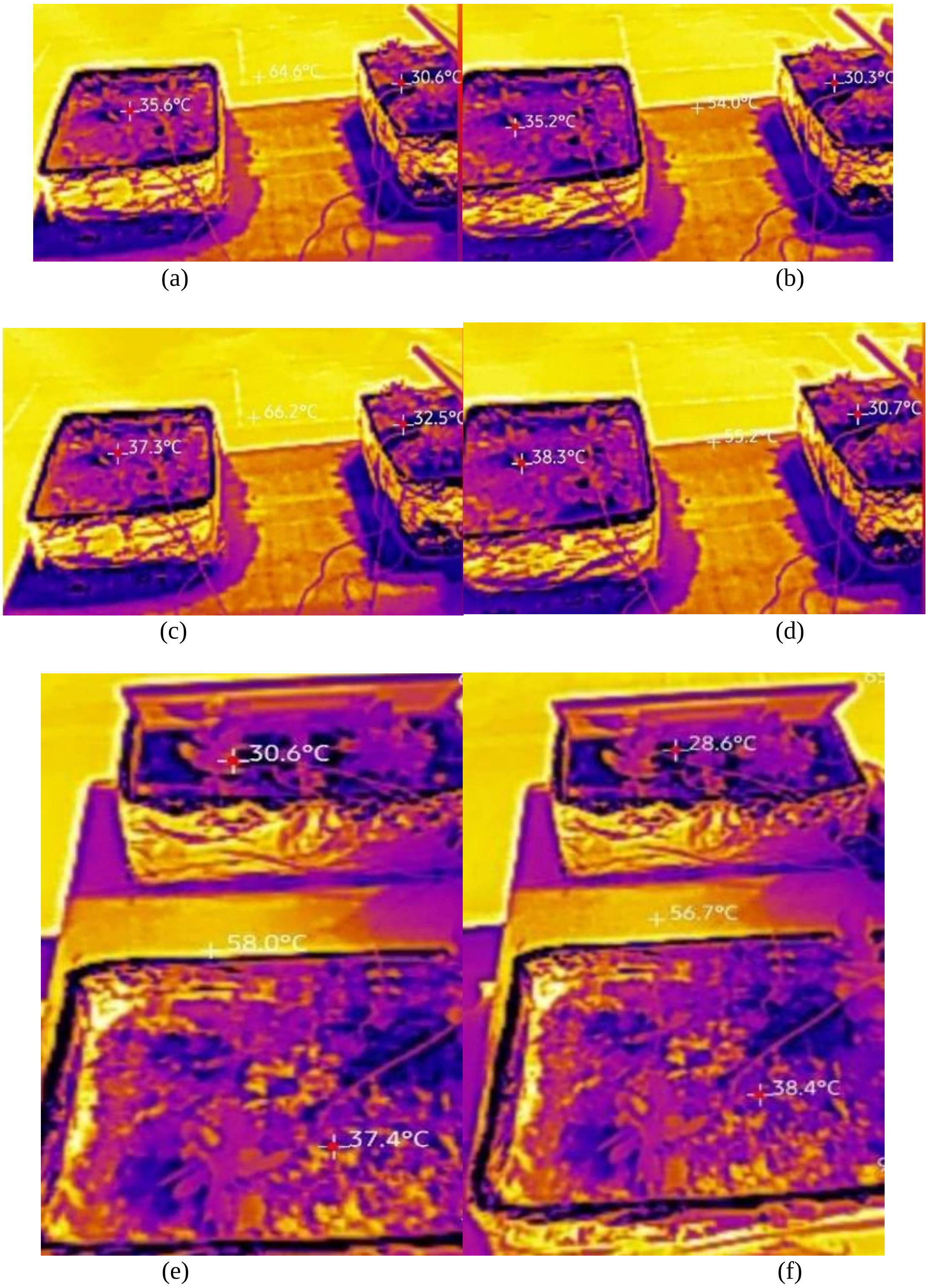


Figure 3. Green roof surface temperature differences in bio-solar and conventional systems on July 6, 2024: 8 AM, 4.9 °C (a); 10 AM, 5 °C (b); 12 PM, 4.8 °C (c); 2 PM, 7.6 °C (d);

