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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 biosolar green roofs over conventional green roofs. The experiments were conducted in Rende, in southern Italy, which has a Mediterranean climate. The comparison of soil temperature and relative humidity aids in understanding temperature, water reduction, and the irrigation cycle in conventional green roofs and pio 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 soll 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 of irrigation requirement for succulents, the relative humidity in bio-solar green roofs was higher than 73.7%. According to the outcomes, the bio-solar green roofs could have lower temperatures nd less water consumption, enhancing the cooling impact of green roofs. The results will innrow 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.

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#### 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 to mitigate the abovementioned issues is implementing 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 utilized in designing green roofs, and the types of plants and amount of irrigation might vary based on the local climate [11]. In addition, water content directly impacts the proper operation of the green roof system because it influences plant survival and enhances plant performance for thermal impact on the building [12], [13]. However, water scarcity is one of the world's most significant issues, and it may worsen over time due to population growth and climate change. Therefore, it is crucial to consider the methods for decreasing the water consumption of green roofs, and one approach could be taking advantage of PV panels' shade impact [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 synergetic relationship between PV panels and green roofs allows the optimal use of roof space for energy production and stormwater management, and the presence of solar PV systems can 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, and 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 important 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 the surface temperature and positively impact the building energy performance [22]. However, the reduction values in different climates, which could be up to 33 °C, would directly depend on the water content and evapotranspiration rate [23].

Scolaro and Ghisi [24] investigated green roofs' life cycle assessment (LCA). Based on their findings, green roofs have lower costs over their life cycle when their whole life span 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, utilizing water directly on green roofs could reduce building energy consumption, and due to the water footprint of energy, less water would be required in the 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, in the case of unirrigated green roofs, the substrate depth must have a minimum of 15 cm. Pirouz et al. [27] investigation showed that the average water consumption of green roofs in regions with a Mediterranean climate during the hot season is approximately 4.5 L/m<sup>2</sup>/day. Additionally, efficiency could increase through the utilization of atmospheric water harvesting systems. The benefits of combining PV panels with green roofs (PV-GR) 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 Housinger et al. [29] demonstrated that irrigation is crucial for solar green roof performance and efficiency to reduce photovoltaic panel heat and achieve 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 photovoltaic (GR-PV) in contrast to a traditional green roof module at the University of Toronto, Canada, with a particular emphasis on GR-PV's lower capacity 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 photovoltaic (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 many factors such as solar module types, installation pattern, operating temperatures and greenery including plant type, water management, and substrate material that require further investigation.

Combining solar panels with green roofs is a remarkable alternative for buildings, particularly those in urban areas lacking green spaces and 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 bio-solar green roofs' irrigation cycle, water consumption, and soil temperature, particularly in Mediterranean climates. This study aims to improve knowledge on the subject by attempting to determine 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 bio-solar green roofs (BS-GRs) performance. 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 by pilot studies could demonstrate the advantages of BS-GRs and show their positive contribution to sustainable urban development and future building technologies, especially for the Mediterranean climate.

### Case study definition and analysis procedures

The case study is situated in southern Italy, at Rende. The city is about 165 meters above sea level and has a Mediterranean climate characterized 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. The first case study examined the irrigation cycle, temperature, and soil humidity in conventional green roofs (CGR) and bio-solar green roofs (BS-GR). 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 degree, which is an optimized slope according to PVGIS tool [32] in the case study location.

Furthermore, bare soil temperature and humidity under the shade of solar panels and in direct sunlight have been investigated in case study two. 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.

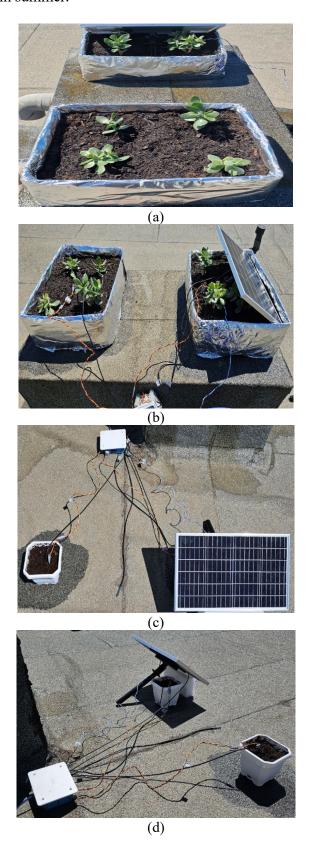


Figure 1. Details of the installed systems and measurement of temperature and humidity: Case study 1: bio-solar test boxes (a); Case study 1: measuring sensors (b); Case study 2: bio-solar test boxes (c); and Case study 2: measuring sensors (d)

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, 20W with size of 45 cm × 25 cm;
- Panel tilt angle: 33 degree;
- 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 thermal camera;
- Measurement days and period: July 6<sup>th</sup>, 2024 for thermal camera images of both bare soil and green roof, July 14<sup>th</sup>, 2024 for measurements of soil temperature and humidity in sunlight and under PV panel shade for both bare soils and green roofs, and 19-21 July 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 and have an adverse effect on the thermal insulation provided by the green roof. The study about green roofs and shadows of photovoltaic panels in a Mediterranean climate in Haifa (Israel) showed that the combination improves plant growing conditions and leads to higher plant diversity. In the case of sedum, the presence of PV prolonged flowering but caused a rise in growth and increased 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 used.

