



# Innovative green roof technologies in Mediterranean climate: Implications for sustainable design of the built environment

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## ABSTRACT

Green roofs are increasingly recognized for their contributions to urban sustainability, offering benefits such as thermal regulation, stormwater management, energy efficiency, improved air quality, and enhanced biodiversity. However, the performance of green roofs in Mediterranean climates remains underexplored. This study evaluates the effectiveness of three distinct green roof technologies—Experimental, Draining Modules, and Green Safe—in Mediterranean conditions, focusing on thermal regulation, water retention, and energy savings. High-precision instruments, including thermocouples, heat flux sensors, and Time Domain Reflectometry (TDR) probes, were deployed to monitor performance over an eight-day summer period. The Experimental Technology, integrating biochar into the substrate, achieved the best thermal performance, with a surface temperature reduction of up to 9.8 °C compared to the reference roof, an average daily cooling energy savings of 3.8 kWh, and a total energy savings of 10 % over the simulation period. The Draining Modules Technology demonstrated moderate performance, with a surface temperature reduction of 6.5 °C and a total energy savings of 6.5 %, equating to 2.5 kWh of daily cooling energy savings. In contrast, the Green Safe Technology exhibited the highest surface temperatures and the lowest water retention, resulting in a surface temperature reduction of 5 °C and energy savings of only 5 % (equivalent to 1.9 kWh of daily energy savings). These findings underscore the potential of biochar-enhanced substrates in mitigating the Urban Heat Island (UHI) effect, reducing cooling energy demand, and improving building energy efficiency. This research provides quantitative insights for urban planners, architects, and policymakers seeking to implement more effective and sustainable green roof designs in regions with challenging climatic conditions, thereby supporting urban resilience and climate adaptation.

## 1. Introduction

Urbanization has led to significant environmental challenges, particularly in densely populated cities where natural landscapes are often replaced by impervious surfaces. This transformation exacerbates issues such as UHI, increased stormwater runoff, and loss of biodiversity [1]. As cities continue to grow, finding sustainable solutions to mitigate these negative impacts has become increasingly crucial. One such solution is the implementation of green infrastructures, which have gained attention for their potential to enhance urban resilience and contribute to the United Nations' Sustainable Development Goals (SDGs) outlined in the Agenda 2030 [2,3].

UHI effects, characterized by elevated temperatures in urban areas compared to their rural surroundings, present significant challenges for Mediterranean cities due to their unique climatic conditions—hot, dry

summers and mild, wet winters [4]. The mitigation of UHI is especially critical in these regions, where high summer temperatures exacerbate energy demands and impact urban livability [5].

Green roofs, also known as vegetative or living roofs, are a form of green infrastructure that involves the installation of a vegetative layer over a waterproof membrane on building rooftops [6]. These systems offer multiple environmental benefits, including the reduction of stormwater runoff, enhancement of urban biodiversity, and mitigation of the UHI effect by providing natural insulation and reducing surface temperatures [7]. Moreover, green roofs contribute to energy efficiency by lowering building cooling demands during the summer period and improving indoor thermal comfort [8].

Despite the well-documented benefits of green roofs, significant gaps remain in the understanding of their performance across different climatic conditions. Existing research has predominantly focused on

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temperate and tropical climates, where green roofs have been shown to effectively reduce building energy demands and mitigate UHI effects [9]. However, the performance of green roofs in Mediterranean climates, characterized by hot, dry summers and mild, wet winters, is not well understood [10]. Mediterranean climates present unique challenges, such as prolonged dry periods, where the ability of green roofs to retain water and sustain vegetation is critical. Additionally, the effectiveness of these systems in providing thermal insulation under such extreme conditions has not been sufficiently studied.

In temperate climates, green roofs have been shown to reduce surface temperatures significantly, enhance biodiversity, and manage stormwater effectively [11]. Similarly, research in tropical climates demonstrates the ability of green roofs to mitigate heat and manage heavy rainfall [12]. However, these findings do not readily translate to Mediterranean regions, where the combination of high temperatures and limited rainfall presents different stress factors on vegetation and substrate performance. As such, there is a critical gap in the literature concerning the specific design and performance metrics needed to optimize green roofs for Mediterranean climates.

Additionally, the impact of innovative materials and technologies, such as biochar-enhanced substrates, on the efficiency and effectiveness of green roofs has not been thoroughly investigated. Biochar, known for its ability to improve soil quality and water retention, presents a hopeful prospect for enhancing green roof performance, yet its application in this context remains underexplored [13]. This gap highlights the need for comprehensive, empirical research that evaluates the performance of various green roof technologies under the specific climatic conditions of Mediterranean regions.

The novelty of this research lies in several aspects:

1. While biochar is known for its benefits in agriculture, its use in green roof substrates, particularly in Mediterranean climates, is a new approach. This study pioneers the evaluation of biochar's impact on water retention, soil quality, and thermal performance in urban infrastructure.
2. Previous research has largely focused on temperate and tropical climates. This study addresses the knowledge gap in Mediterranean climates by evaluating green roof technologies under hot, dry conditions, providing valuable insights for optimizing these systems in such environments.
3. The study employs high-precision instrumentation—such as TDR probes, heat flux sensors, and thermocouples—combined with rigorous statistical analysis (ANOVA, Tukey's HSD) to assess thermal performance and water retention, representing an advancement in green roof performance assessment.
4. The research combines real-world data with simulation-based assessments to predict the impact of green roofs on energy efficiency and UHI mitigation, offering practical insights for urban planners and architects.

To address these gaps and introduce these novel approaches, this study focuses on evaluating the performance of three distinct green roof technologies: Draining Modules, Green Safe, and Experimental Technology, the latter of which incorporates biochar as a key substrate component. Each of these technologies was developed and tested as part of the GIFLUID project, which aims to improve urban resilience to flooding and enhance the quality of rainwater discharges in Mediterranean urban environments.

This research not only contributes to the existing body of knowledge on green roof performance but also provides valuable insights for urban planners, architects, and policymakers. The findings from this study have the potential to inform the design and implementation of more effective green infrastructure in cities facing similar climatic challenges, ultimately promoting more sustainable and resilient urban environments, in line with the SDGs Agenda 2030.

## 2. Literature review

### 2.1. Green roofs in Mediterranean climates and thermal regulation

Green roofs are widely recognized for their ability to mitigate UHI, manage stormwater, and enhance urban biodiversity. However, the effectiveness of these systems can vary significantly depending on the local climate, particularly in Mediterranean regions, which are characterized by hot, dry summers and mild, wet winters [14]. Most of the existing research on green roofs has focused on temperate or tropical climates, leaving a substantial knowledge gap regarding their performance in Mediterranean conditions [15,16].

In temperate climates, green roofs have been shown to provide significant energy savings and cooling effects. For example, studies in temperate regions have demonstrated that green roofs can reduce surface temperatures by up to 40 % and contribute to energy savings by lowering the cooling load of buildings by 30–50 % [17]. In tropical climates, green roofs have proven effective in managing the impact of heavy rainfall, while also reducing indoor temperatures and promoting biodiversity [18]. However, the performance of green roofs in Mediterranean climates, where prolonged dry periods and high summer temperatures can stress vegetation and substrate systems, remains less understood.

The literature reveals that Mediterranean cities face unique challenges in addressing UHI, driven by a combination of high solar radiation, limited rainfall, and dense urbanization. Salvati et al. [19] demonstrated that building orientation, vegetation cover, and urban design significantly influence UHI effects, with implications for energy consumption in residential areas. Their findings align with the broader evidence that green infrastructure, such as green roofs, can reduce surface temperatures and enhance thermal comfort. In their study on Bari, Martinelli et al. [20] examined the impact of vegetation and urban morphology on UHI mitigation. Their results showed that green roofs and urban greenery play a crucial role in reducing daytime temperatures, particularly in coastal Mediterranean cities. These findings underscore the importance of incorporating vegetation in urban design to counteract UHI effects.

In Mediterranean climates, studies have shown that the thermal performance of green roofs is influenced by factors such as substrate composition, vegetation cover, and irrigation strategies. A study by Kaboré et al. [21] demonstrated that green roofs could significantly reduce heat flux through the roof structure, thereby improving indoor thermal comfort during hot summers. Silva et al. [22] studying green roofs in Lisbon, Portugal, found that extensive green roofs could reduce cooling energy needs by 60–70 %, highlighting their potential in Mediterranean regions.

Additionally, Bevilacqua et al. [23] conducted an experimental analysis of green roofs in southern Italy and found that they could reduce roof surface temperatures by an average of 12 °C during summer, providing substantial cooling benefits. However, the study also noted that the cooling effect of green roofs was limited by low substrate moisture levels during prolonged dry periods, which can inhibit evapotranspiration. Gomes et al. [24] emphasized the importance of irrigation to sustain plant health and optimize cooling effects during Mediterranean summers, showing that varying irrigation levels can reduce cooling energy needs by up to 500 %.

Recent studies have further explored these dynamics. For instance, Olivieri et al. [25] found that green roofs with high vegetation density could reduce thermal gain by 60 % in a Mediterranean coastal climate, particularly when paired with adequate irrigation. Shao et al. [26] demonstrated that thicker substrates with higher moisture content could significantly improve the thermal performance of green roofs in Mediterranean-type climates.

## 2.2. Substrate characteristics and biochar's role

Water retention is another critical performance metric for green roofs, especially in Mediterranean climates, where extended dry periods are common. In traditional green roof designs, substrates such as expanded clay, pumice, and perlite are typically used to balance water retention and drainage [27]. However, these materials may not provide sufficient water retention during extended dry spells, which can limit the cooling and ecological benefits of green roofs.

Recent studies have investigated the potential of alternative materials [28]. However, these materials may not provide sufficient water retention in regions with extended dry spells. The importance of substrate characteristics is further highlighted by recent studies on the use of alternative materials in green roof systems. For instance, research by Cascone and Gagliano [29] evaluated the potential of recycled agricultural plastic waste, particularly polyethylene granules, as a drainage layer in green roofs. This study found that recycled plastic granules, while providing adequate water drainage, also offer environmental benefits by reducing the load on the environment compared to traditional materials like expanded clay and perlite. The study also demonstrated that recycled plastic granules maintain their physical properties under varying moisture conditions, making them a viable alternative to traditional materials in green roof applications. Moreover, the Gagliano and Cascone [30] investigated the integration of recycled materials in green roof substrates, finding that these materials could provide comparable or even superior performance in terms of thermal insulation and water retention, especially when combined with biochar.

Recent research has begun to explore the potential of incorporating biochar into green roof substrates as a means of improving water retention. Biochar, a form of charcoal produced from organic materials through pyrolysis, is known for its high porosity and ability to retain moisture [31].

Several studies have demonstrated that biochar can significantly enhance the water-holding capacity and reduce nutrient leaching in green roof substrates. For example, a study by Kuoppamäki and Lehvävirta [32] found that biochar amendments in green roof substrates reduced nutrient leaching and improved water retention, making it an effective solution for managing stormwater and supporting plant growth in Mediterranean climates. Werdin et al. [33] showed that finer biochar particles significantly improved water retention in green roof substrates, although this came at the cost of reduced air-filled porosity and infiltration capacity. In contrast, coarser biochar particles provided a better balance between water retention and drainage, making them more suitable for green roofs in areas with variable rainfall.

Another study by Chen et al. [34] demonstrated that the addition of sludge biochar to green roof substrates could significantly increase substrate moisture and plant growth. The study reported that a 10–15 % biochar amendment led to the most significant improvements in both moisture retention and plant biomass, highlighting its potential to enhance the ecological benefits of green roofs in dry climates. Additionally, Gan et al. [35] explored the hydrological performance of biochar-amended green roofs through both experimental and numerical investigations. The research found that a 10 % biochar content in the substrate provided optimal rainwater management, offering the highest peak outflow reduction and the longest rainwater outflow delay during heavy rainfall events.

## 2.3. Comparative studies of green roofs

Comparative studies of green roof technologies provide valuable insights into the relative performance of different systems under varying conditions [36]. Previous research has employed a range of methodologies to compare the thermal and hydrological efficiency of green roofs, often using experimental setups combined with statistical analysis to identify significant differences between technologies.

For instance, Yang et al. [37] evaluated various green roof

configurations in a sub-tropical climate and found that roofs with 100 mm and 200 mm soil layers reduced indoor air temperatures by 0.95 °C and 0.8 °C, respectively, compared to conventional roofs, which also resulted in a 15.2 % reduction in air conditioning energy consumption.

In another study, Yang and Wang [38] applied a Monte Carlo approach to assess urban hydrological models, showing that green roofs exhibited significantly different thermal behaviors compared to conventional roofs, particularly regarding surface temperatures and heat fluxes, which were less influenced by climatic variations.

Arkar et al. [39] investigated green roofs with lightweight mineral wool growing media across European climates, demonstrating lower heat gains in summer and reduced heat losses in winter, with irrigation further enhancing water retention and cooling.

Moreover, He et al. [40] conducted a comparative study of the thermal and energy performance of green roofs versus cool roofs in Shanghai. The study showed that green roofs could reduce the cooling and heating loads of the top floor by 3.6 % and 6.2 %, respectively, highlighting their dual role in both cooling in summer and insulation during winter. Rapisarda et al. [41] also explored the thermal performance of hydroponic green roofs in a Mediterranean climate. Their research indicated that hydroponic systems not only reduced roof surface temperatures significantly but also outperformed traditional extensive green roofs in terms of temperature regulation during the hot summer months. Cascone [42] conducted an experimental study on the energy-efficient design of sustainable green roofs specifically for Mediterranean climates. This previous research introduced innovative green roof technology using local and recycled materials. Despite higher surface temperatures compared to commercial solutions, the innovative green roof demonstrated superior thermal inertia and a reduction in daily temperature fluctuations, ultimately lowering the building's cooling energy demand by approximately 2 °C.

## 2.4. Comparative studies on green roof optimization in diverse climates

The optimization of green roofs in high-density urban areas has been a focus of several recent studies, particularly in climates with hot and humid conditions [43,44]. These studies emphasize the importance of spatial layout design, substrate composition, and vegetation selection in enhancing green roof performance under challenging climatic conditions.

For example, Yang et al. [45] investigated the impact of spatial configurations in high-density areas, demonstrating that compact layouts promoting efficient air circulation significantly reduced rooftop surface temperatures by up to 3.5 °C. This study highlighted the delicate balance between maximizing vegetation coverage and maintaining airflow to enhance thermal regulation.

In another study, Yan et al. [46] explored the role of plant species with high evapotranspiration rates, such as Sedum and Festuca, in improving cooling performance and mitigating UHI effects in densely populated urban areas. Similarly, Thao et al. [47] found that moisture-retentive substrates incorporating biochar significantly improved water retention and thermal regulation, even under high rainfall conditions. These findings underscore the critical role of substrate innovation in achieving consistent performance across varying environmental stresses.

The lessons learned from these studies provide a valuable comparative framework for regions with different climatic challenges. For example, Mediterranean climates face water scarcity and high solar radiation, making water retention a critical design priority. Techniques such as the integration of biochar into green roof substrates, as demonstrated by Nguyen et al. [48], offer dual benefits of improved water retention and thermal insulation, applicable across diverse climatic contexts.

Future research should explore how strategies like spatial optimization and vegetation selection, proven effective in other climates, can be adapted to meet the specific challenges of Mediterranean cities. These

insights emphasize the importance of designing green roofs that are responsive to both climatic and urban density conditions.

## 2.5. Gaps and research opportunities

While the existing literature provides a solid foundation for understanding the general benefits of green roofs, significant gaps remain [49], particularly regarding their application in Mediterranean climates and the potential of innovative materials like biochar. The limited studies on Mediterranean green roofs suggest that more research is needed to optimize these systems for the unique challenges posed by hot, dry summers and mild, wet winters [50].

Table 1 summarizes the key areas explored in the literature review, highlighting the current understanding and the identified research gaps that this study aims to address.

As summarized in this table, the literature reveals several critical gaps that this research aims to address. There is a clear need for more detailed studies on green roof performance specifically tailored to Mediterranean climates, where the combination of extreme heat and limited rainfall poses unique challenges. Additionally, while biochar has shown promise in other contexts, its application as a green roof substrate remains largely unexplored, particularly in Mediterranean regions.

This study seeks to fill these gaps by providing empirical data on the performance of biochar-enhanced green roofs in Mediterranean environments and by offering comparative insights into different green roof technologies. The research utilizes advanced measurement techniques and rigorous statistical analysis to evaluate thermal regulation, water retention, and overall system efficiency.