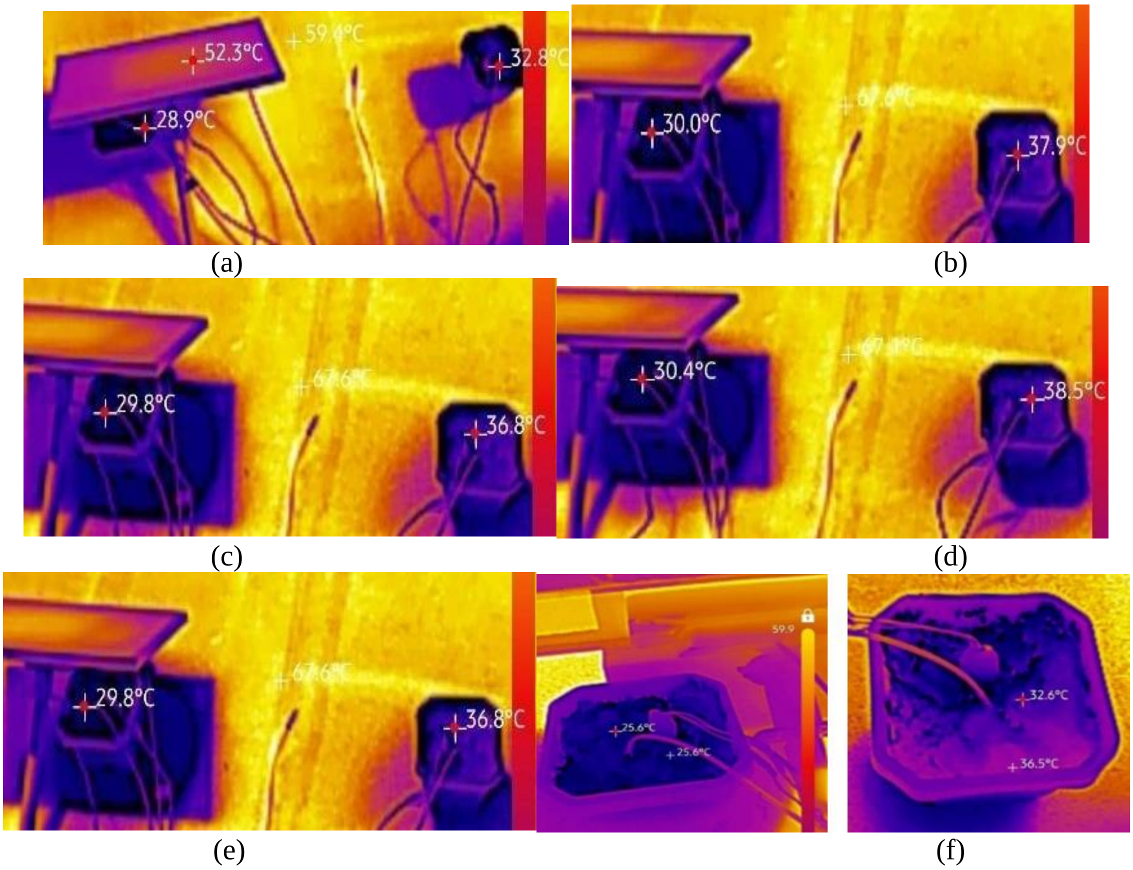
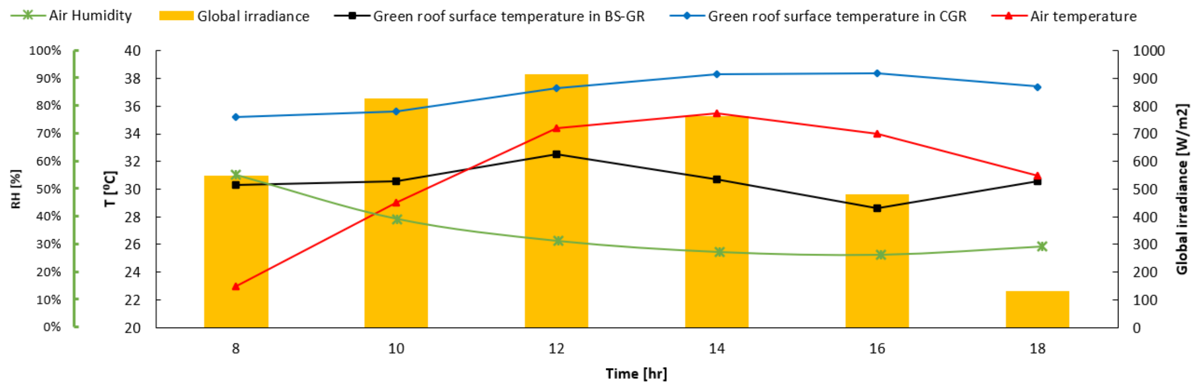


Figure 4. Soil surface temperature differences in PV shade and sunlight (July 6, 2024): 8 AM, 3.9 °C (a); 10 AM, 7.9 °C (b); 12 PM, 9.6 °C (c); 2 PM, 8.1 °C (d); 4 PM, 7.0 °C (e); and 6 PM, 7.0 °C (f)