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

Parameter	Sun-loving plants	Shade-loving plants
Maintenance	High	Low
Water demands	High	Low
		Large thin keeves (smaller leaves near
Leaves size	Small thick	the top (light levels are high), and larger
		leaves near the base.)
	Vertical	Horizontal
Leaves angle/orientation		

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<sup>2</sup>/day [35]. The results of another study by Peng and Jim in a humid-subtropical climate showed a water requirement of 5 L/m<sup>2</sup>/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 is different, and the percentage of water reduction varies depending on the type of plant, the climate, and other factors, including soil type and depth. The results of a study for a Mediterranean climate in Montpellier (France) determined the evapotranspiration (ET) reduction in agrivoltaics (photovoltaic system on land) systems by 14-29% compared to conventional systems [38]. Analyses of cultivated lettuces at the Montpellier 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 temperature variation between areas with direct sunlight and shade. Table 2 presents the temperature changes in shade and direct sunlight 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 temperature in sunlight and shade [°C]	Ref.
Photovoltaic rooftop	San Diego (US)	Mediterranean	Thermography	2.5 °C (Ceiling temperature 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 in one day of summer	Up to 16 °C for pavements and up to 6 °C for facades	[45]
Façade surface temperature	Madrid (Spain)	Warm- temperate subtropical	Thermography	7.4 °C in summer and 1.2 °C in winter	[46]

	,				
Multilayer GR	Seoul (Korea)	Hot and very humid	Sensors for surface temperature measurement	5-9 ° C (surrounding surface)	[47]
The 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 height of 1.1 m) 28.8 °C for	[49]
Building shading effect	Harbin (China)	Monsoon- influenced humid continental	Biometeorological measurement units	surface around building shade and 1.2 °C for air temperature	[50]
Buildings shading effect on soil layer temperature in the green plot	Beijing (China)	Warm temperate zone	Sensors	0.29-24.69 °C (surface soil layer temperature in summer)	[51]
Air temperature under solar panel canopy	Tempe, Arizona (US)	Desert	Sensors 2.6 m from the ground and 3.5 m under panels between 1 June 2014 and 31 May 2015	2 °C (air temperature in height 2.6 m)	[52]

# Study limitations and potential weaknesses

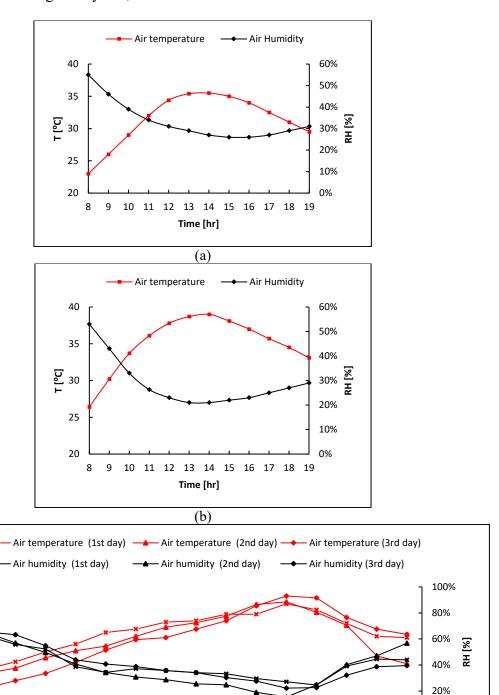
The current study was conducted on cloudless, sunny days, and the role of one solar panel in measuring the temperature and humidity of the bare soil and green roof was measured. However, it might confront with some limits that mainly are:

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

#### **RESULTS & DISCUSSIONS**

Subsequent sections will assess and explore the key findings on the shading effect of PV systems on green roofs, particularly regarding lowering the temperature and water requirements. The experiments were conducted on 6 July, from 8 AM to 7 PM, 14 July, 8 AM to 7 PM, and 19-21 July, each day from 8 AM to 10 PM. Figure 2 shows the humidity and air temperature during the measurement days. The temperature ranges from 23 °C on 6 July to a maximum of 39 °C on

14 July. The humidity ranged during the same period from 15.4% in the evening of July 20<sup>th</sup>, 2024 to 65.5% in the morning of July 21<sup>st</sup>, 2024.



