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Thermographic Analysis of Green Wall and Green Roof Plant Types under Levels of Water Stress

Hisham Elkadi, Mahsa Seifhashemi and Rachel Lauwerijssen *

School of Science, Engineering, and Environment, University of Salford, Salford M5 4WT, UK; h.elkadi@salford.ac.uk (H.E.); s.m.seifhashemi@salford.ac.uk (M.S.)
* Correspondence: r.b.g.lauwerijssen@salford.ac.uk

Abstract: Urban green infrastructure (UGI) plays a vital role in mitigating climate change risks, including urban development-induced warming. The effective maintenance and monitoring of UGI are essential for detecting early signs of water stress and preventing potential fire hazards. Recent research shows that plants close their stomata under limited soil moisture availability, leading to an increase in leaf temperature. Multi-spectral cameras can detect thermal differentiation during periods of water stress and well-watered conditions. This paper examines the thermography of five characteristic green wall and green roof plant types (*Pachysandra terminalis*, *Lonicera nit.* Hohenheimer, *Rubus tricolor*, *Liriope muscari* Big Blue, and *Hedera algeriensis* Bellecour) under different levels of water stress compared to a well-watered reference group measured by thermal cameras. The experiment consists of a (1) pre-test experiment identifying the suitable number of days to create three different levels of water stress, and (2) the main experiment tested the suitability of thermal imaging with a drone to detect water stress in plants across three different dehydration stages. The thermal images were captured analyzed from three different types of green infrastructure. The method was suitable to detect temperature differences between plant types, between levels of water stress, and between GI types. The results show that leaf temperatures were approximately 1–3 °C warmer for water-stressed plants on the green walls, and around 3–6 °C warmer on the green roof compared to reference plants with differences among plant types. These insights are particularly relevant for UGI maintenance strategies and regulations, offering valuable information for sustainable urban planning.

Keywords: thermal infrared data; plant thermography; thermal cameras; green wall; green roof; leaf temperature

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1. Introduction

Urban green infrastructure (UGI) is recognized as an essential element in urban planning and development by cities worldwide to combat the major challenges of urbanization, such as urban-induced climate change impacts, increasing pollution, and the loss of biodiversity [1,2]. Urban-induced climate change impacts such as rising temperatures could negatively affect the public health and well-being of communities [3,4]. For example, the temperature on rooftops often exceeds 60 °C, whereas the area beneath trees can be below 30 °C. A cooling effect is a common attribute of vegetation, as plants can cool themselves and their environment through evaporation [5]. The temperature differences between urban surfaces with and without vegetation become especially pronounced as temperatures rise and more vegetated areas, such as green roofs or vertical structures like green facades or green walls, can create a more pleasant climate on hotter days. The implementation of green walls, green facades, and green roofs can contribute to the reduction of energy costs for heating and cooling buildings, mitigate the heat island effect, provide additional green space, and manage stormwater runoff [6,7]. As the popularity of green walls and green roofs continues to grow in densely built-up areas without space for parks or tree plantings, it is important to understand how different plant types respond to environmental stressors, such as water deficiency. The choice of drought-resistant vegetation, as well as adequate storage capacity and high-water retention, can be effective for green roofs without external irrigation possibilities [8]. Climbing plants are often the preferred option for green facades, where plants root in ground-based soil, whereas green walls offer a wider selection of plants as they grow in baskets with suspended substrate [9]. Since plants have diverse water requirements and optimal soil–moisture ratios for growth, further research is needed to understand how different plant species respond to varying levels of water stress.

Water deficit stress is one of the most common environmental factors that affect plant growth [10,11]. Permanent or temporary water deficit limit the growth and distribution of natural vegetation and the performance of cultivated plants. Water stress induces metabolic changes in plants, accompanied with decreased growth and photosynthesis [12]. In their natural environments, plants have evolved various morphological, physiological, and biochemical mechanisms to cope with and thrive under water-deficient circumstances [10,11]. Biotechnology is one avenue that researchers explored to improve plant tolerance to water stress [12,13]. Sufficient water is a crucial factor in maintaining plant health and performance. Changes in plant growth and performance have been observed due to water stress depending on the severity, duration, and time course of the stress [14]. The interaction between dry soil and the root system of plants significantly affects the severity of drought stress [15,16]. When faced with limited soil moisture availability, plants respond by closing their stomata, leading to drought stress, reduced transpiration, and an increase in leaf temperature [17,18]. Therefore, to maintain the effectiveness of UGI, ongoing maintenance and external irrigation are required, as relying solely on precipitation alone is insufficient, especially under warm and dry conditions. In this paper, we define water stress as a limited water supply to the plant roots [19], primarily caused by the water deficit, i.e., drought or high soil salinity. In this study, we refer to water stress caused by drought.

This study aims to analyze the thermal response of different types of commonly used plants in green wall and green roof installations under varying levels of water stress through thermal imaging in uncontrolled, real-time situation subjected to weather conditions. These plant types include *Pachysandra terminalis*, *Lonicera nit.* Hohenheimer, *Rubus tricolor*, *Liriope muscari* Big Blue, and *Hedera algeriensis* Bellecour [9,20–24]. The study will focus on plant responses to water stress measuring two indicators: leaf surface temperature and soil moisture [17,18]. By analyzing these parameters, we can determine the plants' tolerance to different levels of water stress and whether we can detect thermal variations within and between plant types [11,23]. Understanding the thermal behavior of these plants under water conditions can inform best practices for plant selection in green wall and green roof design, ultimately improving their resilience and long-term viability in urban environments.

1.1. Soil–Water–Plant Interactions

Soil–water interactions play a crucial role in the growth and vitality of plants in both green walls and green roofs. The characteristics of the soil, such as its texture, structure, and porosity, determine its water-holding capacity and the ease with which water can infiltrate and move through it [25,26]. For example, soils with high clay content have smaller pore spaces, which can lead to waterlogging, while sandy soils have larger pore spaces and may drain too quickly, leading to water stress for the plants [26]. The soil's ability to retain water is essential for providing a steady supply to plant roots for their growth and metabolic processes. In addition, plant types, water uptake requirements, transpiration, and root structure and density also influence soil–water interactions [27].

Different plant species have varying water requirements and adaptations to water stress. For example, succulent plants have specialized mechanisms to store water, while other plants may have deep or shallow root systems that influence their ability to access water in different soil layers [28]. Meanwhile, vegetation types and structure and community composition can cause temporal and spatial variations in soil moisture and impact plant water uptake [29]. The type of vegetation in a green wall or green roof can also influence the microclimate around the plants, affecting evapotranspiration rates and soil moisture levels. The strong effects exerted by plants on ecohydrological processes and the coupling of and mutual feedback between soil moisture and plants make soil moisture–plant interactions difficult to study. The availability and distribution of water in the soil directly impact the vitality of plants. Insufficient water in the soil can lead to water stress, causing wilting, reduced growth, and even the death of plants [30,31]. On the other hand, excessive water can lead to root rot and suffocation of the root system [32]. Adequate water supply in the soil is crucial for maintaining plant turgor pressure, nutrient uptake, and photosynthetic activity. Therefore, understanding soil–water interactions and their effects on plant vitality is essential for the successful cultivation of plants in green walls and green roofs.