The thermal images in **Figure 3** and the temperature variations in **Figure 5a** reveal lower temperatures in the shadow, indicating that surface temperatures in conventional and bio-solar green roof systems differed by 4.8 °C to 9.8 °C during the testing hours. The temperature difference was determined to be at its lowest point, around 4.9 °C, at 8 AM, and at its maximum at 4 PM, around 9.8 °C. The maximum temperature difference was observed at 4 PM, with a value of 9.8 °C, as shown in **Figure 3e**. This situation could be primarily due to the hot and dry climate, as the air humidity reached its lowest level between 3 and 4 PM. The temperature difference was reduced in the evening, and at 6 PM, it was equal to 6.8 °C, as depicted in **Figure 3f**, mainly due to a decrease in global irradiance. Therefore, combining photovoltaic panels with green roofs has resulted in a decrease in soil surface temperature compared to conventional green roofs. This approach could reduce water consumption and enhance the cooling impact of green roofs on buildings, consistent with the objective of green roofs **[54]**. The outcome could decline extreme heat events that impact buildings, which are increasing in urban areas **[55]**.

In the case of bare soil, as the captured thermal images are shown in **Figure 4** and the temperature variations in **Figure 5b**, there were notable changes in soil surface temperatures between those in the shadow of the solar panel and those in direct sunlight, which reached 9.6 °C at noon, when the global irradiance was highest. Comparisons between bare soils and green roofs revealed that, for the majority of the day, the surface temperature of the bare soil was slightly higher than that of the green roof, demonstrating the cooling effect of plants on surface temperature.



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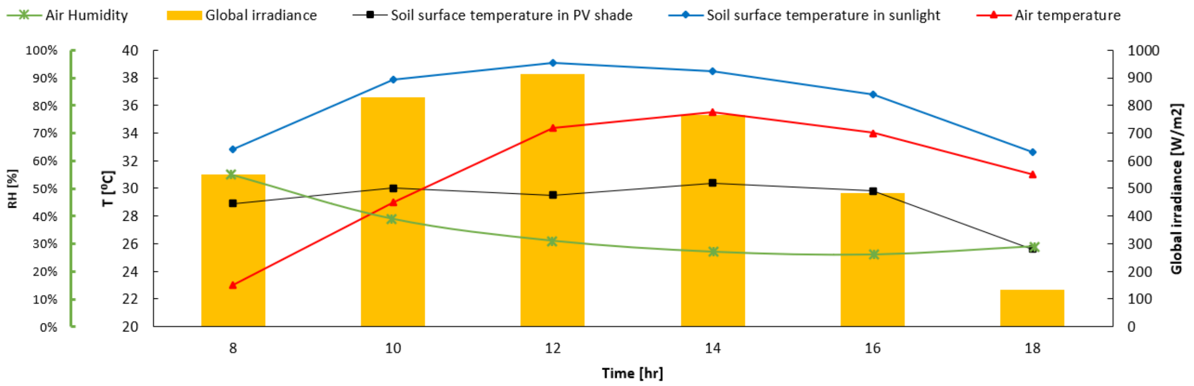
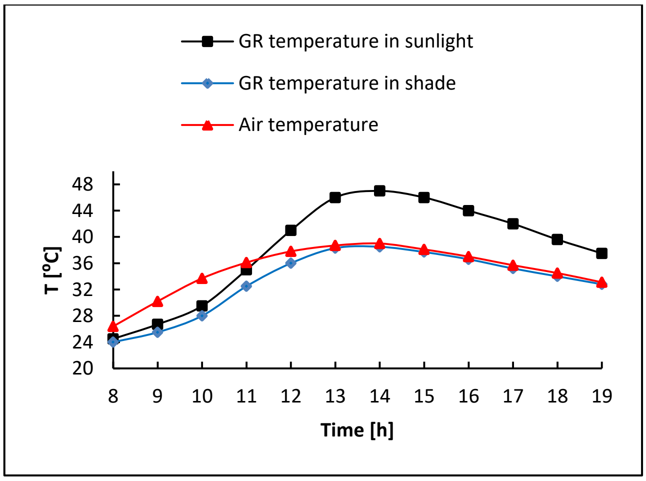


(b)

Figure 5. Variations of soil surface temperatures in direct sunlight and the shade of PV panels: BS-GR and CGR (a); bare soil (b)