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

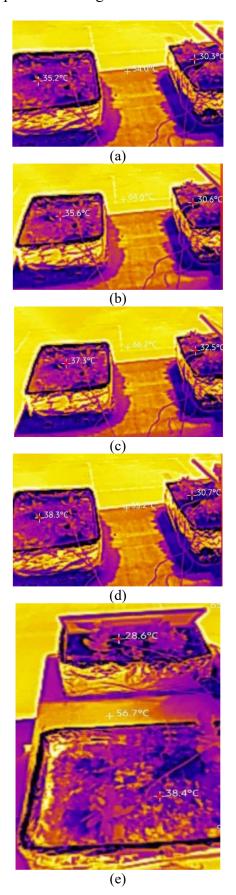
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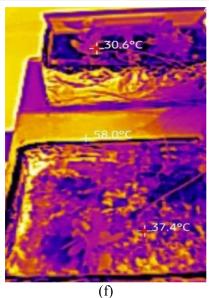
# Temperature variations of the soil surface in sunlight and shade

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

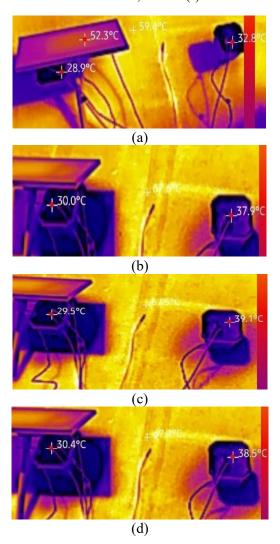
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shadow of solar panels. Moreover, the temperature variations of the soil surface in sunlight and shade in both case studies are presented in Figure 5.





(f)
Figure 3. Green roof surface temperature differences in bio-solar and conventional systems (July 6th, 2024): 8 AM, 4.9 °C (a); 10 AM, 5 °C (b); 12 PM, 4.8 °C (c); 2 PM, 7.6 °C (d); 4 PM, 9.8 °C (e); and 6 PM, 6.8 °C (f)



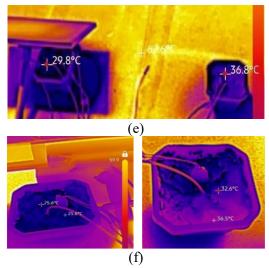
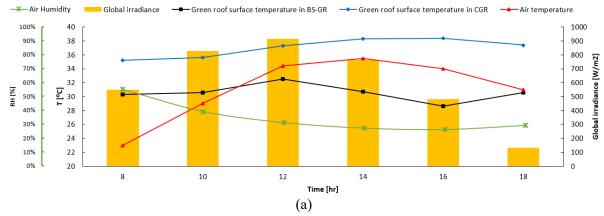


Figure 4. Soil surface temperature differences in PV shade and sunlight (July 6<sup>th</sup>, 2024): 8 AM, 3.9 °C (a); 10 AM, 7.9 °C (b); 12 PM, 9.6 °C (c); 2 PM, 8.1 °C (d); 4 PM, 7.0 °C (e); and 6 PM, 7.0 °C (f)

The thermal images in Figure 3 and the temperature variations in Figure 5(a) show lower temperatures in shadow and indicate that surface temperatures in conventional and bio-solar green roof systems differ 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 to its maximum at 4 PM, around 9.8 °C. The maximum temperature difference was found at 4 PM and equal to 9.8 °C, as shown in Figure 3(e), which could be primarily due to the hot and dry climate, as between 3 and 4 PM, the air humidity was at its lowest level. The temperature difference was reduced in the evening and at 6 PM, equal to 6.8 °C, as depicted in Figure 3(f), mainly due to decrease of global irradiance. Therefore, combining photovoltaic panels with green roofs has decreased soil surface temperature compared to conventional green roofs. This 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 5(b), 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, in which the global irradiance was highest. Comparisons between bare soils and green roofs illustrated 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 effect of plants on reducing surface temperature.



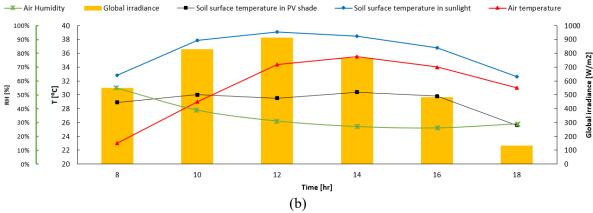
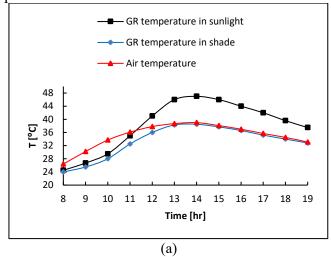


Figure 5. Variations of soil surface temperatures in direct sunlight and shade of PV panels: BS-GR and CGR (a); Bare soil (b)

# Comparisons of temperature and humidity of green roofs in sunlight and shadow

This section investigates the humidity and soil temperature of both conventional and bio-solar green roofs. The experimentation was conducted on July 14th, 2024 from 8 AM to 7 PM, and the ambient temperature during the testing hours was between 26.4 and 39 °C. Figure 6, illustrate the variations in temperature and humidity on a green roof in sunlight and shade by 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, and the biosolar green roof was found to have a lower temperature of about 24 °C in the morning, rising to almost 38.5 °C by midday. A reduction in green roof temperature in the presence of solar panels compared to conventional green roofs has been observed. The maximum soil temperature difference between shade and sunlight was 8 °C at 2 PM. As indicated in Figure 6(b), 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%, correspondingly 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 shade and sunlight led to a difference in soil humidity of about 16.5% at the end of the test, as 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 of energy and water plays an important role.