1.2. Plant Thermography

Leaf surface temperature is a crucial indicator of plant response to water stress [11,33]. As plants experience water scarcity, they regulate their leaf surface temperature as a survival mechanism. When water availability decreases, plants close their stomata to reduce water loss through transpiration [34]. This reduction in transpiration leads to an increase in leaf surface temperature as the plants are unable to cool themselves through this mechanism. Thermal cameras have been instrumental in detecting these changes in leaf surface temperature, providing a non-invasive and efficient method for assessing plant response to water stress. By capturing infrared radiation emitted by the plant leaves, thermal cameras can map variations in temperature across the foliage, identifying areas of increased heat accumulation associated with water stress [35,36]. Research by García-Tejero et al. [37] and Jones et al. [38] demonstrated the effectiveness of thermal imaging in monitoring water stress in plants. The study utilized thermal cameras to assess the leaf surface temperature of different plant species under varying levels of water availability. The findings revealed distinct thermal patterns associated with water-stressed plants, highlighting the potential of thermal imaging as a valuable tool for the early detection of water stress in vegetation. Studies corroborated the utility of thermal imaging in identifying physiological changes in plants under water-limited conditions, providing important insights for sustainable plant cultivation in urban environments [39,40].

1.3. Understanding Plant Thermography through Analyzing Water Stress with Thermal Sensors

The application of thermal imaging to study green roofs and walls is still an emerging field. The literature review emphasized the need for comprehensive data collection and monitoring soil moisture–plant interactions and leaf surface temperature to investigate how various plant species react to different levels of water stress in urban environments. By highlighting how drought stress affects urban vegetation, this study contributes to the understanding of climate change impacts on green infrastructure and urban greening efforts. The study provides valuable insights into optimizing water management, enhancing plant health monitoring, and contributing to the long-term success of green roofs and walls in cities.

To the best of the authors' knowledge, this study is the first to detect drought stress on multiple green infrastructure systems in an uncontrolled, real-time setting exposed to varying weather conditions. The research introduces thermographic imaging as a tool for early detection of drought stress, enabling the more effective, proactive maintenance of UGI, which can enhance its longevity and sustainability. The aim of this study is to conduct thermography analysis through the thermal imaging of five characteristic green wall and green roof plant species under different levels of water stress to understand their response to water scarcity. This study was guided by the following questions which seek (1) to assess the leaf surface temperature of various plant species under different levels of water stress and (2) to evaluate the effectiveness of thermal imaging to detect drought stress in green wall and green roof systems.

2. Materials and Methods

Data for the study were collected in an open-air experiment, consisting of a pre-test experiment (Section 2.2) and the main experiment (Section 2.3), to conduct a thermographic analysis of five characteristic plant species commonly used in green walls and on green roofs. The pre-test experiment aimed to identify the suitable number of days to create three different levels of water stress. The knowledge gained from this pre-test shaped the methodology. Before the main experiment, the plants were dehydrated using a similar protocol to the pre-test experiment. The main experiment then tested the suitability of thermal imaging with a drone to detect water stress in plants across three different dehydration stages in uncontrolled, real-time situations subjected to weather conditions. The thermal images captured were analyzed from three different types of green infrastructure.

2.1. Experiment Location

Both experiments took place on the roof of the Lady Hale Building part of the IGNITION Living Lab at the University of Salford, Greater Manchester, United Kingdom. The roof was chosen as designated area for the experiments because of easy access to water supply and minimal interference from pedestrians, allowing for accurate data collection and observation without external disturbances. Figure 1 presents the position of the industrial wall, roof deck, and the temporary wall on top of the Lady Hale Building.

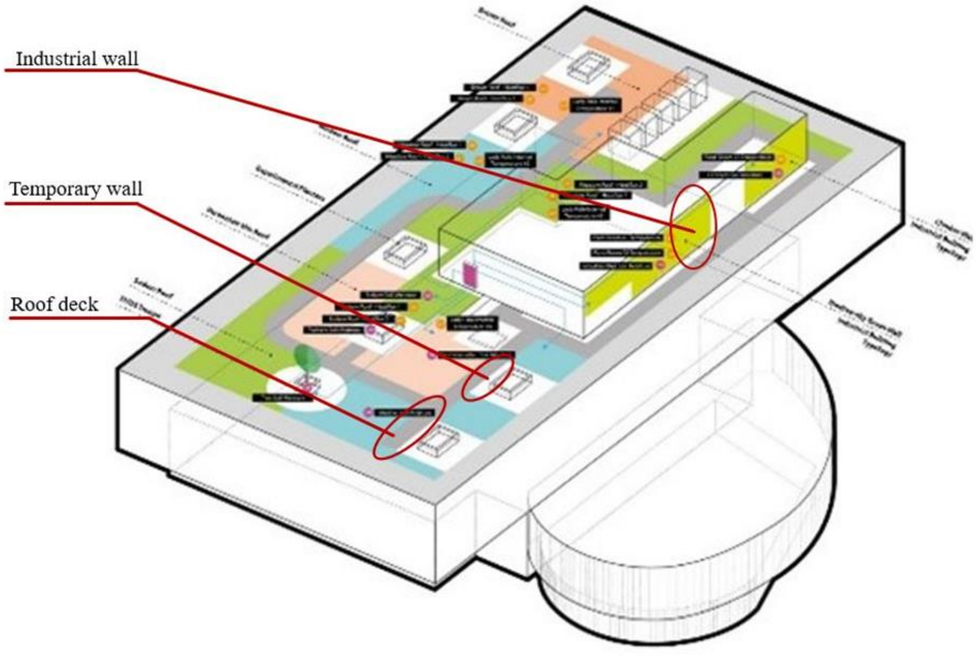
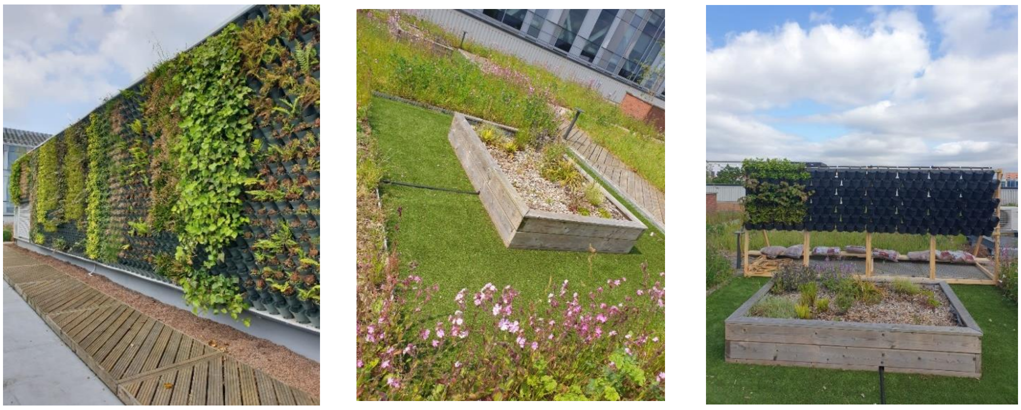


Figure 1. The position of industrial wall, roof deck, and temporary wall on top of the Lady Hale Building, University of Salford.