Comparisons of Temperature and Humidity of Green Roofs in Sunlight and Shadow

This section examines the humidity and soil temperature of both conventional and bio-solar green roofs. The experiment was conducted on July 14, 2024, from 8 AM to 7 PM, and the ambient temperature during the testing hours ranged from 26.4 to 39 °C. **Figure 6** illustrates the variations in temperature and humidity on a green roof in sunlight and the shade of solar panels. The analysis shows that CGRs are confronted with higher temperatures, raising water demand, while BS-GRs could benefit from the generated shadow by solar panels, which preserves their efficiency. The temperature of the conventional green roof varied between 24.5 °C and 47 °C, while the bio-solar green roof was found to have a lower temperature, approximately 24 °C in the morning, rising to nearly 38.5 °C by midday. A reduction in green roof temperature has been observed in the presence of solar panels compared to conventional green roofs. The maximum soil temperature difference between shade and sunlight was 8 °C at 2 PM. As indicated in **Figure 6b**, the relative humidity decline rate was higher on the conventional green roof. The relative humidity in both green roofs was 92% at the beginning of the test, but it dropped to 67% and 83.5%, respectively, in CGR and BS-GR at the end of the experiment at 7 PM. As evidence of the positive impacts of PV systems, the soil temperature difference between shaded and sunny areas resulted in a corresponding difference in soil humidity of approximately 16.5% at the end of the test. Specifically, the decline in green roof humidity was approximately 8.5% in shade and 25% in sunlight. The lower water demands in BS-GRs can promote sustainable construction in urban environments, where the interaction between energy and water is crucial.



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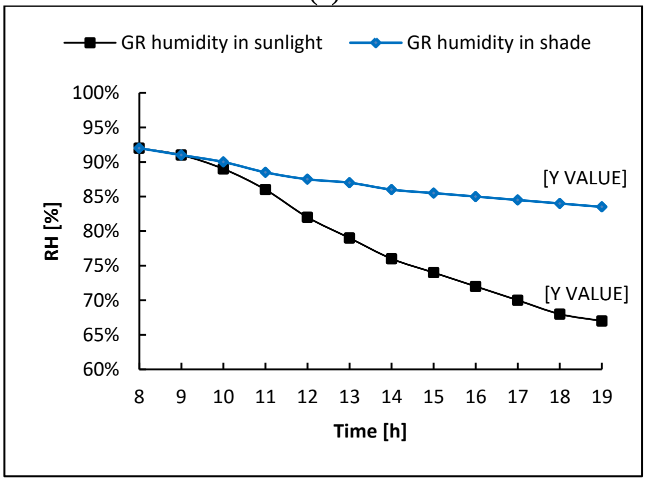


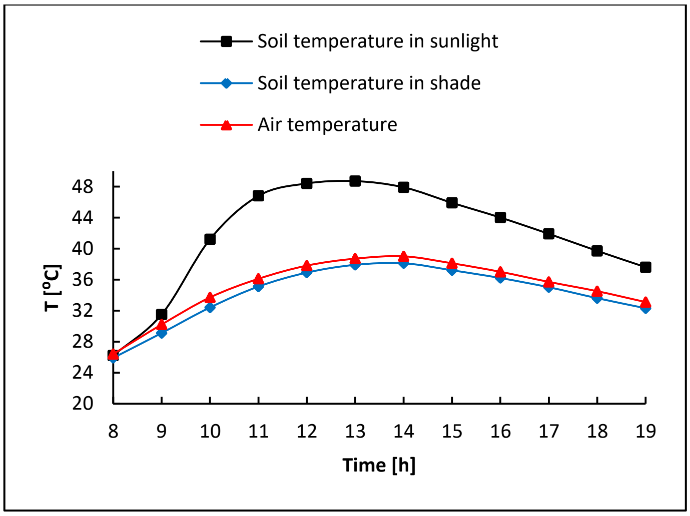
(b)

Figure 6. Soil temperature and humidity of green roof in sunlight and shade (July 14, 2024): temperature (a); and relative humidity (b)

Comparisons of the Temperature and Humidity of Bare Soil in Sunlight and Shadow

The second case study analysis focuses on the temperature and humidity of bare soil, which may differ from those of green roofs due to plant evapotranspiration. The test was conducted from 8 AM to 7 PM on July 14, 2024, and the experimental results are presented in **Figure 7**. **Figure 7a** illustrates the variations in bare soil temperature under PV panel shade and direct sunlight, and a temperature differential is evident. The temperatures in both cases were almost equal at the start of the test; however, the bare soil's temperature in sunlight reached 48.7 °C, while in the shade, it reached a maximum of 39.6 °C. The maximum temperature difference between the two cases occurred at noon, with a value of approximately 11.7 °C. **Figure 7b** illustrates the changes in bare soil humidity, showing that humidity decreased by approximately 4.7% in the shade, from 92% at 8 AM to 87.3% at 7 PM. However, the soil humidity dropped three times more under direct sunlight, from 92% at 8 AM to 76.6% at 7 PM, a decrease of around 15.4%.