## 3. Materials and methods

### 3.1. Methodology

The methodology for this study was designed to evaluate the performance of three green roof technologies under Mediterranean climatic conditions through a combination of in situ experimental analyses and

**Table 1**

Summary of research areas, current understanding, and identified gaps related to green roofs in Mediterranean climates.

Research area	Current understanding	Identified gaps
Green roofs in Mediterranean climates	Green roofs reduce UHI and improve indoor thermal comfort. Thermal performance is influenced by substrate type and roof design.	Limited studies on the performance of green roofs specifically in Mediterranean climates. Need for in-depth analysis of different green roof technologies under Mediterranean conditions.
Thermal regulation	Effective in reducing heat flux and surface temperatures.	Insufficient data on the optimal substrate compositions for thermal regulation in hot, dry climates.
Water retention strategies	Traditional substrates (e.g., expanded clay, perlite) balance water retention and drainage.	Limited research on the effectiveness of these substrates during prolonged dry periods in Mediterranean regions.
Role of biochar in green roofs	Biochar enhances water retention and soil quality in agricultural settings.	Underexplored potential of biochar as a substrate component in green roofs, particularly in Mediterranean climates.
Comparative studies of green roof technologies	Comparative studies often use statistical methods like ANOVA to evaluate performance.	Need for more comparative studies focused on Mediterranean climates and incorporating innovative materials like biochar.

simulation-based assessments. The research process is summarized in Fig. 1.

### 3.2. Project overview and green roof design

The extensive green roof was installed on the atrium roof of Building B in the Bioscientific Hub, located at Via S. Sofia 100, Catania. This facility is home to the Department of Agriculture, Food, and Environment of the University of Catania. The implementation of this project was funded under the "GIFLUID - Green Infrastructures to Mitigate Flood Risks in Urban and Suburban Areas and to Improve the Quality of Rainwater Discharges" initiative, part of the INTERREG V-A Italy-Malta program (2014–2020). The primary goals of this project are to enhance urban resilience to flooding, improve rainwater management, and increase green space in urban environments. The green roof installation covers a total area of approximately 900 m<sup>2</sup> and is directly accessible via a door on the first floor of Building B (Fig. 2). This installation aims to demonstrate the effectiveness of green roofs in reducing stormwater runoff and mitigating the UHI effect by providing natural insulation and promoting biodiversity.

The design of the green roof took into account the roof's natural drainage and runoff lines and was divided into seven sectors, which collectively incorporate three different green roof technologies (Fig. 3). Each technology was selected to assess its efficiency in water retention, thermal performance, and ecological benefits under Mediterranean climate conditions:

- **Draining Modules:** This technology utilizes modules that facilitate efficient water drainage and retention. It is designed to improve stormwater management and reduce peak runoff during heavy rainfall events.
- **Green Safe:** This system integrates sub-irrigation and water storage capabilities, ensuring sustained plant growth even during dry periods. It aims to maximize water use efficiency and support a diverse range of plant species.
- **Experimental Technology:** This innovative approach involves the use of recycled materials for drainage and aims to assess the feasibility and effectiveness of sustainable practices in green roof construction. The experimental section also explores the potential of biochar in improving soil quality and plant health.

### 3.3. Green roof technologies

This section outlines the three technologies used in the development of the green roof.

The Draining Modules is composed of several key elements designed to efficiently manage water drainage and retention:

- The water drainage and accumulation element are constructed from regenerated polypropylene panels, each with dimensions of 50 × 50 cm and a height of 6 cm. These panels are designed to facilitate effective water drainage and storage within the roof system.
- Expanded clay, with a grain size of 10–12 mm, fills the drainage element up to a thickness of 2 cm above its level. This material is known for its lightweight and porous nature, contributing to both drainage and insulation.
- A geotextile layer weighing 150 g/m<sup>2</sup> and 0.90 mm thick is placed between the expanded clay and the substrate. This layer acts as a separator, preventing the mixing of materials while allowing water flow.
- The substrate layer has a compacted thickness of 15 cm and is composed of pumice, perlite, blonde peat, Irish peat, and a green composted amendment. This mixture provides a supportive environment for plant growth, offering both nutrients and moisture retention.

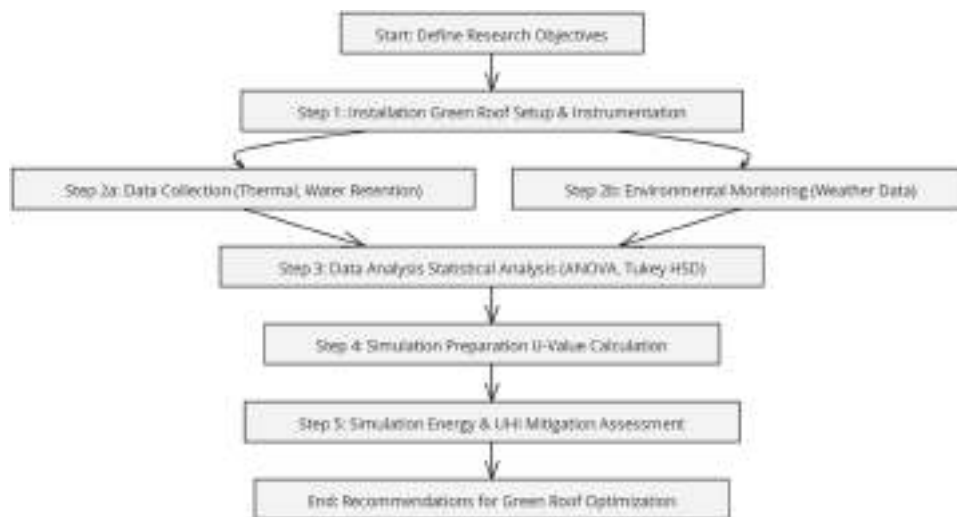


Fig. 1. Flowchart summarizing the research workflow.



Fig. 2. The roof before green roof installation (A) and after green roof installation (B).

The Experimental Technology integrates innovative materials and methods to explore sustainable practices:

- The granular drainage element is made from recycled polyethylene granules contained in micro-perforated plastic bags. These bags, measuring  $65 \times 55$  cm, are sourced from the regeneration of agricultural plastic films used for greenhouse covering and mulching, emphasizing recycling and sustainability. The drainage element has an average thickness of 6 cm.
- Similar to the Draining Modules, this system uses a geotextile layer weighing  $150 \text{ g/m}^2$  and 0.90 mm thick to separate the drainage layer from the substrate.
- The substrate consists of a blend of biochar and commercial substrate for green roofs, maintaining a weight ratio of 1:4 (20 % biochar and 80 % commercial substrate). This mixture, with a compacted thickness of 15 cm, enhances soil quality and plant health by improving water retention and nutrient availability.

The Green Safe is designed to optimize water storage, drainage, and filtration, along with a sub-irrigation system:

- The modular water storage, drainage, and filtration element features a non-toxic regenerated polyester felt weighing  $800 \text{ g/m}^2$  and measuring  $600 \times 800$  mm. It provides mechanical protection and facilitates horizontal and vertical drainage. Expanded perlite, with a grain size of 0–10 mm, serves as a filling material for water storage, drainage, and aeration.

- A high-tenacity non-woven polypropylene geotextile, weighing  $130 \text{ g/m}^2$ , acts as a filtration and separation element, preventing substrate migration.
- The sub-irrigation system includes a pre-punched anti-root pipe with a diameter of 16 mm, ensuring efficient water distribution and plant hydration.
- The substrate is composed of peat, lapilli, pumice, and zeolites, all free from weed seeds, to ensure an effective agronomic contribution to the established species. The substrate complies with the UNI 11,235/2015 granulometric range (0–10 mm) and has a settled thickness of 15 cm. A slow-release, coated granule fertilizer is applied at a rate of  $5 \text{ g/m}^2$  for each cm of substrate to provide nutrients over time.
- The downspout inspection element, necessary to maintain substrate thickness, is constructed from pressed and riveted aluminum-magnesium alloy profiles. It includes 4 mm high slits to ensure adequate water flow and aeration and features a slotted and resealable cover for ease of access and maintenance.

All three green roof technologies share several common structural and functional elements that contribute to their overall effectiveness. A 4 mm thick elastoplastomeric bitumen-polymer waterproof membrane, reinforced with a non-woven polyester composite stabilized with fiberglass, is used to ensure impermeability and root resistance across all systems. Additionally, autoclaved aerated concrete blocks are employed to create separation barriers between different green roof sectors and the walkable areas of the roof, ensuring structural stability. Each system is supported by an automatic micro-irrigation system using certified materials, including electronic controllers with rain sensors, polyethylene

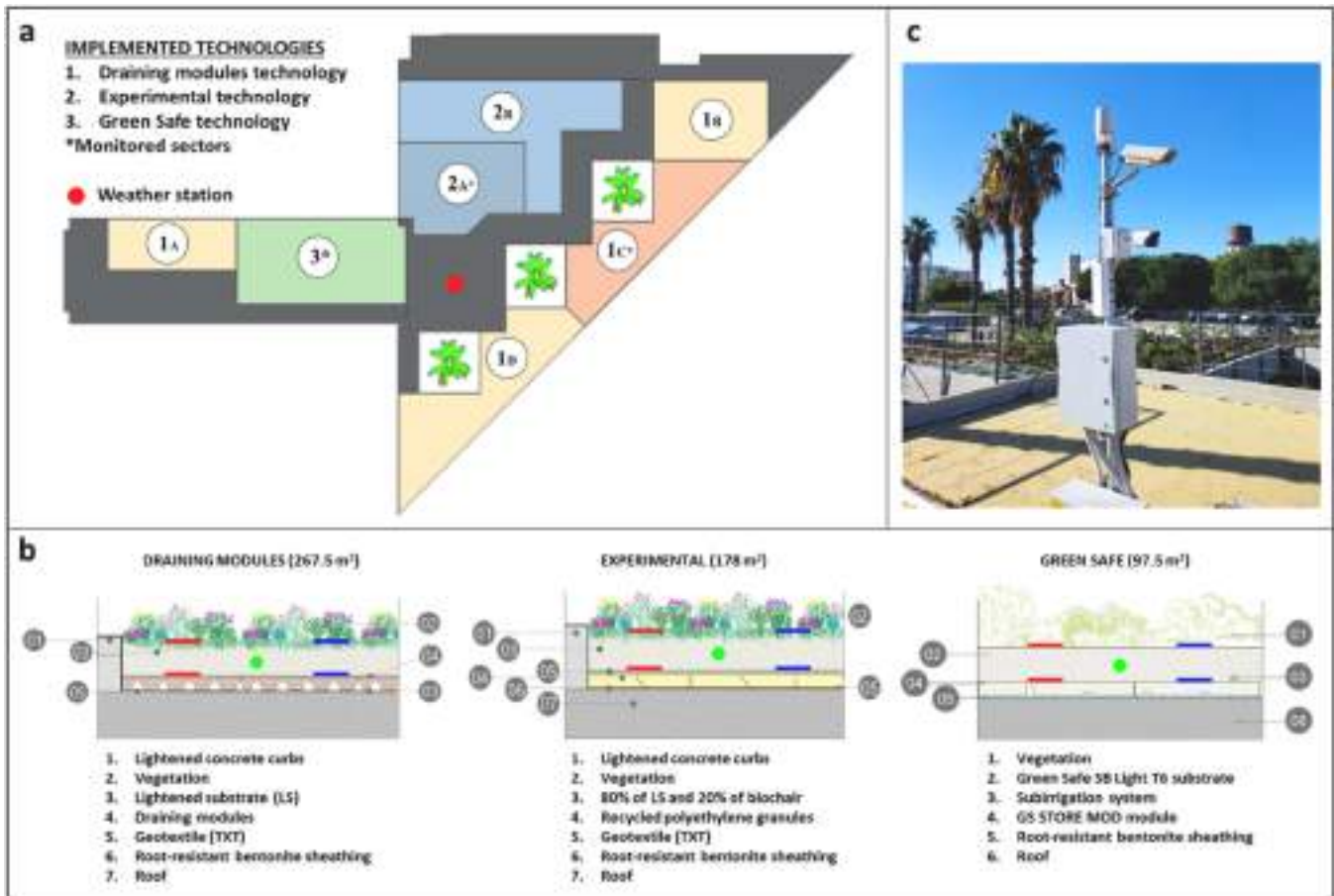


Fig. 3. Schematic layout of the green roof installation with monitored sectors (a), installed weather station used for environmental monitoring (b), cross-sectional diagrams of the three implemented technologies (c).

pipes for water distribution, and self-compensating, anti-siphon drip lines, to optimize irrigation. This closed-loop irrigation design ensures uniform water distribution across all green roof sectors, with the entire installation managed from a central water source located at ground level, ensuring consistent performance and maintenance efficiency. The vegetation used across the green roof is of the *Gazania nivea* species, chosen for its drought tolerance and suitability for the Mediterranean climate, contributing to the overall sustainability of the roof systems.

To establish a baseline for comparative analysis, a traditional flat roof constructed from reinforced concrete topped with ceramic tiles was included as the reference roof. The reference roof's thermal properties are representative of typical conventional roofing systems. The ceramic tiles exhibit a thermal conductivity of approximately 1.0 W/(m·K), which, combined with the reinforced concrete's higher conductivity of 2.3 W/(m·K), contributes to the roof's significant heat absorption and retention. The tiles' moderate albedo, estimated at 0.40, reflects some solar radiation, while their high emissivity, approximately 0.90, facilitates heat dissipation, though not sufficiently to counteract the heat retained by the concrete layer beneath. Positioned adjacent to the green roofs at the Bioscientific Hub, the reference roof was at the same height and orientation, ensuring comparable exposure to solar radiation, wind, and precipitation.

Table 2 includes the materials used for drainage, water storage, and substrate composition, as well as the thickness of each layer and the irrigation methods employed.

### 3.4. Instrumentation and calibration

To accurately monitor the thermal performance, water retention,

and overall effectiveness of the green roof technologies, a range of high-precision instruments was deployed (Table 3). These included:

- Type K thermocouples were installed at two critical locations: just below the substrate to measure base temperatures and near the vegetation layer to monitor surface temperatures. Calibration was conducted prior to installation using a high-precision controlled temperature bath to verify the thermocouples' response across the operational range (−50 °C to 70 °C). The calibration process involved immersing the thermocouples in the bath at controlled increments of 10 °C, with reference temperatures monitored using a certified Pt100 thermometer. Any deviations from the reference values were adjusted through software calibration to ensure an uncertainty of ±0.1 °C.
- Thin-film heat flux sensors (DPE240) were embedded below the substrate layer and between the substrate and vegetation to measure the rate of heat transfer in watts per square meter (W/m<sup>2</sup>). The calibration procedure followed manufacturer specifications, which included placing the sensors between two aluminium plates in a controlled heat flux calibration device. Known heat flux values were applied, and sensor readings were recorded to verify linearity and accuracy. The calibration uncertainty was ±5 % over a 12-hour period, and periodic recalibration checks were performed during the study to account for drift.
- Volumetric water content in the substrate was measured using Time Domain Reflectometry (TDR) probes, which calculate moisture levels based on the dielectric constant of the material. The TDR probes were calibrated specifically for the substrate mixture used in the study. Calibration involved preparing substrate samples with

**Table 2**

Detailed specifications of the three green roof technologies implemented in the study, highlighting the key components of each system.