The green infrastructure structures in this study were an industrial wall, a temporary constructed green wall, and a roof deck area (see Figure 2A–C). The plants selected for the pre-testing phase and the main experiment were selected from the industrial wall on the roof of the Lady Hale Building and used for the temporary green wall and the roof deck area. For this study, the authors worked together with external companies for arrangements regarding the thermal camera (FLIR), the drone (Aerialworx, Manchester, UK and the creation and maintenance of a temporary green wall (GreeningUp, Chorley, UK). The temporary green wall was equipped with a manual controllable irrigation system which allowed us to irrigate the reference plants.



(**A**) (**B**) (**C**)

Figure 2. (**A**) Industrial wall, (**B**) roof deck, and (**C**) temporary wall.

Local Climate Conditions to Salford, UK

The climate in Salford, UK, is temperate maritime, characterized by mild temperatures, consistent rainfall, and overcast skies [41]. Winters are generally mild with average air temperatures ranging from 2 °C to 7 °C, while summers are cool to mild, averaging 12 °C to 19 °C. Rainfall is evenly distributed throughout the year, with an annual average of 800–900 mm. The city is known for its frequent light rain and drizzle. Sunshine is limited, at around 1200–1400 h per year, and cloud cover is common. Wind speeds are moderate and average 8–10 mph. Salford's climate, though not extreme, is defined by its dampness, relatively mild conditions, and frequent cloudy days [41]. Micrometeorological data (air temperature, wind speed, relative humidity, and solar radiation) were collected on the campus of the University of Salford, with the weather station installed on the roof of the Energy House Building.

2.2. Pre-Test Experiment

A pre-test experiment was designed and performed (1) to shape the methodology for the main experiment and (2) to identify the suitable number of days to create three different levels of water stress for the selected plant species. The pre-test experiment started on 30 March 2023 and was completed on the 11 April 2023. The following five plant species were selected: 1—*Hedera algeriensis* Bellecour; 2—*Cotoneaster dammeri*; 3—*Liriope muscari* Big Blue; 4—*Rubus tricolor;* 5—*Lonicera nit.* Hohenheimer (see Table 1).

Table 1. Plant types selected from the green wall for the pre-test experiment.

Plant Type	**1**	**2**	**3**	**4**	**5**
Plant image					
Plant name	*Hedera Algeriensis* Bellecour	*Cotoneaster dammeri*	*Liriope muscari* Big Blue	*Rubus tricolor*	*Lonicera nit.* Hohenheimer

From each plant species, 5 pots were used for the pre-test experiment: 3 pots were used to measure three levels of water stress, 1 pot to measure over watering, and 1 pot for control. Measurements on soil moisture (30 March 2023; 4 April 2023; 6 April 2023; 11 April

2023) and leaf surface temperatures (4 April 2023; 6 April 2023; 11 April 2023) all took place between 13:00 and 14:00 PM on the selected days. The specific time frame was selected to detect the maximum temperature difference between stressed and non-stressed plants under sunny conditions or when the solar radiation is high [17]. On 6 April 2023, five control plants were transferred to the automotive lab and placed inside a large container filled with water and kept for 5 days to prepare the over-watered plants for comparison. A schematic representation of the pre-test experiment is shown in Figure 3.

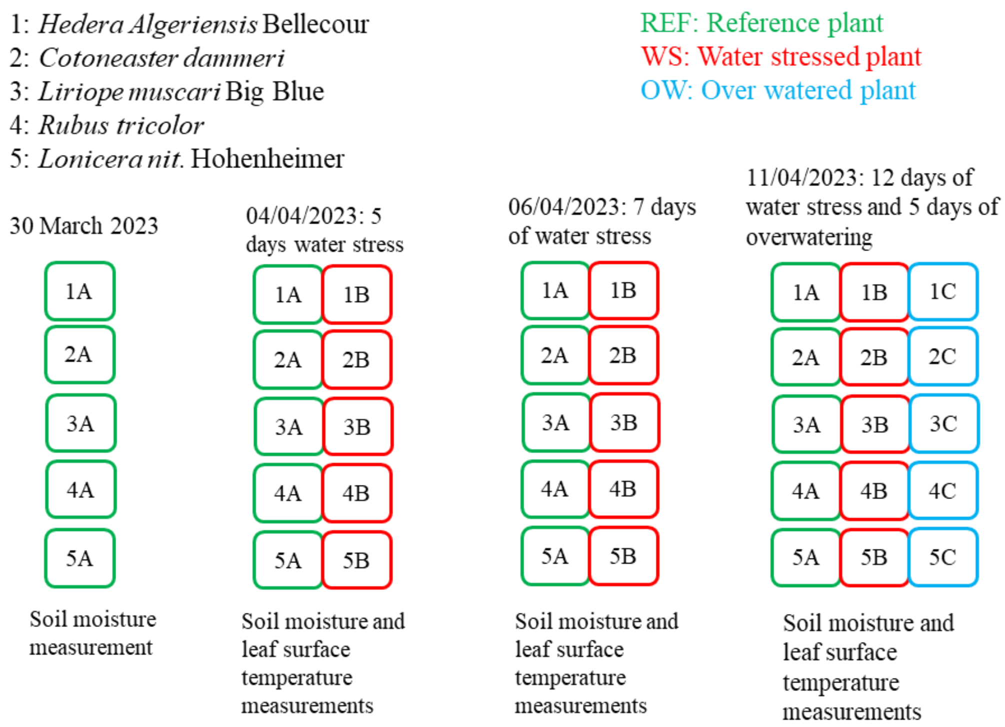


Figure 3. Schematic representation of the pre-test experiment.

On selected days, the leaf surface temperature of each plant was measured three times, and the means and standard deviations were then calculated. Soil moisture was measured once in each plant pot. The results of the pre-test experiment are shown in Section 3.1. All selected plants were collected from the IGNITION living wall and watered by a smart irrigation system. After each measurement moment, the reference plants were returned to the living wall, where they continued to be watered by the smart irrigation system. The water stress selected plants were transferred into an indoor environment (automotive lab) to protect the plants from possible rain in stages with no access to the smart irrigation system. On selected days of measurement, the water-stressed plants were transferred to the outdoor decking for better comparison to control plants and measured on leaf surface temperature and soil moisture. Each plant was planted in a 1 L pot (~13 cm diameter pot).