Comparisons between bare soil and green roof at all testing hours conducted on the same day show that the bare soil temperature was higher. The bare soil's maximum temperature reached at about 12 PM, whereas that of the green roof reached its maximum at around 2 PM. In shadow, a similar temperature trend could be observed. Furthermore, the bare soil humidity in the sunlight and shadow conditions was higher than that of the green roofs, which could be due to plant evapotranspiration in the green roofs.



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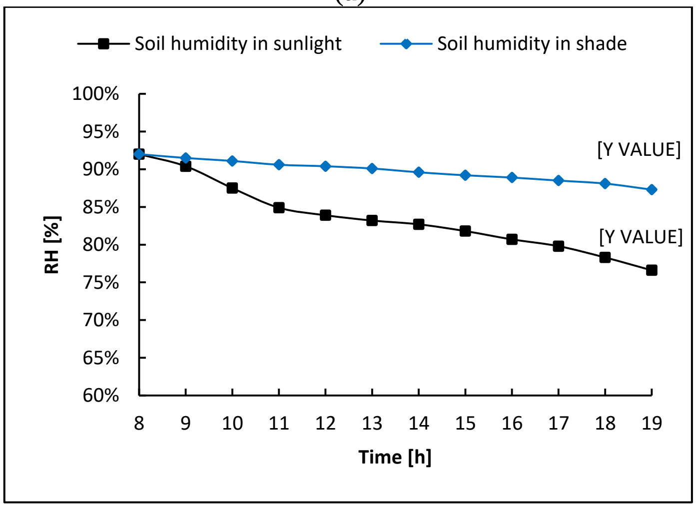


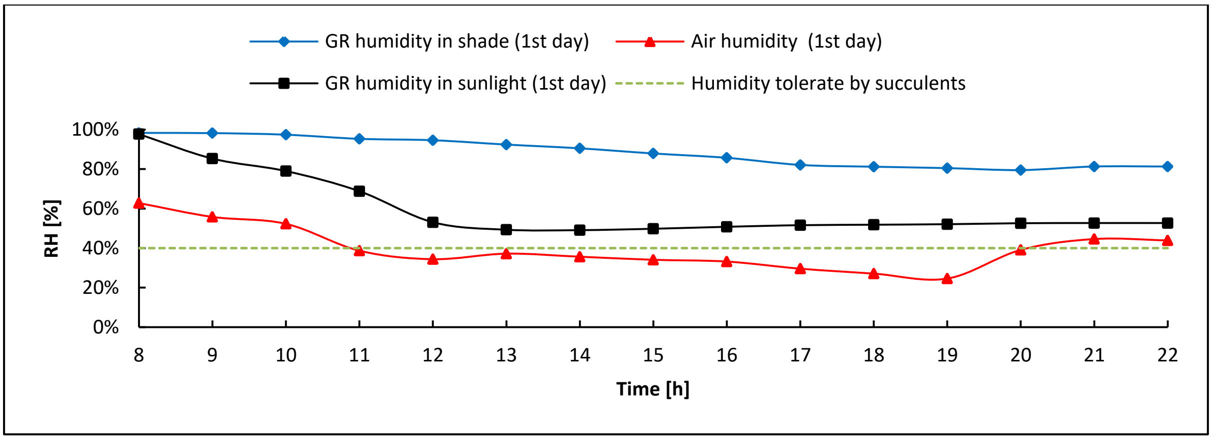
(b)

Figure 7. Air and bare soil temperatures and humidity in PV panel shade and sunlight on July 14, 2024: temperature (a); and relative humidity (b)

Irrigation Cycle Analysis in Conventional and Bio-Solar Green Roofs

The final experimental investigation focuses on the irrigation cycle in CGRs and BS-GRS. The soil's water content or relative humidity can be used to manage the plant's irrigation schedule. For most plants, a relative humidity of 50% to 70% is ideal [56]. However, temperature, soil type, and plant water tolerance rate also play significant roles in the irrigation cycle. In various studies, the average relative humidity of green roofs has ranged from 35% [57] to 56% [58]. The recommended range of humidity for typical green roof plants, including succulents (e.g., sedum and crassula), is between 40% and 50% [59]. Therefore, this study considers the RH threshold of 40% for irrigation cycle determination, which is suitable for the crassula (succulent) plant. The temperature and relative humidity of BS-GR and CGR were measured three days following an irrigation, on July 19–21, 2024, from 8 AM to 10 PM. The average air temperature for all three days was nearly the same, at 31.5 °C, and the maximum temperature was recorded on the evening of the third day, at 38.6 °C, which is representative of the high-temperature summer conditions typical of the Mediterranean climate. Moreover, the first day of testing had an average air humidity of 39.5%, the second day had an average air humidity of 37.3%, and the third day had an average air humidity of 39.3%.