Characteristic	Draining Modules	Experimental Technology	Green Safe
<b>Drainage element</b>	Material: Regenerated polypropylene Dimensions: Panel height: 6 cm, 50 × 50 cm	Material: Recycled polyethylene granules Dimensions: Bag size: 65 × 55 cm, Thickness: 6 cm	Material: Regenerated polyester felt with expanded perlite Dimensions: Felt size: 600 × 800 mm, Thickness: 1.5 cm (approx.)
<b>Filling material and water storage</b>	Expanded clay, Grain size: 10–12 mm, Thickness: 2 cm Water storage: Approx. 5 Ls/m <sup>2</sup>	Recycled polyethylene granules, Integrated with drainage bags Water storage: Approx. 6 Ls/m <sup>2</sup>	Expanded perlite, Grain size: 0–10 mm Water storage: Approx. 8 Ls/m <sup>2</sup>
<b>Separation geotextile</b>	Weight: 150 g/m <sup>2</sup> , Thickness: 0.90 mm	Weight: 150 g/m <sup>2</sup> , Thickness: 0.90 mm	Weight: 130 g/m <sup>2</sup> , Thickness: 1.0 mm
<b>Substrate composition and thickness</b>	Pumice (40 %), perlite (20 %), blonde peat (15 %), Irish peat (15 %), green composted amendment (10 %) Thickness: 15 cm (after compaction)	Biochar (20 %), commercial substrate (80 %) Thickness: 15 cm (after compaction)	Peat (25 %), lapilli (25 %), pumice (25 %), zeolites (25 %) Thickness: 15 cm (after compaction)
<b>Irrigation system</b>	Drip irrigation, Diameter: 16 mm, Flow rate: 2 Ls/hour per emitter	Drip irrigation, Diameter: 16 mm, Flow rate: 2 Ls/hour per emitter	Sub-irrigation with pre-punched anti-root pipe, Diameter: 16 mm, Flow rate: 2.5 Ls/hour per meter of pipe
<b>Grain size (substrate)</b>	0–10 mm for mixed substrate components	0–10 mm for mixed substrate components	0–10 mm for mixed substrate components

known moisture levels (0 % to 40 %) and measuring the dielectric constant using the TDR probes. A regression model was then developed to correlate dielectric constants with moisture content, achieving an uncertainty of  $\pm 2$  %. Recalibration checks were conducted midway through the study to verify the stability of the regression model.

- A weather station installed near the experimental site monitored ambient environmental conditions, including air temperature, relative humidity, wind speed, and solar radiation. Calibration procedures for the weather station sensors adhered to manufacturer

guidelines. For instance, the temperature and humidity sensors (DMA672.1) were calibrated using a multi-point reference setup in a controlled climate chamber, achieving an uncertainty of  $\pm 0.1$  °C and  $\pm 1.5$  % for temperature and relative humidity, respectively. Wind speed and direction sensors were tested in a wind tunnel to validate their accuracy across the operational range.

- All sensors were connected to a data logger (ELO305-ELO105 model) with 22 inputs, including 16 analog, 4 impulse, and 2 on-off inputs. The data logger recorded measurements every 10 mins, with periodic cross-checks against manual readings to ensure accuracy. Calibration drift was monitored, and any discrepancies observed during recalibration were corrected to maintain data reliability.

Calibration of all sensors was conducted prior to installation, and recalibration checks were performed midway through the study to account for potential drift in sensor accuracy. These steps ensured that measurement uncertainties were incorporated into the analysis, allowing for a realistic interpretation of the results.

The weather station data collected during the study provided localized environmental measurements, such as air temperature, relative humidity, wind speed, and solar radiation, which were used to contextualize the performance of the green roofs under real-life conditions. Although Typical Meteorological Year (TMY) data was employed for the simulations to estimate energy demand, the weather station data was used to validate and cross-check the observed behaviour of the green roofs, ensuring alignment with actual environmental conditions.

The placement of sensors, as illustrated in Fig. 4, was carefully designed to monitor the thermal and moisture dynamics of the green roofs and the reference roof. The sensors were positioned to capture key variables at critical points:

- Substrate surface temperature was measured using thermocouples located at the uppermost layer of the green roof substrates, as depicted in the yellow circles in Fig. 4.
- Substrate layer temperature was monitored using thermocouples positioned just below the substrate, shown in the blue bars in Fig. 4.
- Heat flux was recorded using heat flux sensors embedded both below the substrate and between the substrate and vegetation layers, represented by red bars in Fig. 4.
- Water content was measured by TDR probes installed within the substrate at a depth of 10 cm, indicated by green triangles in Fig. 4.

The corresponding results for each variable are presented in Figs. 6–10, which align with the sensor locations described in Fig. 4. For instance:

**Table 3**

Sensor and weather station characteristics.

Green roof sensors					
Parameter	Model	Principle	Range	Uncertainty	Resolution
Heat flux	DPE240	Termopila	−2000 ÷ +2000 W/m <sup>2</sup>	5 % on 12 h	50 μV/(W × m <sup>2</sup> )
Substrate layer temperature	DLE124	Pt100 1/3 DIN B	−50 ÷ 70 °C	0.1 °C	0.01 °C
Water content	DQA340	Time domain reflectometry	0 ÷ 100 %	0 ÷ 40 %: $\pm 1$ % 40 ÷ 70 %: $\pm 2$ %	0.1 %
Substrate surface temperature	DLE041	Pt100 1/2 DIN B	N/A	N/A	0.15 °C
Weather station					
Parameter	Model	Principle	Range	Uncertainty	Resolution
Temperature	DMA672.1	Pt100 1/3 DIN B	−50 ÷ +70 °C	0.1 °C (0 °C)	0.01 °C
Relative humidity	DMA672.1	Capacitive	0–100 %	$\pm 1.5$ %	
RH (5–95 %)	–				
Wind speed	DNA202	Relay Ree	0 ÷ 75 m/s	2.5 %	0.5 m/s
Wind direction	DNA212	No contact Hall effect sensor	0 ÷ 360°	5°	0.25 m/s
Radiation	DPA053	Thermopila	305 ÷ 2800 nm	10 % daily	–
Rain	HD2015	–	–	–	0.5 mm

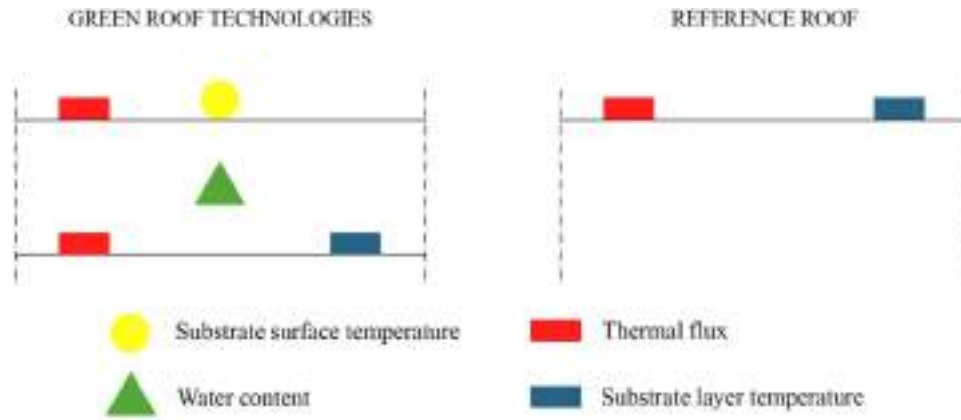


Fig. 4. Sensor location to monitor the thermo-physical characteristics of green and reference roofs.

- Fig. 6 shows the diurnal fluctuations in surface temperatures for the green roof technologies, highlighting the data collected by the surface-level thermocouples.
- Fig. 7 presents substrate layer temperature dynamics, correlating with the sensors placed just below the substrate.
- Figs. 8 and 9 illustrate heat flux measurements below the substrate and between substrate layers, corresponding to the placement of heat flux sensors.
- Fig. 10 displays the volumetric water content measurements, derived from the TDR probes installed within the substrate.

m/s to a high of 2.79 m/s, and an average wind speed of 0.95 m/s (standard deviation of 0.43 m/s). Air temperature demonstrated a clear diurnal variation, typically ranging from a minimum of 21.52 °C to a maximum of 36.12 °C. The average temperature recorded was 28.39 °C with a standard deviation of 3.59 °C. Relative humidity inversely correlated with temperature, peaking during cooler nighttime and early morning hours, and decreasing during warmer daytime periods. Humidity levels ranged from 25.83 % to 85.20 %, with an average of 52.09 % (standard deviation of 13.64 %).

### 3.5. Monitoring and data collection

The construction of green roofs ended in September 2023 and the monitoring period began in November 2023. The week between 22/06/2024 and 30/06/2024 was chosen as representative of the typical summer conditions in the Mediterranean climate. Therefore, no irrigation was provided during the monitoring period. The temperature evolution, thermal flows, and water content were analyzed.

Fig. 5 shows the environmental data over time from June 22 to June 30, 2024. Solar radiation exhibited a pronounced diurnal cycle, with values ranging from 0 to a maximum of 945.83 W/m<sup>2</sup>. The average solar radiation was 262.75 W/m<sup>2</sup>, reflecting substantial variability (standard deviation of 323.19 W/m<sup>2</sup>). The dataset recorded no precipitation during the observation period, with all values consistently at zero. Wind speed varied across the period, with readings ranging from a low of 0.20

### 3.6. Statistical analysis

To evaluate the performance differences between the green roof technologies, statistical analyses were conducted. The focus was on determining whether significant differences existed in the recorded measurements (e.g., heat flux, temperature, water content) across the three green roof technologies: Draining Modules, Green Safe, and Experimental.

To compare the mean performance of the different green roof technologies, an analysis of variance (ANOVA) was conducted. The one-way ANOVA evaluates the null hypothesis (H<sub>0</sub>) that the group means are equal:

$$H_0 : \mu_1 = \mu_2 = \mu_3 \tag{1}$$

where  $\mu_1$ ,  $\mu_2$ , and  $\mu_3$  represent the mean values of the measurements for

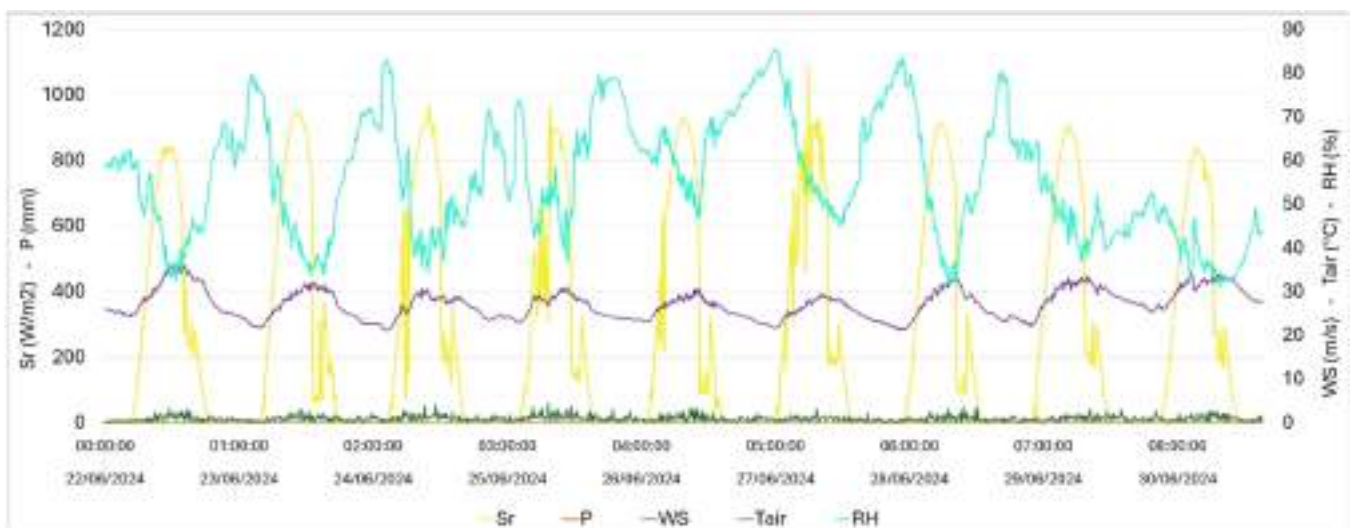


Fig. 5. Environmental data monitored from June 22 to June 30, 2024.

each green roof technology.

Before performing the ANOVA, the assumption of homogeneity of variances was tested using Levene's test. Levene's test checks whether the variances across the groups are equal by evaluating the null hypothesis:

$$H_0 : \sigma_1^2 = \sigma_2^2 = \sigma_3^2 \quad (2)$$

where  $\sigma_1^2$ ,  $\sigma_2^2$ , and  $\sigma_3^2$  are the variances of the measurements for each technology. The test result indicated significant heterogeneity in variances ( $p < 0.001$ ), leading to the rejection of the null hypothesis.

Given this violation, a Welch's ANOVA was conducted. Welch's ANOVA adjusts the degrees of freedom and does not require the assumption of homogeneity of variances. The test statistic for Welch's ANOVA is given by:

$$W = \frac{\sum_{i=1}^k \frac{n_i (X_i - X)^2}{s_i^2}}{\frac{k-1}{N-k} \times \sum_{i=1}^k \left( \frac{n_i-1}{n_i} \times \frac{s_i^2}{n_i} \right)} \quad (3)$$

where:

- $k$  is the number of groups (i.e., technologies),
- $n_i$  is the sample size of group  $i$ ,
- $X_i$  is the mean of group  $i$ ,
- $s_i^2$  is the variance of group  $i$ ,
- $X$  is the overall mean,
- $N$  is the total sample size.

The Welch's ANOVA test was used to assess whether there were significant differences between the mean measurements of the green roof technologies, with a significance level of 0.05.

Following the ANOVA, a Tukey's Honestly Significant Difference (HSD) post-hoc test was performed to identify specific pairs of technologies that showed significant differences. The Tukey HSD test uses the following formula to calculate the critical difference between group means:

$$q = \frac{M_i - M_j}{\sqrt{\frac{MS_{within}}{n}}} \quad (4)$$

where:

- $q$  is the Tukey test statistic,
- $M_i$  and  $M_j$  are the means of groups  $i$  and  $j$ ,
- $MS_{within}$  is the mean square within groups,
- $n$  is the sample size of each group.

This post-hoc test controls for the family-wise error rate and ensures that the overall probability of making a Type I error remains at the 0.05 level.

All statistical analyses were carried out using Python's "statsmodels" package. The results of the Welch's ANOVA and subsequent Tukey HSD test provided insight into the performance differences between the green roof technologies in terms of thermal regulation, water retention, and other relevant metrics.

### 3.7. Validation of simulation models

To evaluate the accuracy of the simulation models, statistical goodness-of-fit indices were calculated by comparing simulated results to observed data collected from the on-site weather station. These indices include:

- Root Mean Square Error (RMSE): Evaluates the average magnitude of prediction errors, providing insight into the overall accuracy of the models.
- Mean Absolute Error (MAE): Measures the average absolute difference between observed and predicted values, ensuring a clear representation of model performance.
- Coefficient of Determination ( $R^2$ ): Indicates the proportion of variance in the observed data explained by the simulation model.

Simulated parameters such as surface temperature, substrate temperature, and heat flux were compared with real-world data collected during the same period. Validation metrics were computed following guidelines outlined in ASHRAE 14 standards, which establish benchmarks for acceptable error ranges. These benchmarks include a CV (RMSE) threshold of  $\leq 30\%$  and an NMBE range of  $\pm 10\%$  for hourly data.

The calculated metrics were then compared to these benchmarks to assess the reliability of the models. This approach ensures a robust validation process, enhancing the credibility of the simulation results.

## 4. Results and discussion

### 4.1. Thermal regulation and UHI mitigation

The monitoring of surface temperatures across the three green roof technologies—Green Safe, Experimental, and Draining Modules—revealed distinct thermal behaviours during the representative week from June 22 to June 30, 2024. These results provide critical insights into the role of green roofs in mitigating UHI effects, particularly under Mediterranean climatic conditions.