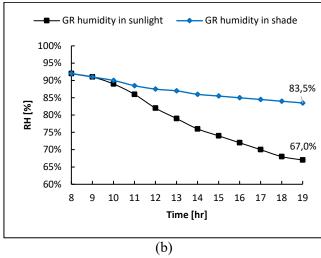
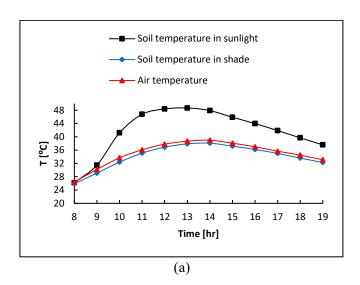


Figure 6. Soil temperature and humidity of green roof in sunlight and shade (July 14<sup>th</sup>, 2024): Temperature (a); and Relative humidity (b)

# Comparisons of 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 green roofs because of plant evapotranspiration. The test was conducted from 8 AM to 7 PM on 14 July 2024, and the experimental results are presented in Figure 7. Figure 7(a) 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, but the bare soil's temperature in the sunlight reached 48.7 °C, while in the shadow, it reached a maximum of 39.6 °C. The maximum temperature difference between the two cases occurred at noon and about 11.7 °C. Figure 7(b) 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, around 15.4%, decreased from 92% at 8 AM to 76.6% at 7 PM.



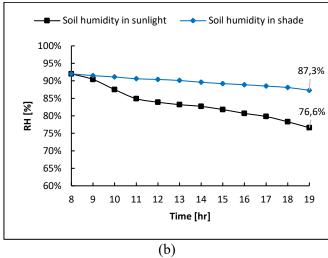


Figure 7. Air and bare soil temperatures and humidity in PV panel shade and sunlight (July 14<sup>th</sup>, 2024): Temperature (a); and Relative humidity (b)

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.

# 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 ranged from 35% [57] to 56% [58], and the recommended range of humidity for typical green roof plants, including succulents (i.e., 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 19-21 July 2024, from 8 AM to 10 PM. The average air temperature for all three days was almost the same, at 31.5 °C, and the maximum temperature was on the third day evening, 38.6 °C, which is representative of the high-temperature summer conditions in 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 level of the CGR and BS-GR during the three measurement days can be seen in Figure 8. The findings revealed that less water is required for green roofs when a bio-solar system is deployed. 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 a few in the afternoon. The RH value remains below the threshold on 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 higher than 73.7% throughout the same period and after three days. 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, following 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 the Mediterranean climate rely on irrigation in summer, a decrease in the water demand by BS-GRs may reduce the 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. RH of soil under the PV panels in BS-GRs is higher, due to shading and less solar radiation on the green roof surface.

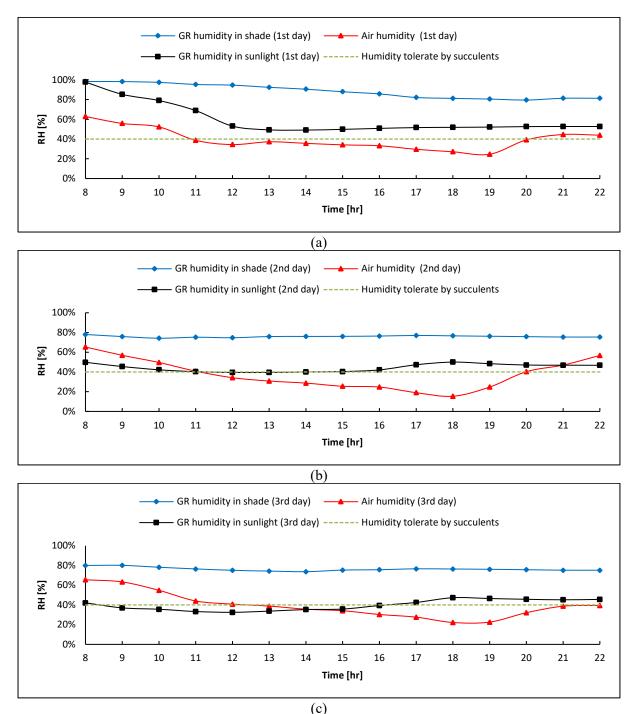
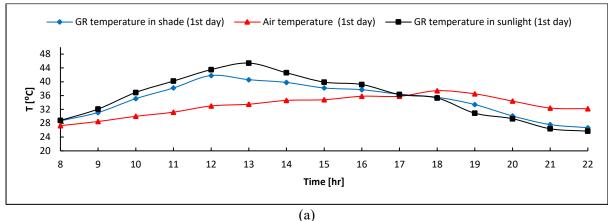
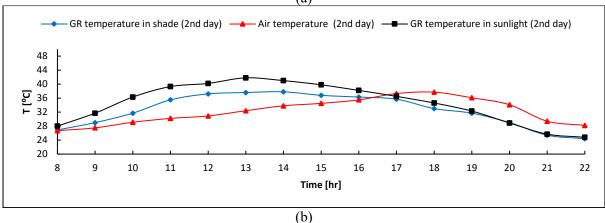