The RH levels of the CGR and BS-GR during the three measurement days are shown in Figure 8. The findings revealed that less water is required for green roofs when a bio-solar system is deployed.



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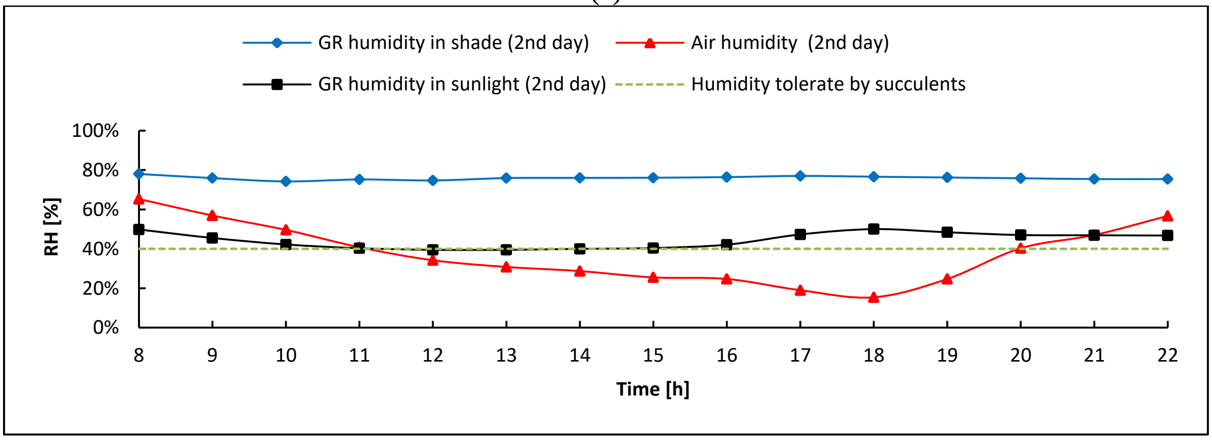