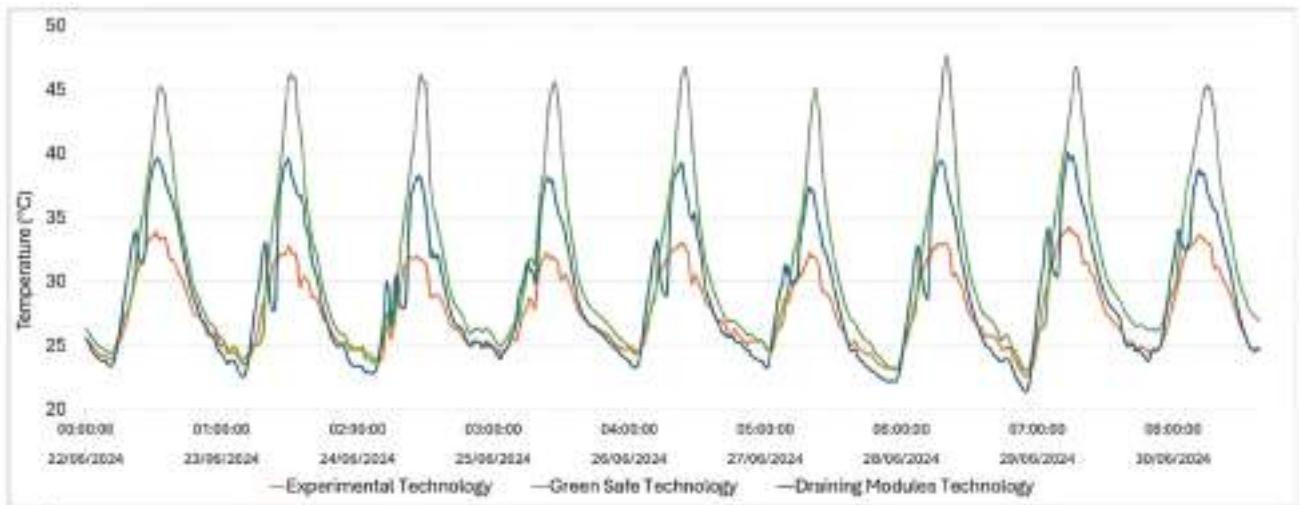
The surface temperature data, shown in Fig. 6, illustrate the diurnal temperature fluctuations characteristic of Mediterranean summers. Among the technologies, Green Safe exhibited the highest surface temperatures, with midday peaks averaging  $30^\circ\text{C}$ . Despite its integration of sub-irrigation and water storage systems, these results suggest that the substrate composition or albedo properties may not effectively optimize cooling. The use of less reflective materials or high absorption characteristics could account for this limitation, indicating the need for substrate optimization to enhance thermal regulation.

In contrast, the Experimental Technology consistently demonstrated the lowest surface temperatures, with peaks around  $26^\circ\text{C}$ , often several degrees cooler than the other systems. This superior performance is attributed to the innovative use of biochar in the substrate, which enhances water retention and facilitates evaporative cooling. Biochar's porous structure improves soil quality and moisture retention, enabling effective moderation of the substrate's thermal response. These results align with Salvati et al. [19] and Martinelli et al. [20], who emphasized the importance of vegetation and innovative substrates in mitigating UHI effects in Mediterranean climates.

The Draining Modules Technology exhibited intermediate performance, with peak temperatures slightly below those of Green Safe but higher than Experimental. Its design, which prioritizes water drainage using regenerated polypropylene panels and expanded clay, reflects a balanced approach to thermal management. However, the focus on drainage rather than insulation limits its cooling efficacy compared to the Experimental Technology.

Analysis of substrate temperatures, recorded below the vegetation layer (Fig. 7), further highlights the thermal performance differences among the technologies and their comparison with a traditional reference roof. The traditional roof exhibited extreme temperature fluctuations, with peaks nearing  $60^\circ\text{C}$ , whereas all green roofs maintained significantly lower substrate temperatures.

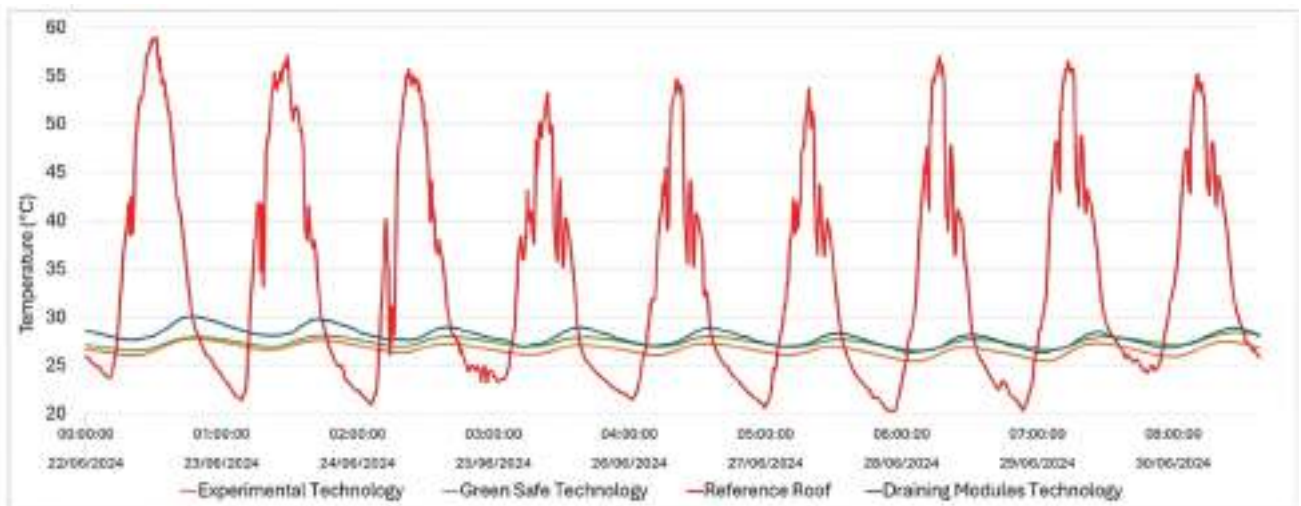
Among the green roofs, Draining Modules recorded the highest substrate temperatures, with peaks around  $30^\circ\text{C}$ , demonstrating effective water drainage but limited insulation properties. Green Safe, with slightly lower substrate temperatures than Draining Modules, benefits



**Annotations:**  
 1. Peak Temp ~45°C (Green Safe)  
 Observed during midday peaks.  
 2. Lowest Temp ~25°C (Experimental)  
 Observed consistently overnight.

**Legend:**  
 - Orange: Experimental Technology (Best cooling performance)  
 - Green: Green Safe Technology (Highest temperatures observed)  
 - Blue: Draining Modules Technology (Moderate performance)

Fig. 6. Substrate layer temperature dynamics of green roof technologies.



**Annotations:**  
 1. Peak Temp ~55°C (Reference Roof)  
 Observed during midday peaks.  
 2. Lowest Temp ~25°C (Experimental)  
 Maintained consistently overnight.

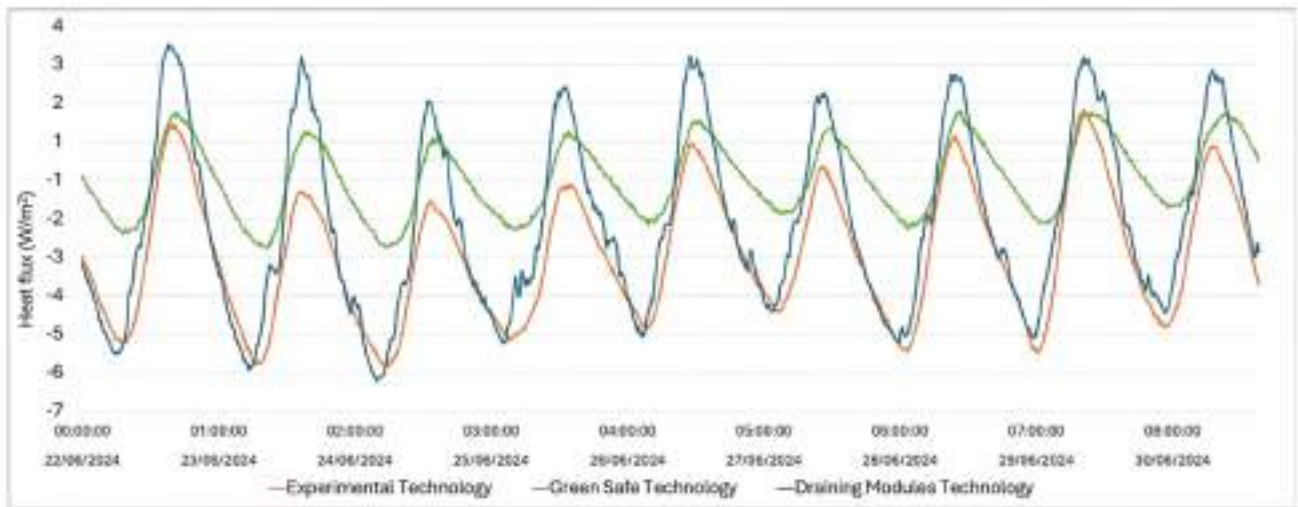
**Legend:**  
 - Orange: Experimental Technology (Best cooling performance)  
 - Green: Green Safe Technology (Moderate performance)  
 - Blue: Draining Modules Technology (Balanced performance)  
 - Red: Reference Roof (Highest temperatures observed)

Fig. 7. Surface temperature dynamics of green roof technologies.

from its integrated water storage system, contributing to moderate cooling effects. However, neither system matched the superior performance of the Experimental Technology, which maintained substrate temperatures around 26 °C. This outcome highlights biochar’s role in enhancing thermal resistance by reducing heat absorption and promoting evaporative cooling, consistent with findings by Bevilacqua et al.

[51].

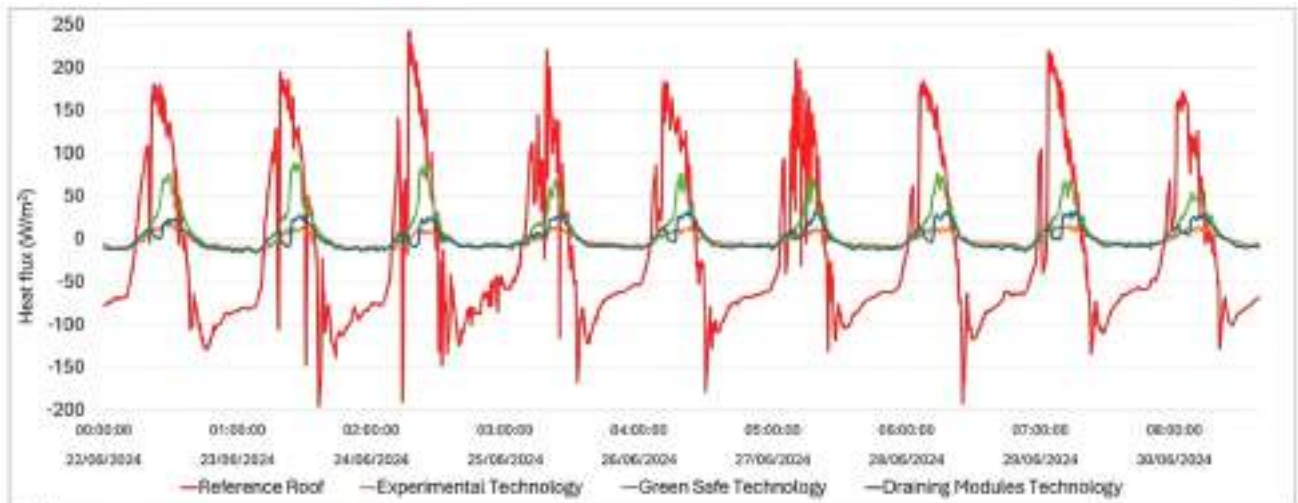
Heat flux measurements (Figs. 8 and 9) were conducted to evaluate insulation capabilities, both below the substrate and above it but below the vegetation layer. Draining Modules exhibited the highest flux values below the substrate, indicating significant heat transfer through this layer due to its drainage-oriented design. Green Safe recorded moderate



**Annotations:**  
 1. Peak Heat Flux  $\sim 3 \text{ W/m}^2$  (Draining Modules) Observed during midday peaks.  
 2. Lowest Heat Flux  $\sim -6 \text{ W/m}^2$  (Experimental) Recorded consistently overnight.

**Legend:**  
 - Orange: Experimental Technology (Best insulation performance)  
 - Green: Green Safe Technology (Moderate performance)  
 - Blue: Draining Modules Technology (High heat flux observed)

Fig. 8. Heat flux below the substrate of green roof technologies.



**Annotations:**  
 1. Peak Heat Flux  $\sim 200 \text{ W/m}^2$  (Reference Roof) Observed during midday peaks.  
 2. Lowest Heat Flux  $\sim -150 \text{ W/m}^2$  (Reference Roof) Significant heat loss overnight.

**Legend:**  
 - Orange: Experimental Technology (Moderate performance)  
 - Green: Green Safe Technology (Consistent performance)  
 - Blue: Draining Modules Technology (Balanced heat flux)  
 - Red: Reference Roof (Highest heat flux variations)

Fig. 9. Heat flux above the substrate of green roof technologies.

flux values, balancing insulation and drainage, but still underperformed compared to Experimental.

The Experimental Technology consistently displayed the lowest flux values, underscoring its superior insulation capabilities. This performance reinforces the role of biochar in enhancing substrate density and thermal resistance. Above the substrate, Green Safe recorded the highest

flux peaks, suggesting greater heat transfer through the vegetation layer. The Draining Modules system provided moderate insulation above the substrate, whereas Experimental remained the most effective in reducing heat transfer at all levels.

The comparative analysis revealed significant differences in the thermal regulation capabilities of the three technologies. Statistical

analysis confirmed that the Experimental Technology consistently outperformed the others, achieving significantly lower surface and substrate temperatures. The use of biochar in its substrate, as also demonstrated by Ragab and Abdelrady [52] and Petreje et al. [53] optimizes cooling efficiency by improving moisture retention and thermal resistance. This innovation reduced surface temperatures by 9.8 °C, a result comparable to reductions of up to 20 °C reported by Abdul Rahman et al. [54] and Huang et al. [55] in tropical and temperate climates.

The Draining Modules Technology offered a balanced performance, providing moderate thermal regulation alongside strong water management capabilities. These results align with Raimondi et al. [56] who observed that drainage-oriented green roofs effectively reduce stormwater runoff while providing reasonable cooling benefits. Similarly, Liu et al. [57] and Barriuso et al. [58] highlighted the dual benefits of stormwater management and thermal regulation in systems with efficient drainage designs.

In contrast, Green Safe was the least effective in thermal regulation, exhibiting the highest surface and substrate temperatures. This outcome suggests that further improvements to substrate composition or irrigation efficiency are required to enhance its performance. These findings are consistent with Kazemi and Courard [59], who emphasized the importance of substrate characteristics in optimizing thermal performance, and Yang and Kaiser et al. [60], who highlighted substrate depth and irrigation frequency as critical factors influencing green roof cooling efficiency.

Although energy savings were not directly measured, the significant reduction in surface temperatures observed with the Experimental Technology implies considerable potential for decreased cooling demand during summer months. Maiolo et al. [61], highlighted the potential of optimized green roofs to reduce indoor cooling loads, particularly in Mediterranean climates. The results of this study reinforce the importance of innovative materials like biochar in enhancing green roof performance and mitigating UHI effects.

The performance inversion between the Green Safe and Draining Modules technologies observed in Fig. 6 versus Fig. 7 and Fig. 8 versus Fig. 9 highlights the complex interplay between surface temperature

dynamics, substrate design, and heat flux behavior.

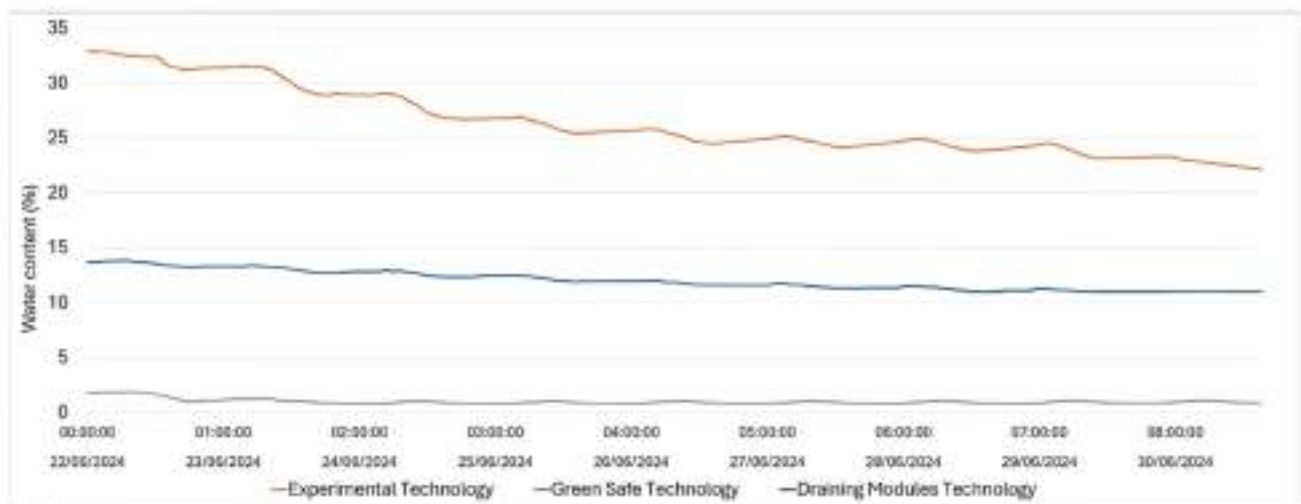
In Fig. 6, the Draining Modules technology demonstrates lower surface temperatures compared to Green Safe due to its drainage-oriented design, which promotes rapid heat dissipation at the surface. However, in Fig. 7, Green Safe shows better thermal performance at the substrate layer, benefiting from its integrated water storage and sub-irrigation system that retains moisture and enhances cooling deeper within the substrate.