Figure 8. Humidity of conventional and bio-solar green roofs in one irrigation cycle (19-21 July 2024): 1<sup>st</sup> day (a); 2<sup>nd</sup> day (b); and 3<sup>rd</sup> day (c)

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 biosolar green roof, ranging from 2.5 to 1.4 °C. This lower temperature after the sunset could be due to a lower humidity content in the conventional green roof that 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 drops the energy input to the soil, and results 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 minimum around noon, when the soil temperature was highest, while the air temperature and humidity at around 6 PM arrived at their maximum and minimum correspondingly. While RH and temperature are interrelated, in the context of BS-GRs, the observed reduction in soil temperature is primarily driven by decreased solar radiation due to the shading effect of the PV panels. As shown in Figure 7, RH values are generally higher under the panels, but this increase is a consequence of the lower temperature and reduced evapotranspiration, not its cause. Therefore, the lower temperature observed in Figure 8 should be interpreted as a direct effect of shading rather than a response to RH variation.





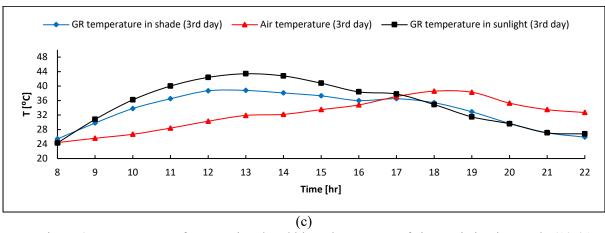


Figure 9. Temperature of conventional and bio-solar green roofs in one irrigation cycle (19-21 July 2024): 1<sup>st</sup> day (a); 2<sup>nd</sup> day (b); and 3<sup>rd</sup> day (c)

# **Future research directions**

Suggested avenues for further investigation are listed below:

- Further studies can be done by utilizing 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 optimization 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 direct 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 long periods without precipitation.

# **CONCLUSION**

The analysis showed that the soil surface temperature was higher in CGR than BS-GR, which differs by 4.8 °C to 9.8 °C. Additionally, the surface temperature of the bare soil was slightly more significant than that of the green roof, demonstrating the effect of plants on reducing surface temperature. Furthermore, the soil temperature difference between shade and sunlight led to a difference in soil humidity of about 16.5%, as the decline in green roof humidity was

approximately 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, less water consumption, and enhanced building cooling impact.

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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 Photovoltaic
LCA Life Cycle Assessment
RH Relative Humidity

### **REFERENCES**

- 1. U. Konbr and M. Abdelaal, "Utilizing Smart Systems to Enhance the Sustainability of Egyptian Administrative Buildings," *Civ. Eng. Archit.*, vol. 10, no. 7, pp. 2779–2808, 2022, https://doi.org/10.13189/cea.2022.100701.
- 2. P. Karanikola, T. Panagopoulos, S. Tampakis, G. Simoglou, and A. Tzelepi, "Perceptions of urban green infrastructure in two contrasting municipalities of the metropolitan area of Athens, Greece," *Nature-Based Solut.*, 2023, https://doi.org/10.1016/j.nbsj.2023.100063.
- 3. M. Shafique, R. Kim, and M. Rafiq, "Green roof benefits, opportunities and challenges A review," *Renewable and Sustainable Energy Reviews*, vol. 90. pp. 757–773, 2018, https://doi.org/10.1016/j.rser.2018.04.006.
- 4. S. S. G. Hashemi, H. Bin Mahmud, and M. A. Ashraf, "Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review," *Renewable and Sustainable Energy Reviews*, vol. 52. Elsevier Ltd, pp. 669–679, Aug. 22, 2015, https://doi.org/10.1016/j.rser.2015.07.163.
- 5. C. Twohig, Y. Casali, and N. Y. Aydin, "Can Green Roofs Help with Stormwater Floods? A Geospatial Planning Approach," SSRN Electron. J., 2022,

https://doi.org/10.2139/ssrn.4101160.