Soil moisture was measured manually with the Suplong soil moisture meter. The scale measurements range between 1 (dry) to 10 (wet). The FLIR E60bx handheld thermal camera (FLIR Systems UK, West Malling, United Kingdom) was used to read leaf surface temperature of each plant in Celsius (°C). The average of three readings for each plant were calculated and recorded. The emissivity was set to 0.98 as per recommendation by Hatfield [42], who stated that the emissivity for plants should typically be between 0.97 and 0.99. The weather data records from the University of Salford weather station were assessed for the days of the pre-test experiment to better understand and interpret the thermography of the plants. Studies argue that weather conditions, including wind, can influence the data [43,44]. The weather conditions assessed were air temperature (°C), relative humidity (%) (both presented in Figure 4), solar radiation (MJ/m²/day) (presented in Figure 5), and wind speed (mph) (presented in Figure 6) at the approximate time of the measurements. In Figures 3–5, 'T' represents air temperature, 'RH' stands for relative humidity, 'S' denotes solar radiation, and 'WS' refers to wind speed.

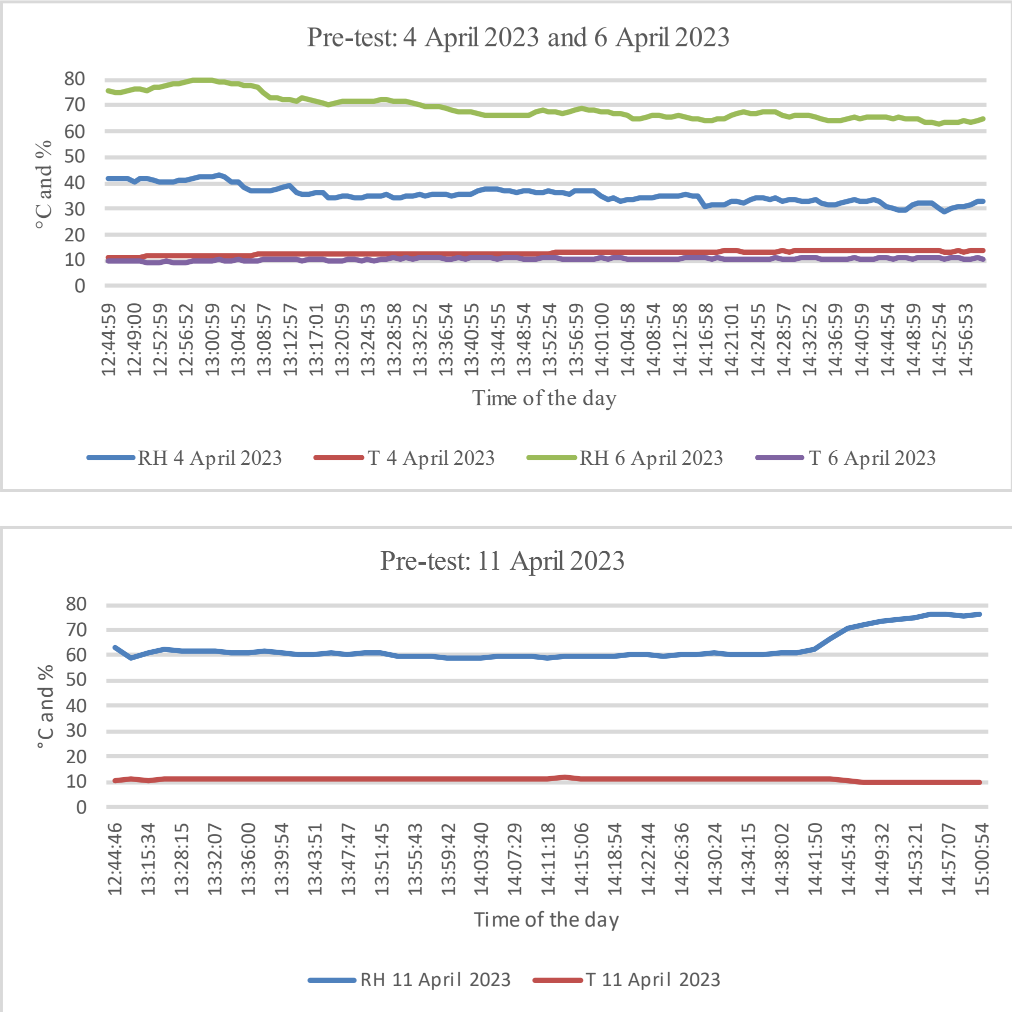


Figure 4. Air temperature (°C) and relative humidity (%) during the pre-test days.

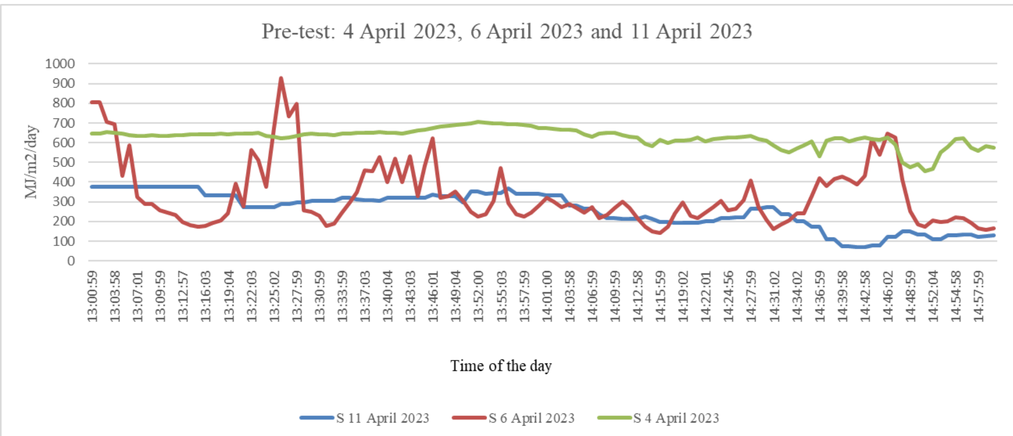


Figure 5. Solar radiation (MJ/m²/day) during the pre-test days.