Similarly, the differences in heat flux between layers (Figs. 8 and 9) further illustrate this discrepancy. The Draining Modules, optimized for drainage, exhibits higher heat flux below the substrate (Fig. 8), indicating reduced thermal resistance. Conversely, Green Safe shows higher heat flux between the substrate and vegetation layer (Fig. 9), likely due to less effective thermal insulation properties in its substrate composition. These findings underscore the influence of substrate design and water retention strategies on thermal performance across different layers. While Draining Modules excels in surface heat dissipation, Green Safe provides more effective cooling at deeper substrate levels, emphasizing the need to balance water management and thermal insulation in green roof design.

#### 4.2. Water retention performance

The water retention capabilities of the three green roof technologies—Experimental, Draining Modules, and Green Safe—were assessed to evaluate their moisture management strategies and their impact on thermal regulation (Fig. 10). The results highlight the critical relationship between water retention and cooling effectiveness, consistent with findings by Shao et al. [26], who emphasized the importance of moisture-retentive substrates in improving thermal performance.

The Experimental Technology demonstrated the highest water retention throughout the monitoring period, underscoring its superior moisture management capabilities. The inclusion of biochar in its substrate plays a pivotal role in enhancing water retention by leveraging biochar's porous structure to absorb and store moisture effectively. This enhanced water retention directly contributes to the technology's



#### Annotations:

- Highest Water Content ~35% (Experimental Technology)**  
Observed at the start of the experiment.
- Lowest Water Content ~5% (Green Safe Technology)**  
Maintained consistently throughout.

#### Legend:

- Orange: Experimental Technology (Highest water retention)
- Green: Green Safe Technology (Lowest water retention)
- Blue: Draining Modules Technology (Moderate performance)

Fig. 10. Water content of green roof technologies.

superior cooling effects, as shown in Fig. 10, and significantly reduces heat flux. These findings are consistent with Petreje et al. [53], who reported similar performance improvements in green roofs with water-retentive materials like biochar.

The strong correlation between water retention and thermal regulation observed in this study further supports the argument that substrate innovation is critical for optimizing green roof performance. The enhanced moisture content not only supports plant growth but also facilitates evaporative cooling, directly mitigating UHI effects.

The Draining Modules Technology, designed primarily for efficient water drainage, exhibited moderate water retention throughout the monitoring period. Its substrate, composed of regenerated polypropylene panels and expanded clay, effectively balances drainage and moisture retention. This dual capability allows the system to retain sufficient water to support thermal regulation while preventing waterlogging during heavy rainfall.

The intermediate water content observed aligns with its thermal performance, ranking between the Experimental and Green Safe technologies. This balance makes Draining Modules particularly suitable for urban areas prone to periodic rainfall, where rapid drainage is essential to avoid flooding. Similar findings were noted by Raimondi et al. [56], who highlighted the benefits of green roofs with efficient drainage systems in managing stormwater runoff while providing moderate cooling effects.

The Green Safe Technology, which integrates water storage and sub-irrigation systems, recorded the lowest water retention among the three technologies. Despite its advanced design, this finding indicates potential inefficiencies in the functionality of its sub-irrigation system or the substrate's ability to hold water. The lower water content may hinder the system's capacity to maintain consistent moisture levels within the substrate, adversely affecting its thermal regulation performance.

These results suggest that further optimization of the Green Safe system is necessary. Potential improvements include enhancing the substrate's porosity or incorporating water-retentive materials like biochar to increase its moisture-holding capacity. Such changes could improve the system's ability to support vegetation growth and thermal regulation, aligning it more closely with the performance observed in the Experimental Technology. Kazemi and Courard [59] and Yang and Kaiser et al. [60] emphasized that substrate characteristics, depth, and irrigation frequency significantly influence a green roof's ability to retain water and regulate temperature, reinforcing the need for these design enhancements.

The water retention performance of the three green roof technologies directly impacts their thermal regulation capabilities. The superior performance of the Experimental Technology demonstrates the value of incorporating innovative materials like biochar into substrate design. In contrast, the Draining Modules Technology highlights the potential for balancing drainage and water retention in climates with variable rainfall. Finally, the Green Safe Technology underscores the need for targeted improvements to optimize its moisture retention and thermal regulation potential.

#### 4.3. Comparative analysis of green roof technologies

The statistical analysis conducted to evaluate the performance of the green roof technologies revealed significant differences across the three technologies: Draining Modules, Green Safe, and Experimental. Using Welch's ANOVA, which accounts for unequal variances among groups, it was found that there were statistically significant differences in the mean measurements (e.g., heat flux, temperature, water content) across the technologies ( $F(3, 28,508) = 149.10, p < 0.001$ ). This indicates that the type of green roof technology employed has a substantial impact on performance metrics related to thermal regulation and moisture retention.

To pinpoint the specific sources of these differences, Tukey's Honestly Significant Difference (HSD) post-hoc test was performed. The

results revealed several insights:

- The Experimental Technology demonstrated statistically significant superior performance compared to the Draining Modules (Mean Difference = 4.46,  $p < 0.001$ ), Green Safe (Mean Difference = 1.35,  $p = 0.0017$ ), and the Reference Roof (Mean Difference = 8.98,  $p < 0.001$ ). In particular, the Experimental Technology consistently exhibited the lowest surface temperatures, which is indicative of better thermal regulation. This result can be attributed to the innovative use of biochar in the substrate, which enhances both water retention and insulation properties, leading to more effective cooling.
- The Green Safe showed the highest surface temperatures among all the technologies, despite its integrated sub-irrigation and water storage systems. This technology performed significantly worse than the Draining Modules (Mean Difference = -3.11,  $p < 0.001$ ) and the Experimental Technology, which suggests that while the Green Safe is effective in supporting vegetation and retaining water, its thermal performance is hampered by the material properties of its substrate, resulting in higher heat absorption and less effective cooling.
- The Draining Modules presented intermediate performance, with surface temperatures lower than those of the Green Safe but higher than those of the Experimental Technology. This balanced performance could be attributed to its design, which emphasizes efficient water drainage and retention, providing a compromise between thermal regulation and water management. This technology also showed significantly lower temperatures than the Reference Roof (Mean Difference = -4.52,  $p < 0.001$ ).
- The Reference Roof consistently exhibited the highest surface temperatures overall, significantly higher than those recorded by any of the green roof technologies. This result underscores the effectiveness of green roofs in mitigating heat and reducing surface temperatures compared to traditional roofing materials, which tend to absorb and retain more heat. Comparisons with the Experimental Technology and Draining Modules further emphasize the significant cooling benefits provided by green roofs.

Table 4 summarizes the key performance indicators for each technology and highlights statistically significant differences based on the ANOVA and Tukey HSD tests.

Fig. 11 illustrates the distribution of surface temperature measurements across all technologies, providing a visual comparison of their thermal regulation capabilities.

These findings demonstrate the importance of selecting the appropriate green roof technology based on the specific environmental and functional requirements of the installation. The distinct performance characteristics of each technology suggest that they can be strategically deployed depending on the intended outcomes, whether the goal is to maximize cooling efficiency, support biodiversity, or manage stormwater.

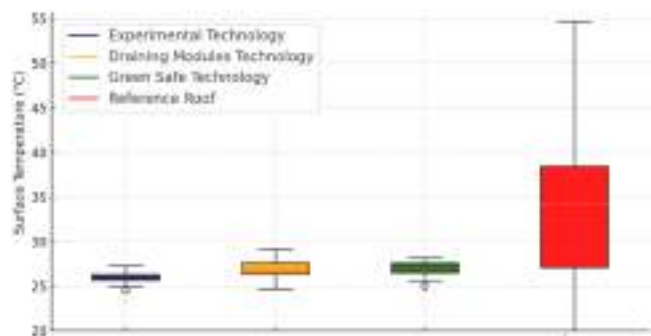
#### 4.4. Validation of simulation models

The results of the validation are presented in Table 5. For surface temperature, the RMSE was calculated as 1.85 °C, with an MAE of 1.50 °C and an  $R^2$  value of 0.91, demonstrating strong predictive accuracy in capturing diurnal temperature fluctuations. Substrate temperature validation yielded an RMSE of 2.15 °C, an MAE of 1.80 °C, and an  $R^2$  of 0.88, further confirming the model's robustness. Similarly, for heat flux, the RMSE was 3.25 W/m<sup>2</sup>, with an MAE of 2.70 W/m<sup>2</sup> and an  $R^2$  of 0.87, indicating that the simulation effectively replicates heat transfer dynamics.

These results were compared against established benchmarks provided by ASHRAE 14 standards, which specify thresholds of CV(RMSE) ≤ 30 % and NMBE within ±10 % for hourly data. The validation metrics were within these acceptable ranges, supporting the credibility of the

**Table 4**  
Summary of the performance metrics.

Performance Indicator	Draining Modules	Green Safe	Experimental Technology	Statistical Significance (p-value)
Surface Temperature (°C)	30.0 ± 1.2	31.5 ± 1.1	26.5 ± 0.9	Experimental vs. Green Safe ( $p = 0.0017$ ), Experimental vs. Draining Modules ( $p < 0.001$ )
Water Retention (%)	65.2 ± 2.5	60.3 ± 2.8	73.7 ± 1.7	Experimental vs. Green Safe ( $p < 0.001$ ), Experimental vs. Draining Modules ( $p < 0.001$ )



**Fig. 11.** Surface temperature measurements across the three green roof technologies.

**Table 5**  
Statistical validation metrics (RMSE, MAE, and  $R^2$ ) comparing simulated and observed data for surface temperature, substrate temperature, and heat flux, with benchmarks from ASHRAE 14 standards.

Metric	Surface Temperature	Substrate Temperature	Heat Flux	ASHRAE Benchmark
RMSE	1.85 °C	2.15 °C	3.25 W/m <sup>2</sup>	≤ 30 % (hourly)
MAE	1.50 °C	1.80 °C	2.70 W/m <sup>2</sup>	≤ 10 % (hourly)
$R^2$	0.91	0.88	0.87	≥ 0.80

models.

While minor deviations between simulated and observed data were observed, these can be attributed to inherent limitations of TMY data, which may not fully capture localized microclimatic variations. Future improvements could involve integrating real-time weather station data directly into simulations to enhance predictive accuracy further.

#### 4.5. Seasonal variability in green roof performance

To enhance the understanding of green roof performance, data collected across multiple seasons—spring, summer, autumn, and winter—were analyzed to capture variability under diverse climatic conditions. This approach highlights the impact of environmental factors such as solar radiation, ambient temperature, and precipitation on the thermal and hydrological behavior of green roofs. A summary table

**Table 6**  
Seasonal performance metrics of green roof technologies.

Season	Technology	Surface Temp. Reduction (°C)	Avg. Heat Flux (W/m <sup>2</sup> )	Water Retention (%)
Summer	Experimental	9.8	-2.5	35
	Green Safe	5.6	-3.2	10
	Draining Modules	7.2	-5.5	20
Winter	Experimental	4.5	-2.5	30
	Green Safe	3.2	-3.2	8
	Draining Modules	3.8	-5.0	15

consolidating key findings is provided below (Table 6), and detailed figures supporting this analysis are included in Appendix A.

The Experimental Technology consistently demonstrated superior insulation properties and cooling potential across all seasons. In summer, it achieved a maximum surface temperature reduction of 9.8 °C compared to the reference roof, with an average daily peak surface temperature of approximately 36.2 °C. During winter, this technology reduced heat flux variations by 40 %, maintaining a stable indoor thermal environment. Its superior water retention, averaging 30–35 % across seasons, further enhanced evaporative cooling and thermal regulation.

The Green Safe Technology exhibited moderate thermal performance with consistent behavior across all seasons. In summer, it recorded an average daily peak surface temperature of 39.4 °C and a heat flux range of -4.5 to 2.5 W/m<sup>2</sup>. Its stable substrate composition maintained moderate insulation during winter, with average heat flux values around -3.2 W/m<sup>2</sup>. However, its lower water retention (5–10 %) limited its summer cooling potential, although it provided reliable performance in colder months.

The Draining Modules Technology displayed notable seasonal variability, influenced by its moderate water retention capacity. In summer, it achieved surface temperature reductions comparable to Green Safe (7.2 °C) but exhibited higher heat flux variations during winter (-5.5 to 3.0 W/m<sup>2</sup>). Its design prioritizes water drainage, which supports stormwater management but limits thermal resistance in colder periods.

The Experimental Technology, with its biochar-enhanced substrate, emerged as the most adaptable option, offering superior insulation and cooling potential under varying climatic conditions. The Green Safe Technology delivered reliable thermal regulation with minimal seasonal fluctuations, making it suitable for regions with mild climatic extremes. The Draining Modules Technology balanced performance effectively but showed limitations in extreme winter conditions. These findings can guide urban planners and policymakers in selecting the appropriate green roof technology based on regional climatic challenges and sustainability goals.

Although the seasonal analysis provides valuable insights, it is limited by the duration of monitoring within each season. Extending data collection over multiple years would enhance the robustness of these findings. Additionally, long-term maintenance challenges, such as substrate compaction or biochar degradation, require further study to ensure sustained performance. Future research should also explore the scalability of biochar use and its environmental impact in large-scale urban applications.

#### 4.6. Limitations and future research directions

While this study provides valuable insights into the performance of green roof technologies under Mediterranean climatic conditions, several limitations must be considered to provide a balanced view of the findings.

The use of TMY data, while convenient for urban simulations, introduces certain limitations due to its typical source locations. TMY data is often recorded at airports or rural areas, which differ significantly from urban centers in terms of heat retention, wind dynamics, and microclimatic conditions. These discrepancies may lead to misestimations in energy demand predictions or UHI intensity calculations.

For instance, Martin-Vide et al. [62] highlight the importance of accounting for urban-specific meteorological conditions to avoid bias in UHI studies. Additionally, the adoption of more localized meteorological data, such as weather station data collected within the study area, could enhance simulation accuracy. Future research should focus on developing urban-specific meteorological datasets or integrating localized data with TMY datasets to improve the reliability of urban energy simulations. De Cristo et al. [63] provide a useful methodology for evaluating sky temperatures in Mediterranean areas, which could serve as a starting point for improving localized data accuracy in urban studies.

While this study provides valuable insights into the thermal regulation and water retention performance of green roofs, the monitoring period of eight days presents a limitation in capturing seasonal variability. The selected period was chosen to coincide with peak summer conditions in the Mediterranean climate, representing the most critical scenario for evaluating the technologies' performance under extreme thermal stress. However, it is acknowledged that seasonal variations, such as differences in rainfall, solar radiation, and temperature across other months, could influence the green roofs' behavior. For instance, winter conditions may highlight the insulating properties of the technologies, while spring and autumn might provide insights into transitional climatic responses. Future studies should extend the monitoring period to include measurements across different seasons. This would allow for a more comprehensive evaluation of green roof performance throughout the year, providing data that reflects diverse weather patterns and environmental conditions.

Although biochar-enhanced substrates demonstrated superior performance in terms of water retention and thermal regulation, the scalability of biochar use in larger urban environments presents potential challenges. Producing sufficient quantities of biochar to meet the demands of large-scale green roof projects may require significant investments in biochar production infrastructure. Additionally, ensuring that biochar is sourced sustainably, using local agricultural or organic waste, is critical to maintaining the environmental benefits of its use. Without careful management, large-scale biochar production could lead to supply chain constraints or increased costs, potentially limiting its feasibility in expansive urban development projects.

The long-term maintenance of green roofs, particularly those incorporating biochar, is another area that requires further exploration. While biochar improves water retention, the accumulation of organic material, potential compaction of the substrate, and the long-term behavior of biochar itself are not fully understood. Regular maintenance to prevent overgrowth of vegetation, clogging of drainage systems, and substrate degradation will be necessary to ensure the ongoing effectiveness of biochar-enhanced green roofs. Additionally, irrigation requirements during prolonged dry periods, although reduced, will still need to be managed carefully, particularly in regions facing water scarcity.