- 6. A. Palla, I. Gnecco, M. Carbone, G. Garofalo, L. G. Lanza, and P. Piro, "Influence of stratigraphy and slope on the drainage capacity of permeable pavements: laboratory results," *Urban Water J.*, vol. 12, no. 5, pp. 394–403, 2015, https://doi.org/10.1080/1573062X.2014.900091.
- 7. E. Burszta-Adamiak, "The influence of green roofs on runoff quality 6 years of experience," *Desalin. Water Treat.*, vol. 186, pp. 394–405, 2020, https://doi.org/10.5004/dwt.2020.25448.
- 8. P. Piro, M. Carbone, N. Penna, and J. Marsalek, "Characterization of the settling process for wastewater from a combined sewer system," *Water Res.*, vol. 45, no. 20, pp. 6615–6624, 2011, https://doi.org/10.1016/j.watres.2011.09.034.
- 9. T. Van Renterghem, "Chapter 3.8. Green roofs for acoustic insulation and noise reduction," in *Nature Based Strategies for Urban and Building Sustainability*, K. P. Gabriel Pérez, Ed. Oxford, UK, 2018, pp. 167–179.
- 10. D. Kostadinović, M. Jovanović, V. Bakić, and N. Stepanić, "Mitigation of urban particulate pollution using lightweight green roof system," *Energy Build.*, vol. 293, 2023, https://doi.org/10.1016/j.enbuild.2023.113203.
- 11. S. Sakenova, U. Konbr, T. Kisselyova, Z. Aimagambetova, G. Mugzhanova, and D. Amandykova, "Conformation Factors of Building Bioclimatic Microclimate," *Civ. Eng. Archit.*, vol. 12, no. 1, pp. 350–360, 2024, https://doi.org/10.13189/cea.2024.120126.
- 12. Intergovernmental Panel on Climate Change (IPCC), "Climate Change 2022 Impacts, Adaptation and Vulnerability," *Clim. Chang. 2022 Impacts, Adapt. Vulnerability*, 2023, https://doi.org/10.1017/9781009325844.
- 13. G. Mihalakakou *et al.*, "Green roofs as a nature-based solution for improving urban sustainability: Progress and perspectives," *Renewable and Sustainable Energy Reviews*. 2023, https://doi.org/10.1016/j.rser.2023.113306.
- 14. A. Benato, A. Stoppato, F. De Vanna, and F. Schiro, "Spraying cooling system for pv modules: Experimental measurements for temperature trends assessment and system design feasibility," *Designs*, 2021, https://doi.org/10.3390/designs5020025.
- 15. M. Shahmohammad, M. Hosseinzadeh, B. Dvorak, F. Bordbar, H. Shahmohammadmirab, and N. Aghamohammadi, "Sustainable green roofs: a comprehensive review of influential factors," *Environmental Science and Pollution Research*, vol. 29, no. 52. pp. 78228–78254, 2022, https://doi.org/10.1007/s11356-022-23405-x.
- 16. L. J. Houchmand, M. M. Martí, and S. Gassó-Domingo, "Photovoltaics and green roofs: Holistic analysis in built environments," *Renew. Sustain. Energy Rev.*, vol. 207, 2025, https://doi.org/10.1016/j.rser.2024.114987.
- 17. Y. Zheng and Q. Weng, "Modeling the effect of green roof systems and photovoltaic panels for building energy savings to mitigate climate change," *Remote Sens.*, 2020, https://doi.org/10.3390/RS12152402.
- 18. T. A. Paço, R. Cruz de Carvalho, P. Arsénio, and D. Martins, "Green Roof Design Techniques to Improve Water Use under Mediterranean Conditions," *Urban Sci.*, 2019, https://doi.org/10.3390/urbansci3010014.
- 19. N. Balvedi and T. Giglio, "Influence of green roof systems on the energy performance of buildings and their surroundings," *J. Build. Eng.*, vol. 70, 2023, https://doi.org/10.1016/j.jobe.2023.106430.
- 20. M. Fiori, T. Poli, A. G. Mainini, J. D. Blanco Cadena, A. Speroni, and D. Bocchiola, "Assessing water demand of green roofs under variants of climate change scenarios," in *Research for Development*, Springer, Cham, 2020, pp. 375–380.
- 21. W. T. Wang, H. Yang, and C. Y. Xiang, "Green roofs and facades with integrated photovoltaic system for zero energy eco-friendly building A review," Sustainable Energy Technologies and Assessments. 2023,