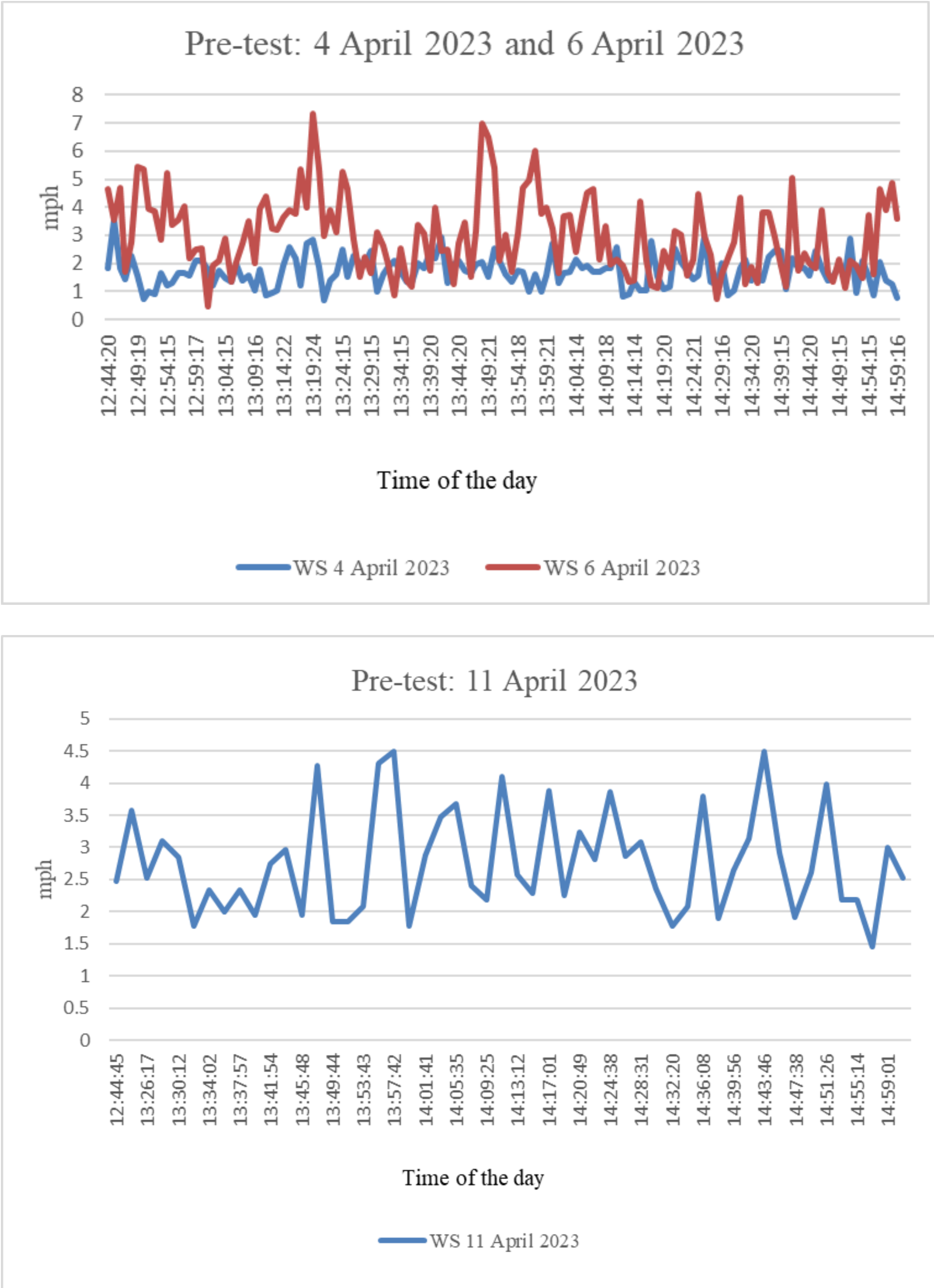


Figure 6. Wind speed (mph) during the pre-test days.

2.3. Main Experiment

The main experiment was conducted to monitor the health profiles of five plant species in different green infrastructure types. The plants selected are five characteristic plant species used for green walls and green roofs (1—*Pachysandra terminalis*; 2—*Lonicera nit.* Hohenheimer; 3—*Rubus tricolor*; 4—*Liriope muscari* Big Blue; 5—*Hedera algeriensis* Bellecour*)*. The thermal imaging experiment, using a FLIR T1030 thermal camera (FLIR Systems UK, West Malling, United Kingdom) mounted on a Freefly Alta 8 drone (Aerialworx, Manchester, United Kingdom), took place on 2 June 2023, at 16:00.

2.3.1. Plant Species

Pachysandra terminalis is a widely studied indicator species for assessing the functionality of green facades and green walls [21,22]. Native to Japan, Korea, and China, it is cultivated as an evergreen, ornamental plant in Western countries. The plant's leaves are arranged alternately, with a glossy, leathery texture and a deep green color. They have scalloped edges [45]. *Pachysandra terminalis* is commonly used as a massed groundcover, filling in shaded areas, and prefers a moist, well-drained soil.

Lonicera nit. 'Hohenheimer' is a hybrid cultivar native to Germany [46]. It is a dense, evergreen shrub with small, ovate, and glossy mid-green leaves arranged in opposite pairs and suitable for planting on green walls [9]. This plant is well-suited for low hedges and ground cover plantings, and it prefers a dry to moist, well-drained soil.

Rubus tricolor is an evergreen shrub native to China, bearing orange-red edible fruits. The plant has glossy, heart-shaped leaves with a dark green hue and prefers well-drained soil [47]. *Rubus tricolor* is a hardy and low-maintenance species, making it suitable for ground cover plantings even in shaded areas.

Liriope muscari 'Big Blue' is a shade-tolerant, evergreen groundcover species native to Japan, Korea, and China [48]. This herbaceous perennial form narrow, linear, and dark green leaves that are approximately 2.5 cm wide and grow up to 30–45 cm tall. The plant is known for its broad tolerance to various climatic and polluted conditions, making it a useful indicator species for green infrastructure studies [18].

Hedera algeriensis Belleceour is a member of the *Hedera* genus and is often planted in green walls due to its resilience against air pollution and low maintenance requirements [20,24]. The plants are evergreen climbing shrubs that cling to surfaces using aerial roots. Their leaves are triangular, oval, and glossy in appearance [49]. This plant can serve as an effective ground cover, even in shady areas. *Hedera algeriensis* Belleceour thrives in a moist, well-drained soil.

2.3.2. Pre-Main Experiment: Preparing Plants to Detect Water Stress

Prior to the experiment, five characteristic plant species used for green walls and green roofs (1—*Pachysandra terminalis*; 2—*Lonicera nit.* Hohenheimer; 3—*Rubus tricolor*; 4—*Liriope muscari* Big Blue; 5—*Hedera algeriensis* Bellecour) (see Table 2) were stressed through three levels of dehydration to detect water stress. The five selected plant species, of which four were tested in the pre-test experiment, were collected on the industrial wall on top of the Lady Hale Building. Dehydrating the plants for three levels of water stress started on 22 May 2023 and ended on 1 June 2023. In total, 25 pots (10 for green roof decking and 15 for the walls) for each plant species were removed from the industrial wall in each three stages, i.e., on three (level 3), eight (level 2), and eleven days (level 1) prior to the experiment. Like the pre-experiment procedure, water-stressed plants were kept indoors to avoid possible rain. The schematic representations of preparing the plants for the three levels of water stress until the date of the experiment (2 June 2023) are visualized in Figure 7 (industrial and temporary wall) and Figure 8 (green roof decking).

Table 2. Plant types selected for the experiment.