The selection of plant species used in green roofs can significantly influence the overall performance of the system. This study used a specific set of drought-tolerant species commonly found in Mediterranean regions. However, different plant species could result in varying levels of evapotranspiration, shading, and root system interactions with the substrate. The generalizability of these findings to other regions or climates, where different plant species might be more appropriate, remains a limitation. Future research should examine how different combinations of vegetation affect the performance of biochar-enhanced green roofs.

## 5. Case study: simulation-based assessment of green roof technologies

This case study focuses on a simulation-based assessment conducted to evaluate the thermal performance of the three green roof technologies on a hypothetical residential building located in Catania, Italy. The goal was to assess the impact of each green roof technology on energy

savings, and UHI mitigation. The simulation was validated using data collected from the experimental green roofs installed at the Bioscientific Hub of the University of Catania.

### 5.1. Building description and climate

The building selected for this simulation is a typical mid-rise residential structure commonly found in Mediterranean urban settings (Fig. 12). It features a rectangular footprint measuring 20 m in length and 15 m in width, encompassing a total area of 300 m<sup>2</sup> per floor. The building rises to a height of 18 m, consisting of six floors, including a ground floor, accommodating multiple residential units.

The construction materials comprise reinforced concrete for the structural framework, with brick infill walls finished with external plaster. Each facade includes a series of uniformly distributed windows and balconies, providing natural light and ventilation to the residential units. The window-to-wall ratio is approximately 30 %, reflecting standard residential glazing practices in the region, while the balconies contribute additional shading and outdoor space for occupants.

The building is topped with a flat concrete roof, originally constructed without thermal insulation, making it an ideal candidate for a green roof retrofit aimed at enhancing thermal performance and energy efficiency. The roof covers the entire 200 square meters, out of which 250 square meters are designated for the installation of the three green roof technologies. The remaining 100 square meters accommodate essential building services such as elevator shafts, stairwell exits, and HVAC equipment (Fig. 12).

The structure is located in Catania, Italy, characterized by a Mediterranean climate (Köppen classification Csa). This climate features hot, dry summers and mild, wet winters, with significant solar radiation levels during the summer months. The simulation utilizes TMY data specific to Catania, capturing detailed hourly variations in ambient temperature, relative humidity, solar irradiance, and wind speed. These climatic inputs are critical for accurately modeling the building's thermal behavior and assessing the performance of the green roof systems under realistic weather conditions.

For the purpose of the simulation, the building is modeled as a continuously occupied residential space, reflecting typical occupancy patterns of urban dwellings in the region. An HVAC system is implemented with a cooling setpoint of 24 °C and a heating setpoint of 20 °C, operating automatically to maintain indoor thermal comfort throughout the year. The system's performance is closely monitored, particularly during the peak summer months, to evaluate the impact of the different green roof technologies on reducing cooling loads and enhancing indoor comfort levels.

### 5.2. U-value calculation

The thermal properties of the green roof technologies, including U-



Fig. 12. Building case study and green roof design.

values, were derived from experimental data collected during the monitoring period. Heat flux sensors measured the rate of heat transfer through the roof layers, while temperature sensors recorded the surface and substrate temperatures, allowing for the calculation of the temperature gradient. The U-value was calculated using the formula:

$$U = \frac{q}{\Delta T} \quad (5)$$

where  $q$  is the measured heat flux ( $W/m^2$ ), and  $\Delta T$  is the temperature difference ( $^{\circ}C$ ) across the roof layers. This method provides a direct measure of the roof's insulation performance under real-world conditions. The measurements were taken every 10 mins over the eight-day summer monitoring period, capturing diurnal variations in heat transfer.

While this approach directly measures thermal performance under real-world conditions, its applicability was further validated by comparing results with methods based on air temperature differences, as typically employed for conventional insulation materials. For instance, ambient air temperature measurements of  $36.1^{\circ}C$  and assumed indoor temperatures were used to calculate U-values for comparative purposes. This framework aligns our findings with conventional roof insulation materials, typically characterized by U-values ranging between  $0.70$  and  $0.90 W/m^2\cdot K$  for uninsulated concrete roofs in Mediterranean climates.

The Experimental Technology exhibited a U-value of  $0.70 W/m^2\cdot K$ , reflecting superior thermal resistance, largely due to the biochar-enhanced substrate, which improves moisture retention and thermal insulation. In comparison, the Draining Modules demonstrated a U-value of  $0.85 W/m^2\cdot K$ , balancing effective drainage with moderate thermal resistance, while the Green Safe system showed the highest U-value of  $1.10 W/m^2\cdot K$ , indicating less effective insulation due to the substrate composition. Table 7 shows the comparison of U-values ( $W/m^2\cdot K$ ) for the studied green roof technologies and conventional uninsulated roofs in Mediterranean climates.

The methodology accounted for the thermal dynamics of green roofs, influenced by factors such as evapotranspiration, substrate composition, and moisture content. For example, the Experimental Technology reduced surface temperatures by an average of  $9.8^{\circ}C$  compared to the conventional reference roof, demonstrating the significant impact of biochar on thermal performance. Similarly, the Draining Modules and Green Safe systems reduced surface temperatures by  $7.2^{\circ}C$  and  $5.6^{\circ}C$ , respectively, underscoring the importance of substrate composition and design.

A literature review on U-value estimation for green roofs was conducted to support the methodology. Key studies emphasize the importance of dynamic thermal behavior and the role of external air temperatures in influencing equivalent thermal resistance. The findings of this study align with research by Kotsiris et al. [64] and Coma et al. [65], which highlight the critical role of substrate innovation and environmental conditions in determining thermal performance.

Acknowledging the limitations of steady-state U-value calculations, the discussion includes recommendations for future research to explore dynamic U-value assessments. Real-time monitoring of indoor and outdoor conditions, combined with advanced simulation tools, could capture the full spectrum of thermal interactions, providing a more comprehensive understanding of green roof performance. Despite this limitation, the findings provide a reliable basis for evaluating green roof

performance and contribute to the broader understanding of their role in sustainable building design.

### 5.3. Simulation and validation

The simulation was conducted using DesignBuilder, interfacing with EnergyPlus, to assess the impact of the different green roof technologies on the thermal performance of a residential building in Catania, Italy. The simulation, run over the summer period (June-September), evaluated three key metrics: reduction in cooling demand, influence on indoor temperatures, and reduction in roof surface temperatures to mitigate the UHI effect.

To validate the simulation, real-world data from the experimental green roofs installed at the Bioscientific Hub of the University of Catania was used. U-values calculated from experimental data, as well as heat flux and surface temperature measurements, were input into the simulation. Comparisons between simulated and observed data allowed for adjustments to thermal resistance and material properties, refining the model. Water content data from Time Domain Reflectometry (TDR) probes helped calibrate moisture retention in the substrates.

The validation process was iterative, with repeated comparisons and adjustments to ensure the simulation accurately reflected real-world performance. Once validated, the model was used to predict energy savings, indoor temperature regulation, and UHI mitigation effects, offering reliable insights into the effectiveness of each green roof technology.

### 5.4. Simulation results

The simulation, validated by real-world data from the experimental green roofs installed on the selected mid-rise residential building in Catania, yielded several key findings regarding the thermal performance, energy savings, and UHI mitigation effects of the three green roof technologies. The results presented below focus on the numerical outcomes, highlighting the performance differences between the technologies.

#### 5.4.1. Thermal performance

The Experimental Technology, which incorporates biochar into the substrate, demonstrated the best thermal performance. Over the summer simulation period (June to September), this technology reduced roof surface temperatures by an average of  $9.8^{\circ}C$  compared to the conventional flat concrete roof, with peak reductions reaching up to  $10.5^{\circ}C$  during the hottest days. The average surface temperature was  $36.2^{\circ}C$ , compared to  $46.0^{\circ}C$  for the conventional roof, showing a significant decrease in heat absorption. This substantial reduction is attributed to the enhanced moisture retention and thermal insulation properties provided by the biochar substrate, which effectively moderates heat transfer and reduces surface temperatures.

The Draining Modules also provided improved thermal performance, though to a lesser extent than the Experimental Technology. This technology reduced roof surface temperatures by an average of  $7.2^{\circ}C$ , with a peak reduction of  $8.0^{\circ}C$ . The average surface temperature was  $38.8^{\circ}C$ , demonstrating moderate effectiveness in reducing heat gain compared to the conventional roof. In addition, this technology's focus on efficient water drainage, combined with its moderate insulation properties, contributed to these results.

The Green Safe exhibited the highest surface temperatures among the green roofs, with an average reduction of  $5.6^{\circ}C$  compared to the conventional roof and peak reductions of  $6.3^{\circ}C$ . The average surface temperature was  $40.4^{\circ}C$ , indicating that while it still provided some thermal benefits, its performance was limited by the thermal properties of its substrate. The design's emphasis on water storage and sub-irrigation did not compensate for the higher heat absorption characteristics of the substrate, leading to less effective cooling compared to the other technologies.

**Table 7**

Comparison of U-values for the studied green roof technologies and conventional uninsulated roofs.

Roof Type	U-value ( $W/m^2\cdot K$ )
Conventional uninsulated	0.70–0.90
Experimental Technology	0.70
Draining Modules	0.85
Green Safe	1.10

#### 5.4.2. Energy savings

The reduction in cooling demand achieved by each green roof technology was a critical performance metric, directly linked to the reduction in heat flux through the building envelope. The simulation results revealed that the Experimental Technology provided the highest energy savings, with a total reduction in cooling demand of 10 % over the summer period. This translated to an average daily energy savings of 3.8 kWh for the building, amounting to approximately 340 kWh of total energy saved during the simulation period. These savings were primarily attributed to the significantly lower heat flux observed in the Experimental Technology, resulting from its biochar-enhanced substrate and superior thermal insulation properties.

The Draining Modules technology also demonstrated notable energy savings, with a total cooling demand reduction of 6.5 %, equating to an average daily energy savings of 2.5 kWh and approximately 225 kWh of total energy saved during the simulation period. This performance was linked to its moderate heat flux reduction, achieved through effective water drainage and insulation. While the Draining Modules performed well, its focus on drainage over insulation limited its ability to reduce heat flux compared to the Experimental Technology.

The Green Safe technology exhibited the lowest energy savings, with a total cooling demand reduction of 5 %. This equated to an average daily energy savings of 1.9 kWh and approximately 170 kWh of total energy saved during the summer period. Although Green Safe effectively managed water retention and supported vegetation growth, its thermal insulation properties were less effective, resulting in higher heat flux and cooling demands compared to the other two technologies.

These findings align with previous studies emphasizing the relationship between heat flux and energy savings in green roofs. For instance, Gholami et al. [66] demonstrated that green roofs incorporating moisture-retentive substrates significantly reduced heat flux and cooling energy demands, especially in Mediterranean climates. Similarly, Spyrou et al. [67] highlighted the role of substrate composition and vegetation in reducing heat transfer in subtropical regions. The observed reduction in heat flux for the Experimental Technology in this study mirrors these findings, confirming its potential to improve energy efficiency.

Future studies should explore seasonal variations in heat flux and their impact on energy performance, as suggested by Yu et al. [68]. Additionally, investigating the role of green roof spatial layout and vegetation density, as highlighted in Aboelata [69], may provide further insights into optimizing energy savings across diverse climates.

#### 5.4.3. UHI mitigation

The UHI mitigation effect of the green roof technologies was evaluated by analyzing the reduction in roof surface temperatures and their impact on the surrounding environment. The Experimental Technology achieved the most significant reduction in surface temperatures, contributing to an average decrease of 3.8 °C in the local UHI effect. This reduction was particularly noticeable during peak afternoon hours, when the biochar-enhanced roof effectively moderated heat absorption and re-radiation.

The Draining Modules contributed to a 2.7 °C reduction in the UHI effect, which was moderate compared to the Experimental Technology. This technology's focus on water management helped reduce heat absorption, though its thermal performance was less pronounced.

The Green Safe showed the least impact on UHI mitigation, with an average reduction of 2.1 °C. While it still contributed to lowering surface temperatures compared to a conventional roof, its performance was limited due to the thermal properties of the substrate, which absorbed more heat during the day.

## 6. Conclusions

This study provides a comprehensive evaluation of three green roof technologies under the specific climatic conditions of a Mediterranean

environment. The findings reveal significant differences in the performance of these technologies in terms of thermal regulation, water retention, and overall efficiency, supported by quantitative metrics.

The Experimental Technology, which incorporates biochar into the substrate, demonstrated the most effective performance across all measured parameters. It consistently maintained surface temperatures up to 9.8 °C lower than the reference roof and reduced cooling energy demand by 10 % over the summer period, equating to an average daily energy savings of 3.8 kWh (approximately 340 kWh over the entire simulation period). The biochar's high porosity and moisture retention capabilities enhanced evaporative cooling, contributing to reduced heat flux and superior thermal insulation. Additionally, this technology exhibited the highest water retention levels, reinforcing its suitability for UHI mitigation and sustainable water management in arid climates.

In contrast, the Green Safe Technology, despite its focus on water storage and sub-irrigation, showed the highest surface temperatures and the lowest water content among the technologies. Surface temperatures were reduced by only 5 °C compared to the reference roof, and the cooling demand decreased by 5 %, equating to an average daily energy savings of 1.9 kWh (approximately 170 kWh over the simulation period). These results suggest that while Green Safe effectively supports vegetation growth, its thermal regulation and moisture management capabilities are limited by its current substrate composition. Optimization of the substrate and thermal insulation properties is necessary to enhance its performance in Mediterranean climates.

The Draining Modules Technology provided a balanced approach, with moderate performance in thermal regulation and water retention. This system reduced surface temperatures by 6.5 °C and cooling energy demand by 6.5 %, corresponding to an average daily energy savings of 2.5 kWh (approximately 225 kWh over the simulation period). Its efficient water drainage design makes it particularly suitable for urban areas prone to heavy rainfall, where rapid drainage is essential to prevent flooding. However, its thermal insulation properties were less effective than the Experimental Technology, indicating potential for further improvement.

These findings hold important implications for urban planners, architects, and policymakers. The results demonstrate that biochar-enhanced green roofs provide the most significant benefits in terms of thermal regulation, energy savings, and water retention, making them highly suitable for Mediterranean climates and similar environments. Conversely, technologies that prioritize vegetation support require further adjustments to optimize their thermal and water retention performance under extreme heat and limited rainfall conditions.

This study underscores the importance of continued research and innovation in green roof technologies. Future research should explore the long-term effects of biochar on substrate durability, soil health, and plant growth, as well as the economic and social implications of large-scale adoption. Additionally, investigating these technologies across different climatic conditions and over extended periods will provide deeper insights into their year-round performance and broader applicability.

In conclusion, this research contributes valuable empirical data to the field of green infrastructure, demonstrating the potential of innovative materials like biochar to enhance the sustainability and resilience of urban environments. By providing actionable insights for green roof design and implementation, this study supports the development of livable, sustainable cities that align with global climate adaptation and mitigation goals.

## Data availability

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**CRedit authorship contribution statement**

**Stefano Cascone:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Serena Vitaliano:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation.

**CRedit authorship contribution statement**

**Stefano Cascone:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Serena Vitaliano:** Writing – original draft,

Visualization, Validation, Investigation, Formal analysis, Data curation.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Appendix A**

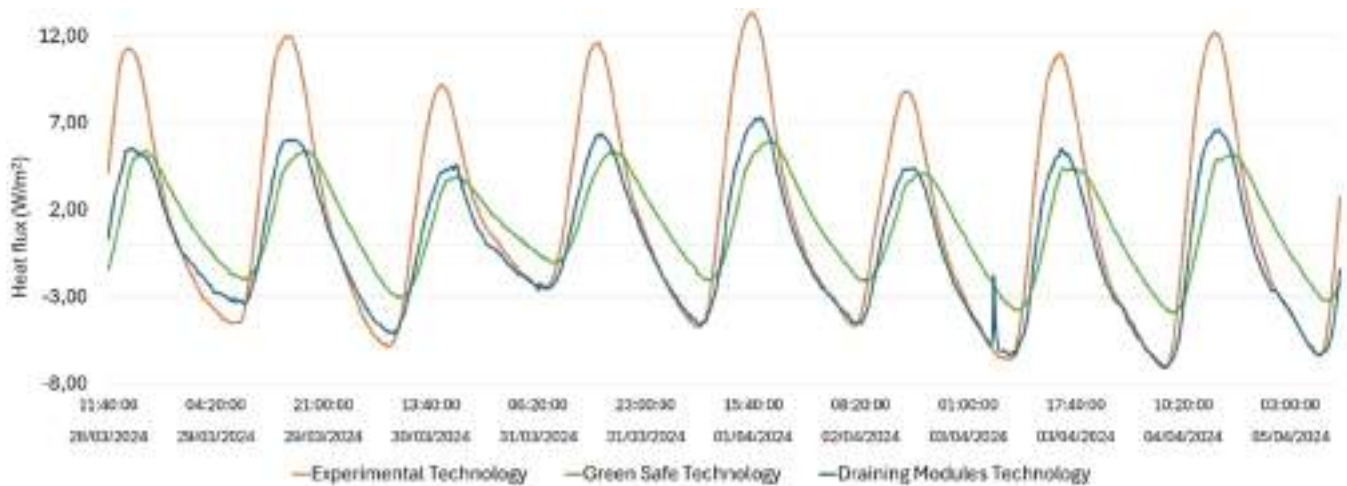


Fig. A1. Heat flux below the substrate of green roof technologies during the spring period.