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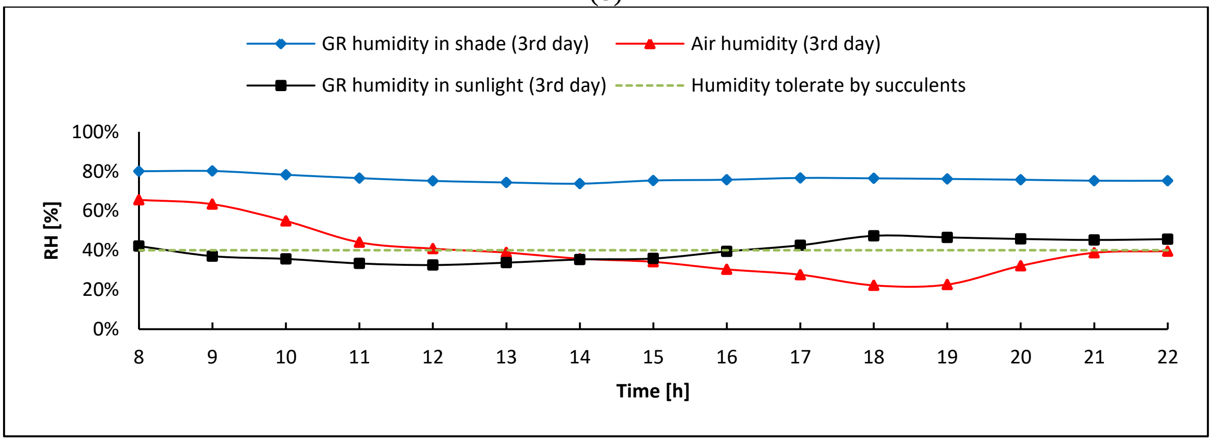
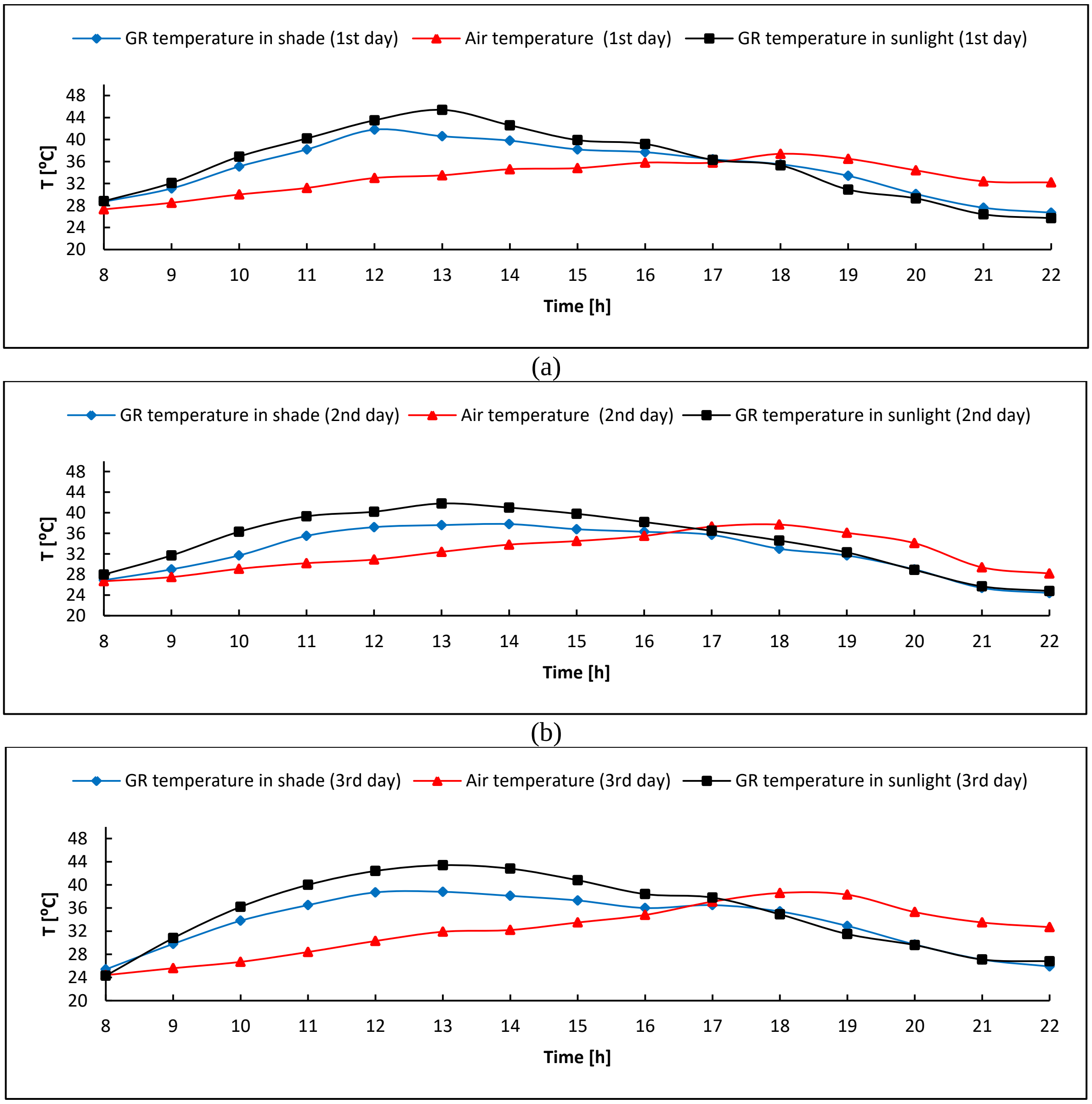


(c)

Figure 8. Humidity of conventional and bio-solar green roofs in one irrigation cycle (July 19 21, 2024): 1st day (a); 2nd day (b); and 3rd day (c)

One day following irrigation, in the case of CGR, the relative humidity declined by approximately half, from 97.7% to 49.8%. The relative humidity in the middle of the second day (at 2 PM) reached 40%, the tolerable threshold for succulent or crassula plants, and increased slightly in the afternoon. The RH value remains below the threshold for most of the hours on the third day, with a minimum of 32.5% at noon. These findings show that CGR may require irrigation every two to three days. However, the relative humidity of the bio-solar green roof was consistently higher than 73.7% throughout the same period and for three days after. In the case of BS-GR, the RH decreased by 18.8% on the first day, dropping from 98.3% at 8 AM to 79.5% at 8 PM. On the second and third days, the lowest RH values were 74.7% (at 12 PM) and 73.7% (at 2 PM), respectively.

The experimental analysis indicates that, after three days, there was a difference of 41.2% between the RH in two cases of CGR and BS-GR. According to the findings, in a Mediterranean climate, a decline in the RH of conventional green roofs in the summer could be 2.6 times faster than that of bio-solar green roofs. Given that GRs in Mediterranean climates rely on irrigation in summer, a decrease in water demand by BS-GRs may reduce pressure on the urban water network. Furthermore, the water content directly affects the GRs' capacity to ensure plant survival and building thermal impact [60], and lower temperatures and higher relative humidity in BS-GRs may significantly enhance green roof performance. The RH of soil under the PV panels in BS-GRs is higher due to shading and reduced solar radiation on the green roof surface.