Plant Type	**1**	**2**	**3**	**4**	**5**
Plant image					
Plant name	*Pachysandra terminalis*	*Lonicera nit.* Hohenheimer	*Rubus tricolor*	*Liriope muscari* Big Blue	*Hedera algeriensis* Bellecour

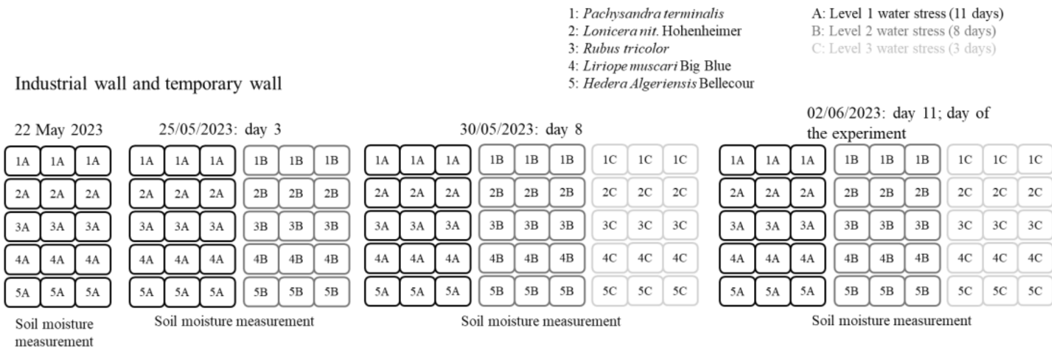


Figure 7. Schematic representation of preparing the plants for the three levels of water stress (level 1—11 days; level 2—8 days; level 3—3 days) for the industrial and the temporary wall until the experiment (2 June 2023).

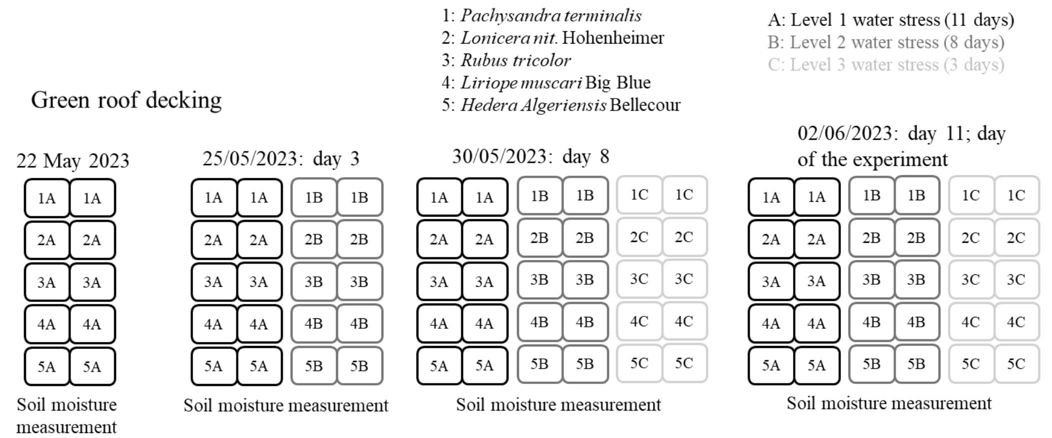


Figure 8. Schematic representation of preparing the plants for the three levels of water stress (level 1—11 days; level 2—8 days; level 3—3 days) for the green roof decking until the experiment (2 June 2023).

Soil moisture levels of all plant species for each level of water stress were measured and recorded four times during the dehydration process (22 May 2023; 25 May 2023; 30 May 2023; 1 June 2023) and on the day of the experiment (2 June 2023). The results are presented in Table 3.

Table 3. Soil moisture measurements of selected plants before and on the day of the experiment.

Plant Name/Type		***Pachysandra terminalis*/1**	***Lonicera nit.* Hohenheimer/2**	***Rubus tricolor*/3**	***Liriope muscari* Big Blue/4**	***Hedera algeriensis* Bellecour/5**
Level 1—water-stressed	Water stress start	30 May 2023	30 May 2023	30 May 2023	30 May 2023	30 May 2023
	Day 0—30 May 2023	9	9	9	9	9
	Day 2—1 June 2023	8.5	8.5	7.5	8.5	8
	Day 3—2 June 2023	8.5	8.5	7.5	8.5	8
Level 2—water-stressed	Water stress start	25 May 2023	25 May 2023	25 May 2023	25 May 2023	25 May 2023
	Day 0—25 May 2023	9	9	9	9	9
	Day 7—1 June 2023	8.5	8.5	7	7.5	7.5
	Day 8—2	8	8	7	7	7

	June 2023					
Level 3—water-stressed	Water stress start	22 May 2023	22 May 2023	22 May 2023	22 May 2023	22 May 2023
	Day 0—22 May 2023	8.5	9.5	8.5	9.5	8
	Day 3—25 May 2023	8.5	9	7	8.5	7.5
	Day 10—1 June 2023	7	7.5	6.5	5.5	6
	Day 11—2 June 2023	6.5	7	6.5	5	4.5

2.3.3. Main Experiment Setup

At the day of the experiment, the plants were arranged in a particular layout to identify temperature differences between different levels of water-stressed plants and to compare them to the reference plants (see Figure 9).

On the industrial wall (see Figure 9A), plant type 4 (*Liriope muscari* Big Blue) and plant type 5 (*Hedera algeriensis* Belleceour) were placed under the control plants in order of level 1, level 2, and level 3 from the top to bottom of the wall. On the day of the experiment, the irrigation system on the industrial wall was turned off. Before placing the water-stressed plants inside the potholders on the walls, the remaining water was soaked up manually using sponges to ensure that there was no water inside the potholders.

On the temporary wall (see Figure 9B), plant type 1 (*Pachysandra terminalis*), plant type 2 (*Lonicera nit.* Hohenheimer), and plant type 3 (*Rubus tricolor*) were placed in order from top to bottom. The levels of water-stressed plants were placed from left to right.

All plant species were placed on the roof decking (see Figure 9C). However, due to shade casting from the reference plants over water-stressed plants, only *Hedera algeriensis* Belleceour was considered for analysis because its water-stressed plants were located outside of the shadow of the reference plants.