- https://doi.org/10.1016/j.seta.2023.103426.
- 22. M. Maiolo, B. Pirouz, R. Bruno, S. A. Palermo, N. Arcuri, and P. Piro, "The role of the extensive green roofs on decreasing building energy consumption in the mediterranean climate," *Sustain.*, vol. 12, no. 1, 2020, https://doi.org/10.3390/su12010359.
- 23. T. Piccinini Scolaro, E. Ghisi, and C. M. Silva, "Assessing the impact of evapotranspiration from green roofs on reducing surface temperatures," *J. Build. Eng.*, vol. 95, 2024, https://doi.org/10.1016/j.jobe.2024.110095.
- 24. T. P. Scolaro and E. Ghisi, "Life cycle assessment of green roofs: A literature review of layers materials and purposes," *Science of the Total Environment*, vol. 829. 2022, https://doi.org/10.1016/j.scitotenv.2022.154650.
- 25. B. Pirouz, S. A. Palermo, M. Maiolo, N. Arcuri, and P. Piro, "Decreasing water footprint of electricity and heat by extensive green roofs: Case of southern italy," *Sustain.*, vol. 12, no. 23, pp. 1–16, 2020, https://doi.org/10.3390/su122310178.
- 26. H. Zhang *et al.*, "Is sustainable extensive green roof realizable without irrigation in a temperate monsoonal climate? A case study in Beijing," *Sci. Total Environ.*, 2021, https://doi.org/10.1016/j.scitotenv.2020.142067.
- 27. B. Pirouz, S. A. Palermo, and M. Turco, "Improving the efficiency of green roofs using atmospheric water harvesting systems (An innovative design)," *Water (Switzerland)*, vol. 13, no. 4, 2021, https://doi.org/10.3390/w13040546.
- 28. M. Ramshani, A. Khojandi, X. Li, and O. Omitaomu, "Optimal planning of the joint placement of photovoltaic panels and green roofs under climate change uncertainty," *Omega (United Kingdom)*, 2020, https://doi.org/10.1016/j.omega.2018.10.016.
- 29. J. Heusinger, D. J. Sailor, and S. Weber, "Modeling the reduction of urban excess heat by green roofs with respect to different irrigation scenarios," *Build. Environ.*, 2018, https://doi.org/10.1016/j.buildenv.2018.01.003.
- 30. R. Fleck, R. Gill, T. J. Pettit, F. R. Torpy, and P. J. Irga, "Bio-solar green roofs increase solar energy output: The sunny side of integrating sustainable technologies," *Build. Environ.*, vol. 226, 2022, https://doi.org/10.1016/j.buildenv.2022.109703.
- 31. A. Jahanfar, J. Drake, B. Sleep, and L. Margolis, "Evaluating the shading effect of photovoltaic panels on green roof discharge reduction and plant growth," *J. Hydrol.*, vol. 568, pp. 919–928, 2019, https://doi.org/10.1016/j.jhydrol.2018.11.019.
- 32. European Commission, "PVGIS." https://re.jrc.ec.europa.eu/pvg\_tools/en/ (accessed Oct. 01, 2024).
- 33. B. Y. Schindler, L. Blaustein, R. Lotan, H. Shalom, G. J. Kadas, and M. Seifan, "Green roof and photovoltaic panel integration: Effects on plant and arthropod diversity and electricity production," *J. Environ. Manage.*, vol. 225, pp. 288–299, 2018, https://doi.org/10.1016/j.jenvman.2018.08.017.
- 34. O. Speck, M. Caliaro, A. Mader, and J. Knippers, "Plants In Action," in *Biomimetics for Architecture*, Jan Knippers, Ulrich Schmid and Thomas Speck, Ed. Berlin, Boston: Birkhäuser, 2019, pp. 14–21.
- 35. O. Schweitzer and E. Erell, "Evaluation of the energy performance and irrigation requirements of extensive green roofs in a water-scarce Mediterranean climate," *Energy Build.*, vol. 68, no. PARTA, pp. 25–32, Jan. 2014, https://doi.org/10.1016/j.enbuild.2013.09.012.
- 36. L. L. H. Peng and C. Y. Jim, "Seasonal and diurnal thermal performance of a subtropical extensive green roof: The impacts of background weather parameters," *Sustain.*, vol. 7, no. 8, pp. 11098–11113, 2015, https://doi.org/10.3390/su70811098.
- 37. D. Gößner, M. Mohri, and J. J. Krespach, "Evapotranspiration measurements and assessment of driving factors: A comparison of different green roof systems during summer in Germany," *Land*, vol. 10, no. 12, 2021, https://doi.org/10.3390/land10121334.
- 38. H. Marrou, L. Dufour, and J. Wery, "How does a shelter of solar panels influence water