(a) (b) (c)

Figure 9. Temperature of conventional and bio-solar green roofs in one irrigation cycle (July 19–21, 2024): 1st day (a); 2nd day (b); and 3rd day (c)

Figure 9 illustrates the temperature variations that occurred during the experimental days. The temperature fluctuation shows the same trend in both CGR and BS-GR. Maximum temperature variations occurred at 1 PM on the first testing day (4.8 °C), 10 AM on the second day (4.6 °C), and 2 PM on the third day (4.7 °C). Around 7 PM, when both green roofs were in the shade zone, the temperature of the conventional green roof was slightly lower than the temperature of the bio-solar green roof, ranging from 2.5 to 1.4 °C. The lower temperature after sunset could be due to a lower humidity content in the conventional green roof, which may accelerate the loss of absorbed energy. Additionally, between 6 PM and 10 PM, the temperatures of both green roofs were approximately 5 °C lower than the air temperature, demonstrating the positive thermal impacts of the green roofs. The primary cause of lower soil temperature in BS-GR is that shading from photovoltaic panels reduces incoming solar radiation, which in turn decreases the energy input to the soil, resulting in lower soil temperature.

The variations of the temperature and RH in both cases were similar, showing the dependency of the RH values on the soil temperature rather than air humidity. The RH was at its minimum around noon, when the soil temperature was highest, while the air temperature and humidity reached their maximum and minimum, respectively, around 6 PM. While RH and temperature are interrelated, in the context of BS-GRs, the observed reduction in soil temperature is primarily driven by a decrease in solar radiation due to the shading effect of the PV panels. As shown in **Figure 7**, RH values are generally higher under the panels; however, this increase is a consequence of the lower temperature and reduced evapotranspiration, rather than its cause. Therefore, the lower temperature observed in **Figure 1** should be interpreted as a direct effect of shading rather than a response to RH variation.

Future Research Directions

Suggested avenues for further investigation are listed below:

- Further studies can be done by utilising various types of solar panels with different patterns on the green roofs;
- Analyses in windy conditions that could affect temperature and evapotranspiration rate can improve the knowledge in this field;
- Variations in plant species and substrate depths: Investigating the performance of BS-GRs with different types of vegetation and substrate compositions could offer broader applicability and optimisation strategies.
- Long-term and annual simulations to achieve the result on a broader scale: This means extending the experimental period to cover full seasonal cycles or conducting annual simulations to provide a more complete understanding of the long-term benefits and variations in performance;
- The thermal performance of BS-GRs on the buildings: This can be done by directly measuring or simulating the impact of BS-GRs on the energy consumption of the underlying building to provide crucial data for assessing their overall sustainability benefits;
- Water quality and biodiversity: Exploring the effects of BS-GRs on stormwater runoff quality and their potential to enhance urban biodiversity could add further dimensions to their environmental benefits;
- Economic analysis: A cost-benefit analysis, including installation, maintenance, and savings from reduced water and energy consumption, could be highly valuable for stakeholders considering implementation;
- Impact on PV Panel Efficiency: While this study focuses on the green roof, quantifying any potential increase in the efficiency of the PV panels due to the cooling effect of the green roof would further highlight the synergistic benefits;
- Finally, future research could investigate the effects of solar panels on green roofs in other climates with prolonged periods of dry weather.

CONCLUSION

The analysis revealed that the soil surface temperature was higher in CGR than in BS-GR, with a difference of 4.8 °C to 9.8 °C. Additionally, the surface temperature of the bare soil was slightly higher than that of the green roof, demonstrating the effect of plants in reducing surface temperature. Furthermore, the soil temperature difference between shade and sunlight resulted in a difference in soil humidity of approximately 16.5%, as the decline in green roof humidity was 8.5% (from 92% to 83.5%) in shade and 25% (from 92% to 67%) in sunlight. The experimental analysis indicates that three days after irrigation, there was a difference of 41.2% between the RH in two cases of CGR and BS-GR, showing that BS-GRs may require less irrigation than CGRs. In conclusion, in a Mediterranean climate, a decline in the RH of CGRs in the summer could be 2.6 times faster than that of BS-GRs. Moreover, given that GRs in the Mediterranean climate rely on irrigation in summer, BS-GRs could be a better choice for urban sustainability. The new system can guarantee a lower temperature, reduced water consumption, and an enhanced cooling impact on buildings.

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NOMENCLATURE

Symbols

L	length	[cm]
H	height	[cm]
W	width	[cm]
T	temperature	[°C]

Abbreviations

BIPV	Building Integrated Photovoltaic
BS-GRs	Bio-Solar Green Roofs
CGRs	Conventional Green Roofs
GR-PV	Green Roof Photovoltaics
LCA	Life Cycle Assessment
RH	Relative Humidity

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