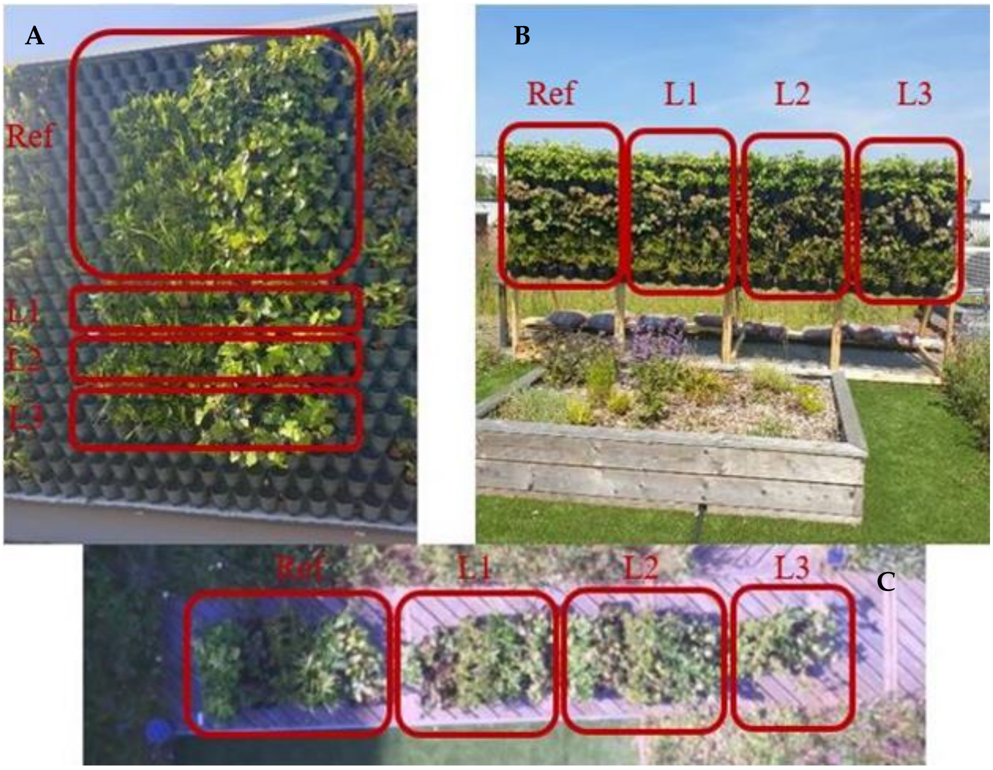


Figure 9. Arranging the plant categories on the industrial wall (**A**), temporary wall p1 (**B**), and roof decking (**C**) for thermal imaging.

The weather conditions (air temperature, relative humidity, and reflected temperature) were assessed using data from the MetOffice website for Salford on the day of the experiment [50]. The values set in the camera were 61% RH, 19 °C, and 18 °C. During the experiment, the average temperature outside was 19.5 °C (18–21 °C) and the humidity was 39% (35–43%). Solar radiation was between 15–615 W/m^2, measuring 615 at the start of the experiment and slowly decreasing over time. Similarly to the pre-test phase, the emissivity is at 0.98 as per the recommendations of Hatfield [42], who stated that an emissivity for plants should typically be between 0.97 and 0.99.

2.3.4. Materials: Thermal Camera and Drone

The thermal imaging experiment utilized a FLIR T1030 thermal camera (FLIR Systems UK, West Malling, United Kingdom) mounted on a Freefly Alta 8 drone（Aerialworx, Manchester, United Kingdom）. The Freefly Alta 8 drone was equipped with a Freefly Movi Pro gimbal and could lift cameras weighing up to 5.9 kg. The drone was well-suited for the experiment as it can accommodate cameras mounted on the top or bottom, is weather-resistant, offers high speeds (up to 35 mph), and provides an extended flight time of approximately 15 min depending on payload weight and flight conditions [51,52].

The FLIR T1030 thermal camera generates clear and accurate thermal images due to its thermal sensitivity and HD resolution, which makes it eligible for researchers to use [53]. The color palette of Rainbow HC was set to capture the smaller graduation range of temperatures. Furthermore, the color palette assigns more colors to the images, which helped us to analyze the thermal images with more accuracy. The Rainbow HC color palette ranges from red (highest temperature), orange, yellow, green, light blue, dark blue, to purple (lowest temperature). Depending on the distribution of colors within thermal images, the authors can emphasize the temperature variations and patterns between different level of water-stressed plants and reference plants, as well as between the layout of vegetated and non-vegetated structures.

Thermal images were analyzed with the FLIR tools software (FLIR Tools 5.X). The FLIR tools helped us to detect and measure the infrared radiation that is emitted by objects and convert it into temperature data, allowing the visualization of heat patterns. To isolate and emphasize the temperature variations and patterns within the plant section, a box was drawn around the plants in the thermal image. The FLIR tools software (FLIR Tools 5.X) was then used to establish the temperature scale of the image based on the minimum and maximum temperature values within this box. Of each thermal image, three different temperatures were taken for each plant type in a category (L1, L2, L3, reference). In each category, the average temperature was recorded.

3. Results

3.1. Pre-Test Experiment: Thermography Reactions from Plant Typologies

Figure 10 presents the thermography and soil moisture measurements of the pre-test experiment, including the mean of each plant. Table 4 presents the standard deviation of each plant on selected days. The findings reveal that (1) an increase in leaf surface temperature was measured in all water-stressed and over-watered plants compared to the reference plants, (2) a decrease in soil moisture was measured in all water-stressed plants with noticeable differences between plant types, and (3) leaf surface temperature differences between plant species were noted. For example, the leaf surface temperature of *Cotoneaster* decreased over time while for the remaining four plant species, the leaf surface temperature increased from day 7 compared to day 12.

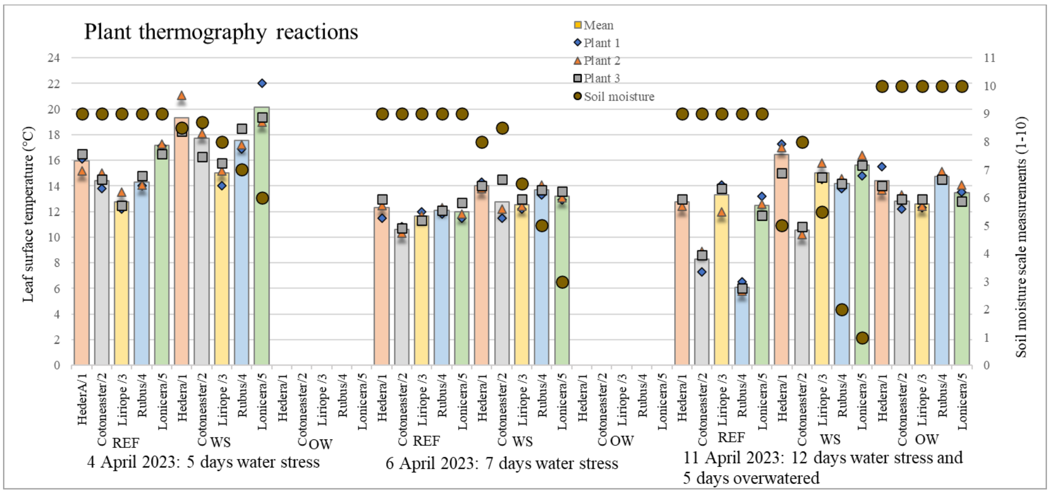


Figure 10. Thermography analysis and soil moisture measurements of five plant types analyzed in the pre-test phase. Measurements were performed on reference plants (REF), water-stressed plants (WS), and over-watered plants (OW) on the dates 4 April 2023, 6 April 2023, and 11 April 2023. Noted is that only on 11 April 2023 over-watered plants were measured.

Table 4. Standard deviation calculations of five plant types on the selected days in the pre-test phase. Calculations were conducted on reference plants (REF), water-stressed plants (WS), and over-watered plants (OW).