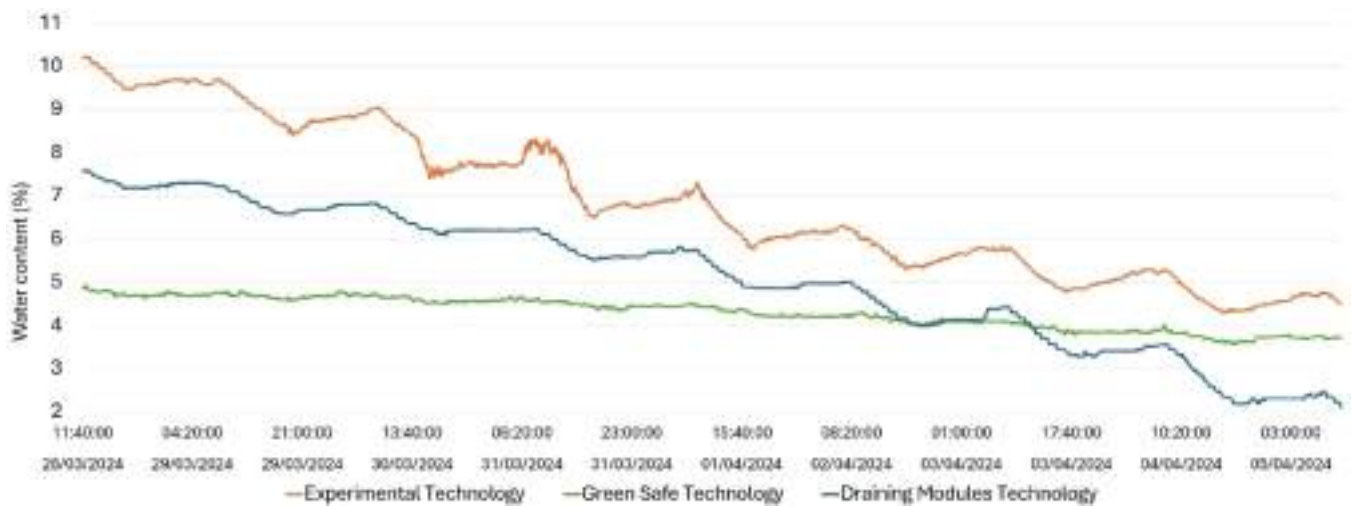


Fig. A2. Water content of green roof technologies during the spring period.

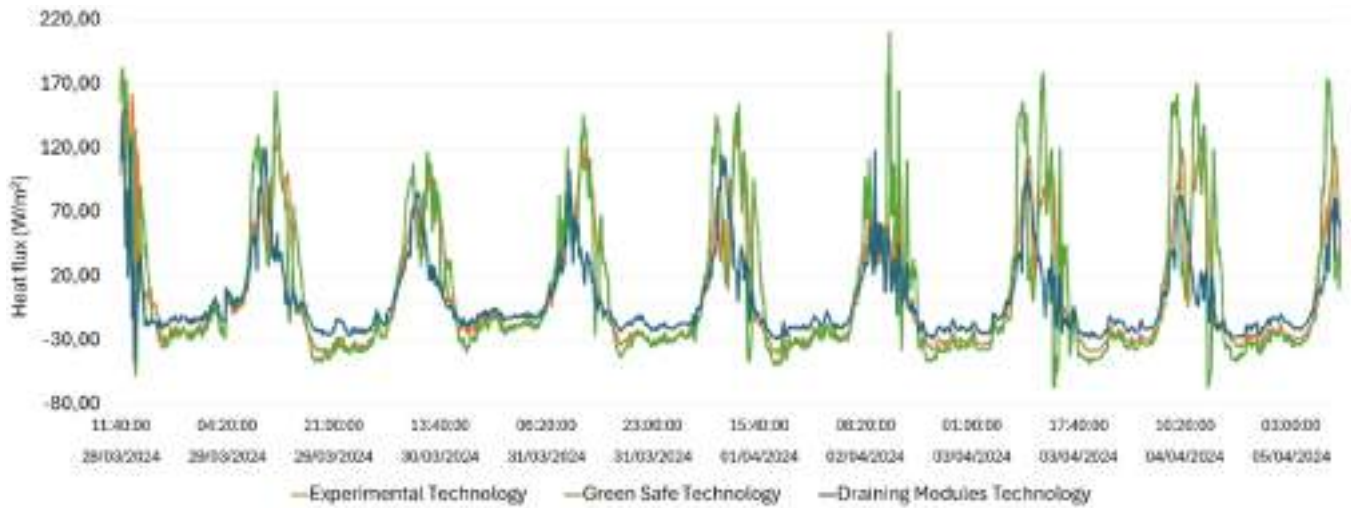


Fig. A3. Heat flux above the substrate of green roof technologies during the spring period.

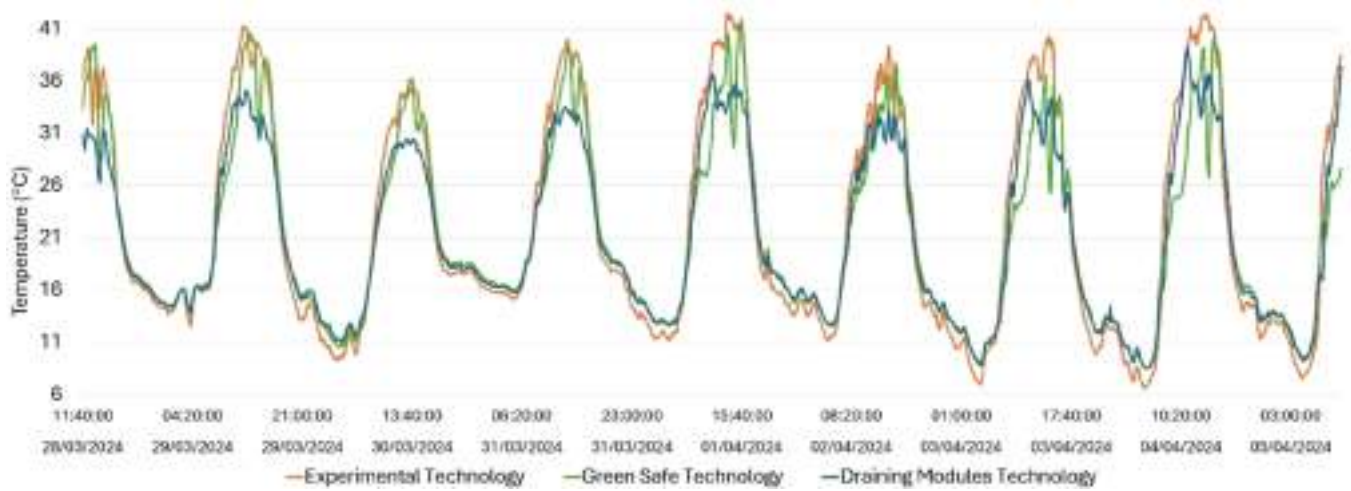


Fig. A4. Substrate layer temperature dynamics of green roof technologies during the spring period.

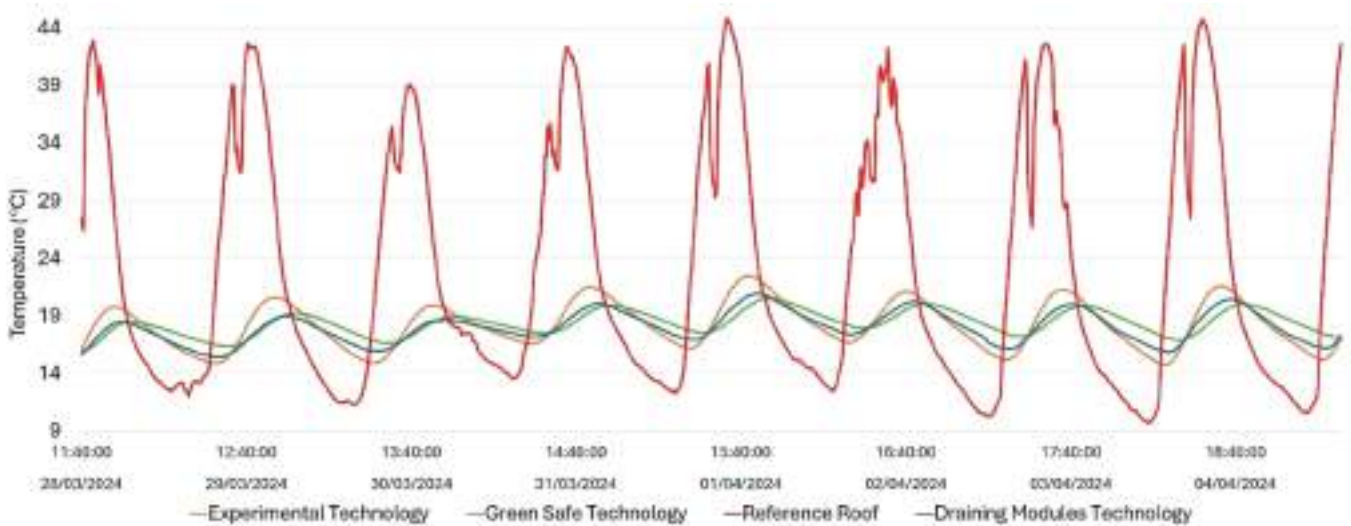


Fig. A5. Surface temperature dynamics of green roof technologies during the spring period.

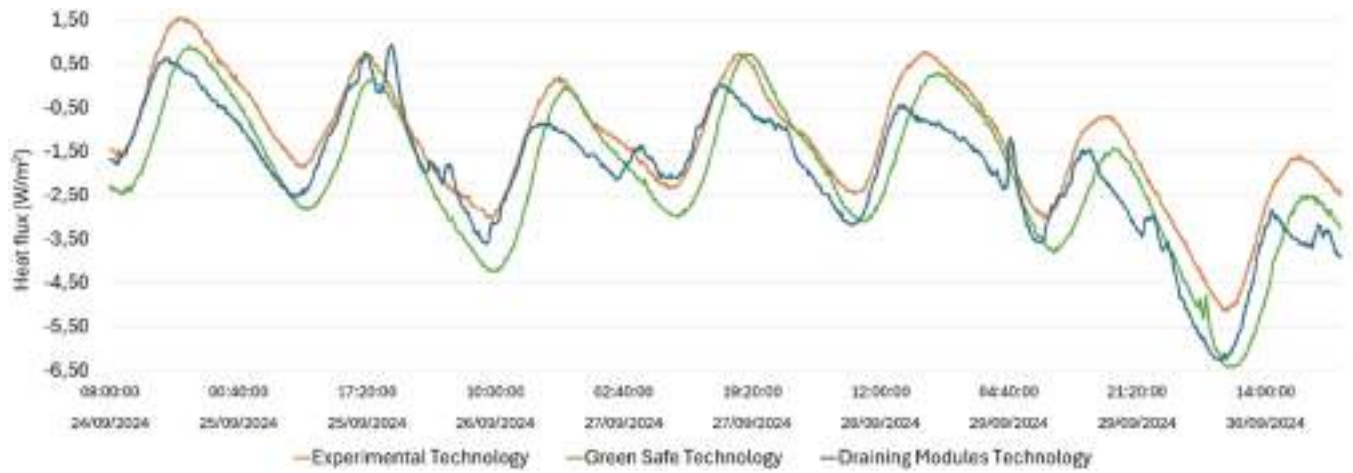


Fig. A6. Heat flux below the substrate of green roof technologies during the autumn period.

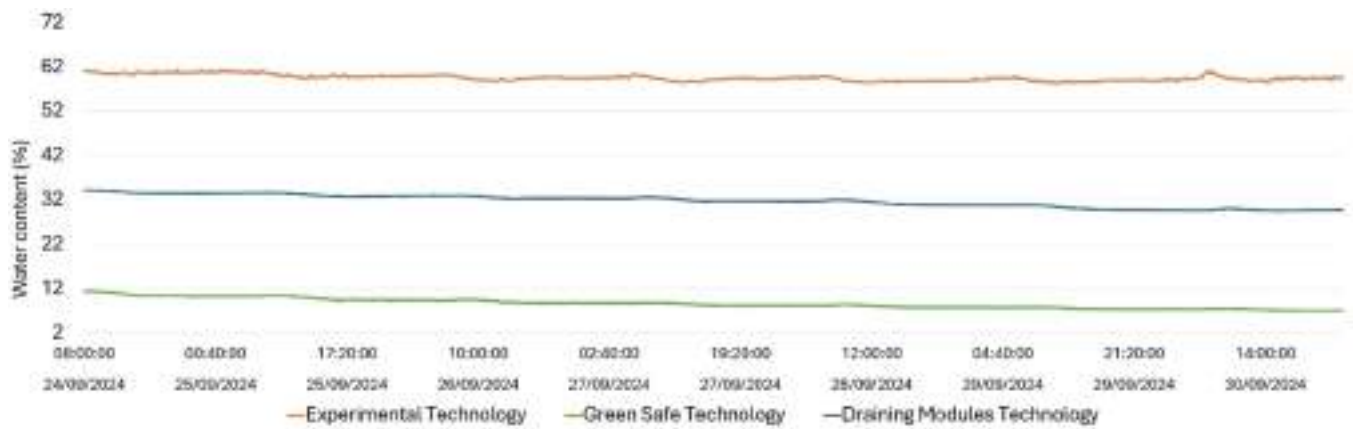


Fig. A7. Water content of green roof technologies during the autumn period.

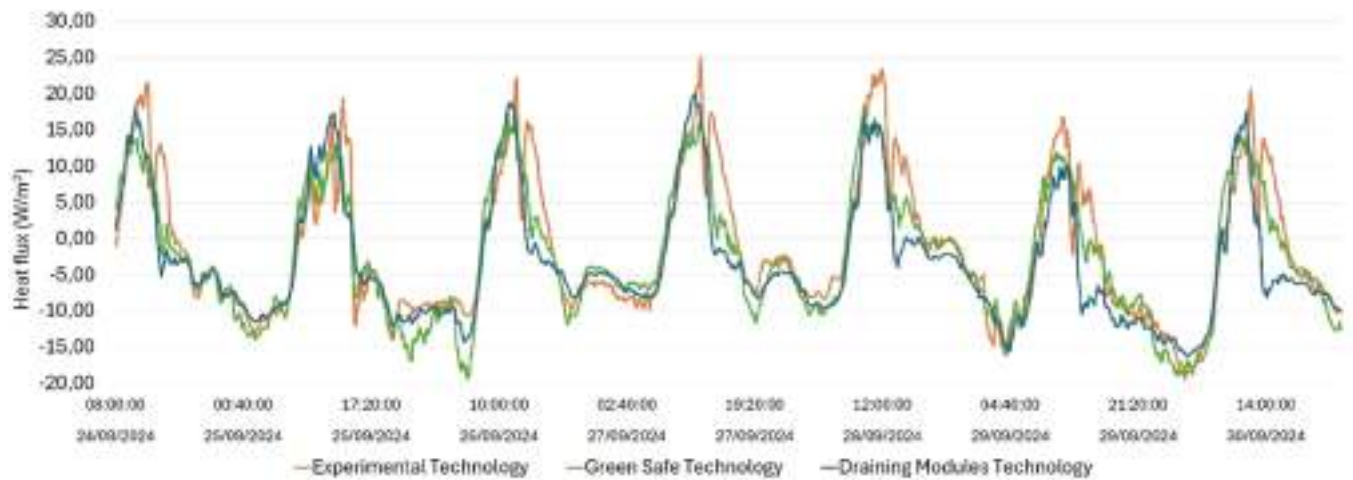


Fig. A8. Heat flux above the substrate of green roof technologies during the autumn period.