- flows in a soil-crop system?," Eur. J. Agron., vol. 50, pp. 38–51, 2013, https://doi.org/10.1016/j.eja.2013.05.004.
- 39. Y. Elamri, B. Cheviron, J. M. Lopez, C. Dejean, and G. Belaud, "Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces," *Agric. Water Manag.*, vol. 208, pp. 440–453, 2018, https://doi.org/10.1016/j.agwat.2018.07.001.
- 40. A. Ali Abaker Omer *et al.*, "Water evaporation reduction by the agrivoltaic systems development," *Sol. Energy*, vol. 247, pp. 13–23, 2022, https://doi.org/10.1016/j.solener.2022.10.022.
- 41. E. H. Adeh, J. S. Selker, and C. W. Higgins, "Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency," *PLoS One*, vol. 13, no. 11, 2018, https://doi.org/10.1371/journal.pone.0203256.
- 42. L. Tams, E. N. Paton, and B. Kluge, "Impact of shading on evapotranspiration and water stress of urban trees," *Ecohydrology*, vol. 16, no. 6, 2023, https://doi.org/10.1002/eco.2556.
- 43. A. Dominguez, J. Kleissl, and J. C. Luvall, "Effects of solar photovoltaic panels on roof heat transfer," *Sol. Energy*, vol. 85, no. 9, pp. 2244–2255, 2011, https://doi.org/10.1016/j.solener.2011.06.010.
- 44. V. Kapsalis and D. Karamanis, "On the effect of roof added photovoltaics on building's energy demand," *Energy Build.*, vol. 108, pp. 195–204, 2015, https://doi.org/10.1016/j.enbuild.2015.09.016.
- 45. E. Garcia-Nevado, B. Beckers, and H. Coch, "ASSESSING THE COOLING EFFECT OF URBAN TEXTILE SHADING DEVICES THROUGH TIME-LAPSE THERMOGRAPHY," *Sustain. Cities Soc.*, vol. 63, 2020, https://doi.org/10.1016/j.scs.2020.102458.
- 46. M. del M. Barbero-Barrera, R. Tendero-Caballero, and M. García de Viedma-Santoro, "Impact of Solar Shading on Façades' Surface Temperatures under Summer and Winter Conditions by IR Thermography," *Architecture*, vol. 4, no. 2, pp. 221–246, 2024, https://doi.org/10.3390/architecture4020014.
- 47. M. Shafique and R. Kim, "Application of green blue roof to mitigate heat island phenomena and resilient to climate change in urban areas: A case study from Seoul, Korea," *J. Water L. Dev.*, vol. 33, no. 1, pp. 165–170, 2017, https://doi.org/10.1515/jwld-2017-0032.
- 48. L. S. H. Lee, P. K. Cheung, C. K. W. Fung, and C. Y. Jim, "Improving street walkability: Biometeorological assessment of artificial-partial shade structures in summer sunny conditions," *Int. J. Biometeorol.*, vol. 64, no. 4, pp. 547–560, 2020, https://doi.org/10.1007/s00484-019-01840-9.
- 49. P. K. Cheung and C. Y. Jim, "Comparing the cooling effects of a tree and a concrete shelter using PET and UTCI," *Build. Environ.*, vol. 130, pp. 49–61, 2018, https://doi.org/10.1016/j.buildenv.2017.12.013.
- 50. J. Du, L. Liu, X. Chen, and J. Liu, "Field Assessment of Neighboring Building and Tree Shading Effects on the 3D Radiant Environment and Human Thermal Comfort in Summer within Urban Settlements in Northeast China," *Adv. Meteorol.*, vol. 2020, 2020, https://doi.org/10.1155/2020/8843676.
- 51. H. Zhou, X. Yan, B. Ge, and D. Hu, "Horizontal heat impacts and shading effects of buildings on surface soil layer in Beijing, China," *Indoor Built Environ.*, vol. 31, no. 7, pp. 1806–1821, 2022, https://doi.org/10.1177/1420326X221078996.
- 52. A. Middel, N. Selover, B. Hagen, and N. Chhetri, "Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona," *Int. J. Biometeorol.*, vol. 60, no. 12, pp. 1849–1861, 2016, https://doi.org/10.1007/s00484-016-1172-5.
- 53. J. R. C. E. Commission, "Photovoltaic Geographical Information System (PVGIS)," *Joint Research Centre - Institute for Energy and Transport*, 2017. https://re.jrc.ec.europa.eu/pvg\_tools/es/#PVP%0Ahttps://ec.europa.eu/jrc/en/pvgis

(accessed Dec. 16, 2024).

- 54. E. Jamei, H. W. Chau, M. Seyedmahmoudian, and A. Stojcevski, "Review on the cooling potential of green roofs in different climates," *Science of the Total Environment*, vol. 791. 2021, https://doi.org/10.1016/j.scitotenv.2021.148407.
- 55. L. Mentaschi *et al.*, "Global long-term mapping of surface temperature shows intensified intra-city urban heat island extremes," *Glob. Environ. Chang.*, vol. 72, 2022, https://doi.org/10.1016/j.gloenvcha.2021.102441.
- 56. C. J. A. Catigday, C. Sace, C. Pascual, and V. Malamug, "Relationships of Water Quality Parameters for Hydroponic Production of Kale (Brassica oleracea) with In-Ground Passive Cooling System," *CLSU Int. J. Sci. Technol.*, vol. 7, no. 2, pp. 63–73, 2023, https://doi.org/10.22137/ijst.2023.v7n2.07.
- 57. F. Fantozzi, C. Bibbiani, C. Gargari, R. Rugani, and G. Salvadori, "Do green roofs really provide significant energy saving in a Mediterranean climate? Critical evaluation based on different case studies," *Front. Archit. Res.*, vol. 10, no. 2, pp. 447–465, 2021, https://doi.org/10.1016/j.foar.2021.01.006.
- 58. M. Anwar, M. G. Rasul, and M. M. K. Khan, "Performance Analysis of rooftop greenery systems in Australian subtropical climate," in *Energy Reports*, 2020, vol. 6, pp. 50–56, https://doi.org/10.1016/j.egyr.2019.08.017.
- 59. S. Agostino, "14 Popular Types of Succulents," 2022. https://florasense.com/blogs/14-popular-types-of-succulents/ (accessed Jul. 20, 2024).
- 60. M. G. Gomes, C. M. Silva, A. S. Valadas, and M. Silva, "Impact of vegetation, substrate, and irrigation on the energy performance of green roofs in a Mediterranean climate," *Water (Switzerland)*, vol. 11, no. 10, 2019, https://doi.org/10.3390/w11102016.