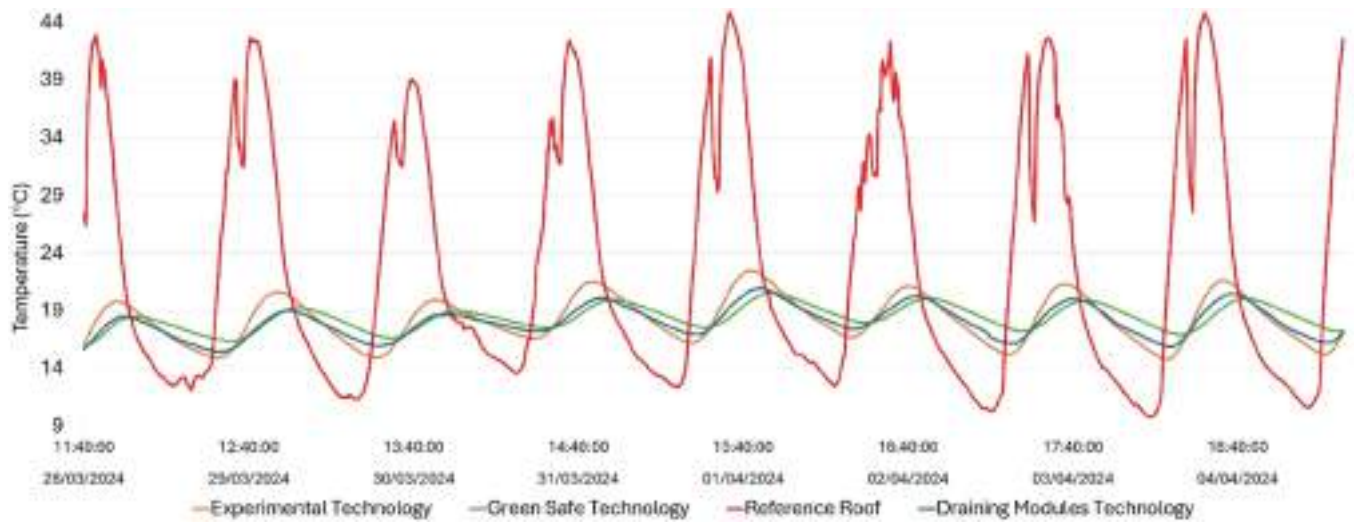


Fig. A9. Substrate layer temperature dynamics of green roof technologies during the autumn period.

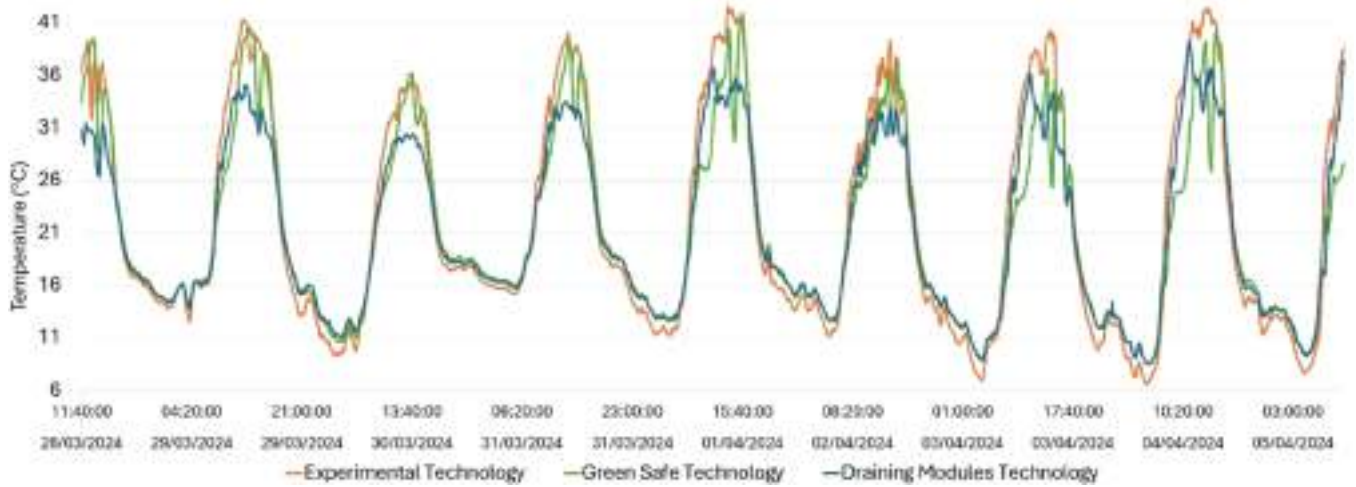


Fig. A10. Surface temperature dynamics of green roof technologies during the autumn period.

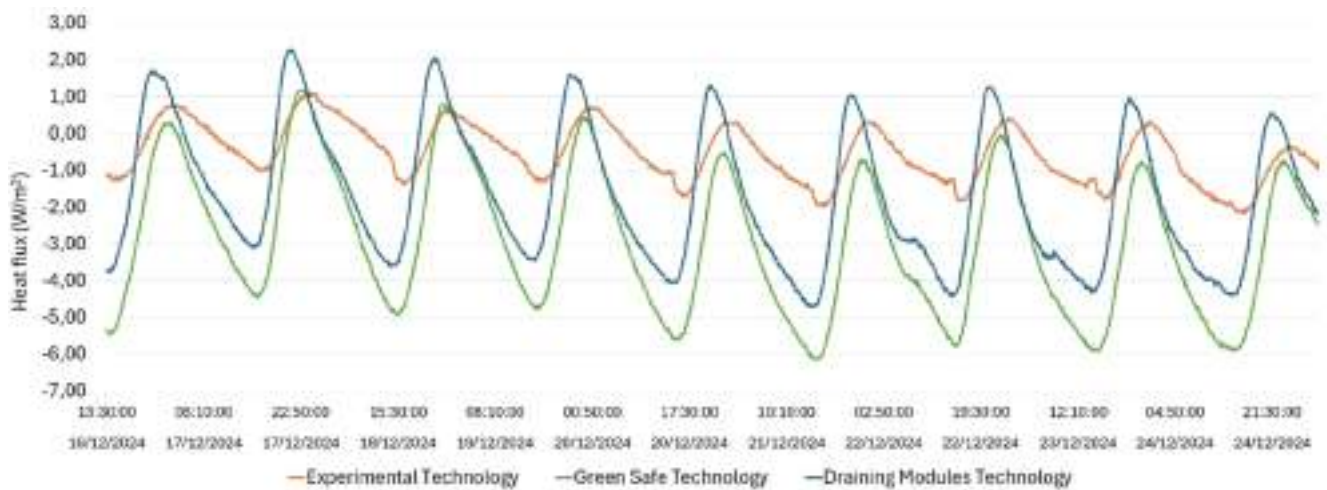


Fig. A11. Heat flux below the substrate of green roof technologies during the winter period.

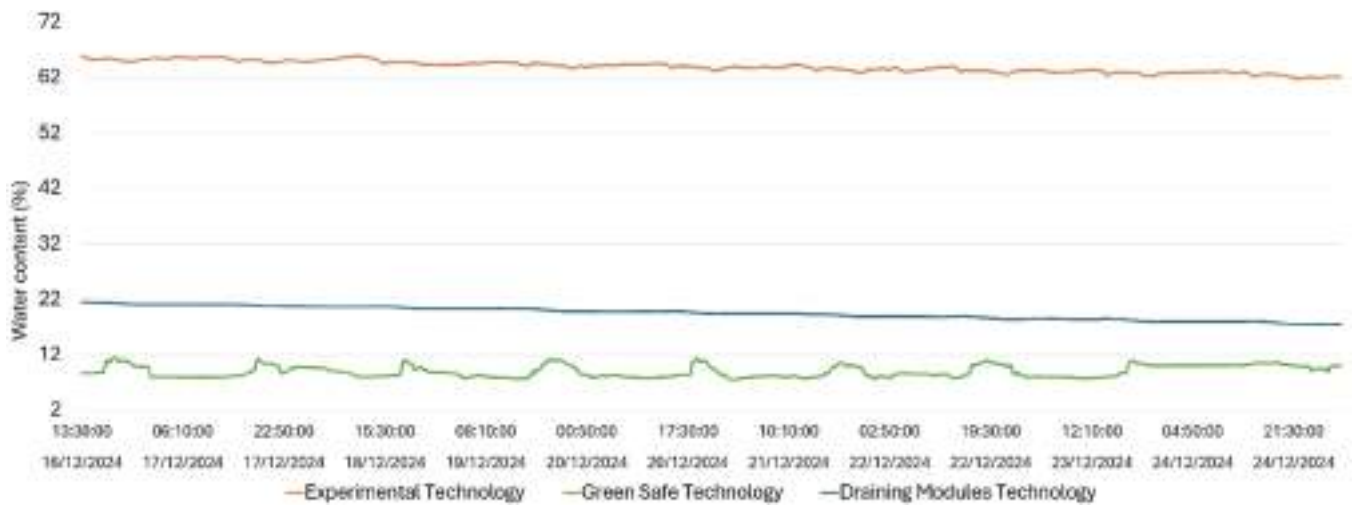


Fig. A12. Water content of green roof technologies during the winter period.

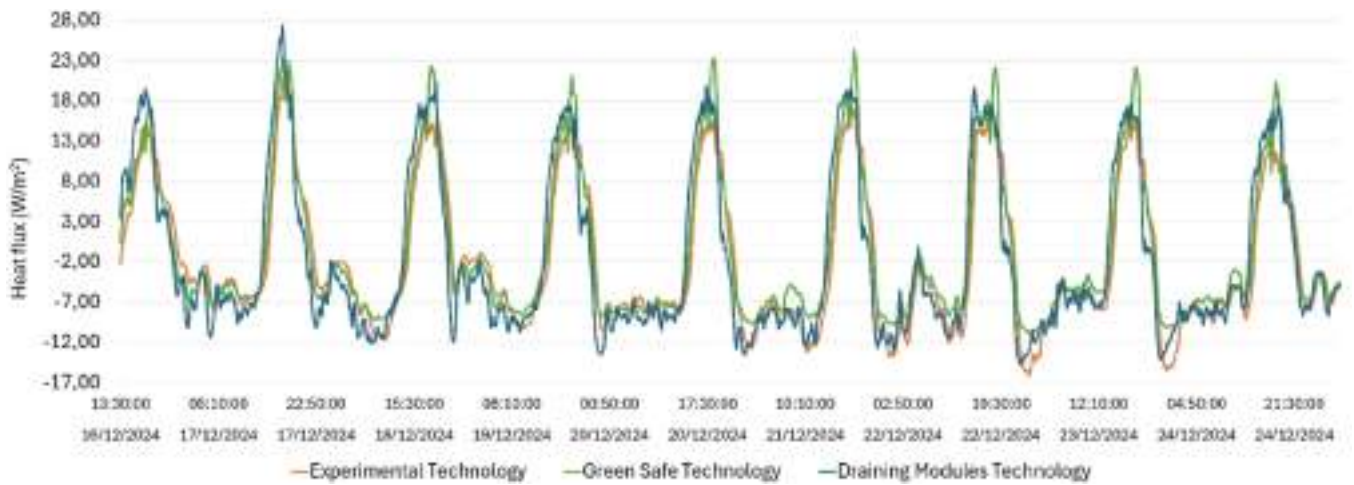


Fig. A13. Heat flux above the substrate of green roof technologies during the winter period.

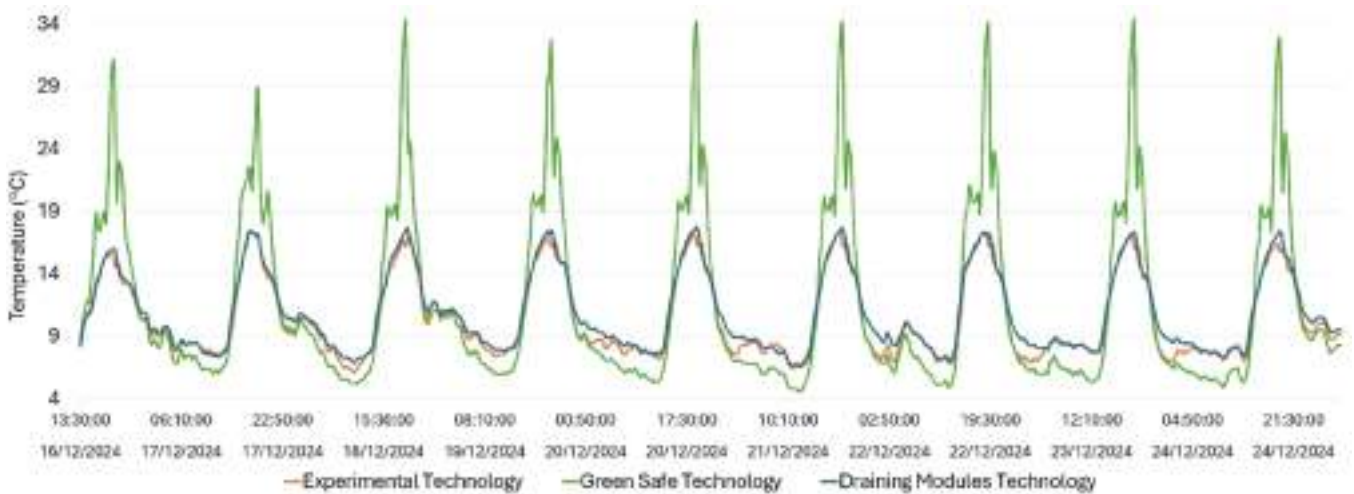


Fig. A14. Substrate layer temperature dynamics of green roof technologies during the winter period.

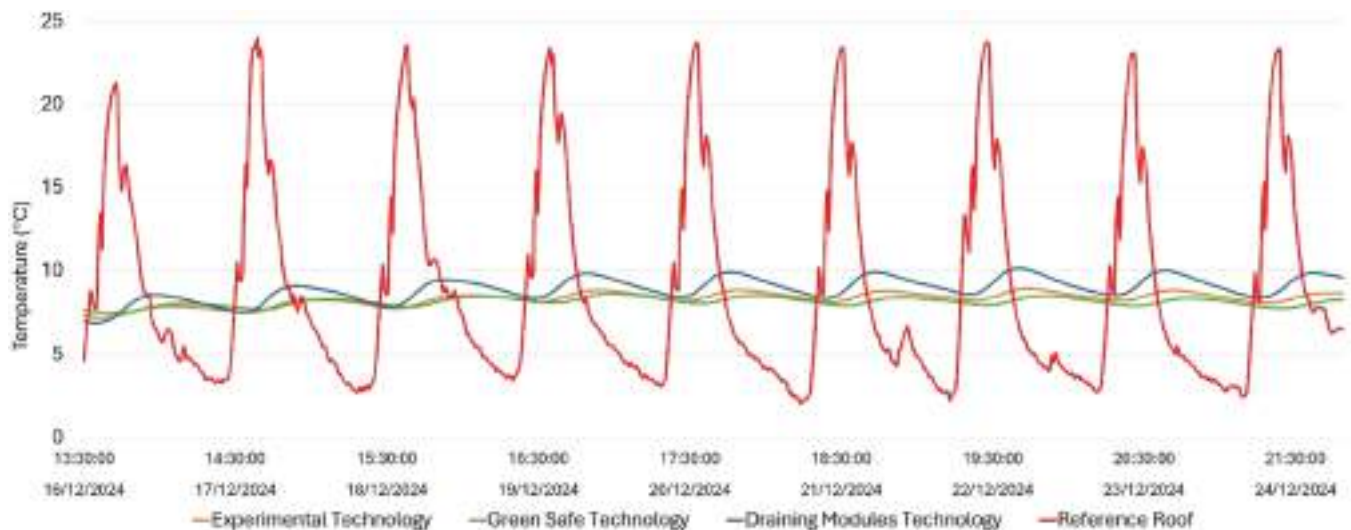


Fig. A15. Surface temperature dynamics of green roof technologies during the winter period.

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