Date	Measurement Performed	*Hedera*/1	*Cotoneaster*/2	*Liriope*/3	*Rubus*/4	*Lonicera*/5
4 April 2023	REF	0.544	0.492	0.556	0.356	0.340
	WS	1.276	1.020	0.748	0.694	1.330
6 April 2023	REF	0.624	0.216	0.287	0.205	0.510
	WS	0.205	1.281	0.340	0.327	0.294
11 April 2023	REF	0.262	0.694	0.927	0.294	0.616
	WS	1.021	0.249	0.572	0.327	0.653
	OW	0.787	0.464	0.309	0.262	0.531

Interestingly, the leaf surface temperature was highest at 5 days of water stress compared to 7 and 12 days of water stress. This can be explained by the assessed weather conditions such as air temperature and relative humidity because a higher air temperature and lower relative humidity was measured on 4 April 2023 compared to 6 April 2023 and 11 April 2023 (see Figure 4), which had a slightly lower air temperature and higher relative humidity. Moreover, wind could potentially have influenced leaf surface temperatures because higher wind speeds were measured on 6 April 2023 compared to 4 April 2023 and 11 April 2023 (see Figure 6).

For over-watered plants, four plant types, except *Liriope*, reported an increase in leaf surface temperature in comparison to the well-watered plants. For example, the leaf surface temperatures of the over-watered plants *Cotoneaster* and *Rubus* increased on average by 4.56 °C and 8.63 °C. All water-stressed plants showed a decrease in soil moisture levels over time with noticeable measurements for *Rubus* and *Lonicera*, respectively, decreasing from 9 to 2 and 1 on 11 April 2023. The soil moisture of *Cotoneaster* reduced the least over time from 9 to 8. These findings emphasize the importance of considering the specific water requirements of each plant type during the selection process for irrigation panels in green walls or green roofs.

3.2. Main Experiment: Thermography between Green Infrastructure Typologies

The findings report higher average leaf surface temperatures for water-stressed plants which rise gradually with increasing days of water stress. The findings of the experiment are in line with the findings from the pre-test experiment and previous studies, such as Gräf et al. [11]. The findings presented in Figures 11–15 and Table 5 show (1) thermal imaging as a successful method to detect drought stress in plants on green walls and green roofs and (2) temperature variations between plant species, (3) between levels of water-stressed plants compared to the reference plants, and (4) between green infrastructure typologies.

Figure 11 presents the thermography of three levels of water stress in plant types on the temporary wall and the industrial wall, while Figure 12 presents it on the roof decking. Table 5 reports the average temperature differences with reference plants for each GI structure. Figures 13–15 present the thermal images and marked temperature reading spots on the industrial wall (Figure 13), the temporary wall (Figure 14), and green roof decking (Figure 15). The temperature differences between *Hedera* on the green wall (19.6–23.1 °C) and green roof (30.1–38.2 °C) can be explained as vertical structures receiving less direct sunlight compared to horizontal structures.

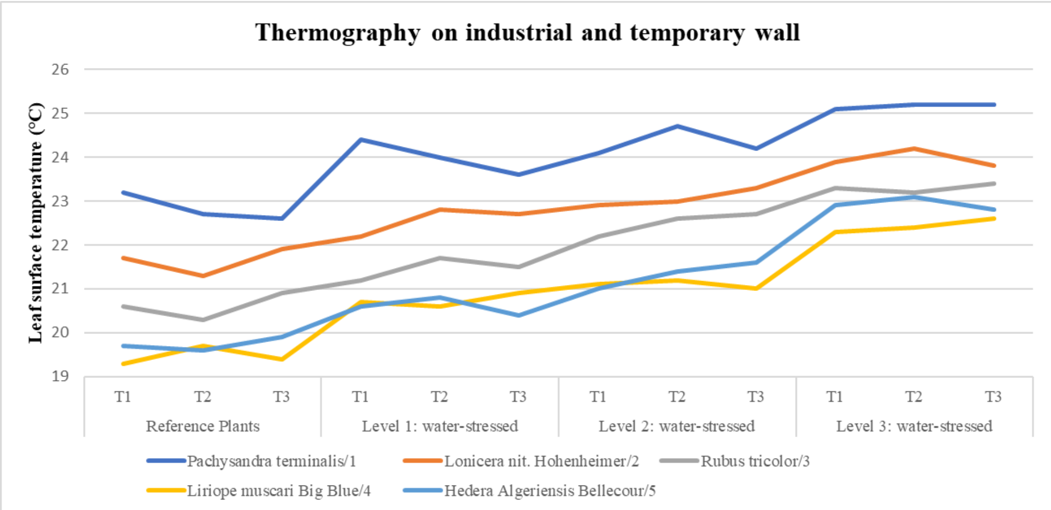


Figure 11. Thermography of three levels of water stress in five plant types on the temporary wall (1–3) and the industrial wall (4–5). Leaf surface temperatures were measured in °C.

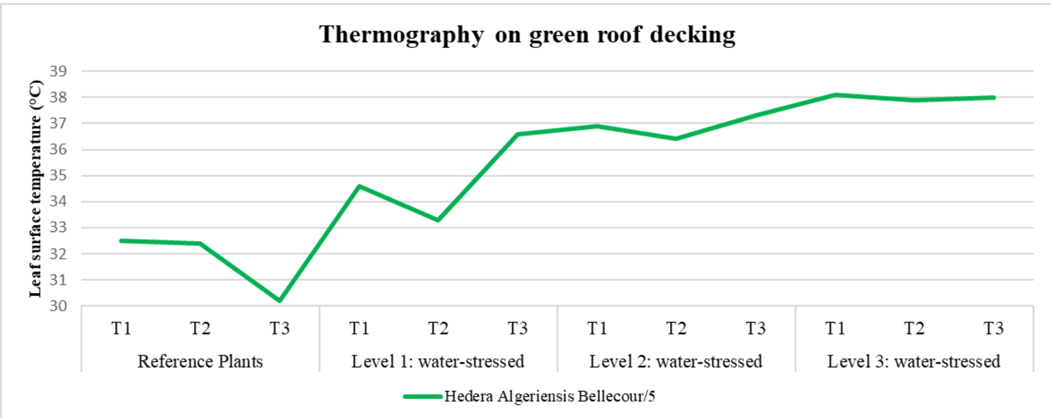


Figure 12. Thermography of three levels of water stress in *Hedera* on green roof decking. Leaf surface temperatures were measured in °C.

The findings in Figure 11 revealed leaf surface temperature differences between plant species, meaning that each plant species has a different tolerance to water stress. On the temporary wall, *Pachysandra* and *Lonicera* reported similar temperature increase in water-stressed plants compared to references plants (+2.34 °C) in comparison to *Rubus* (+2.7 °C). On the industrial wall, *Liriope* measured at +2.96 °C and *Hedera* at +3.2 °C in comparison to the reference plants. For the results of the green roof decking, presented in Figure 12, only *Hedera* was considered for comparison with water-stressed plants due to its location outside of the shadow from the other reference plants. The shade could potentially influence the results for the other plant species and were, therefore, not included in the analysis. A 6.3 °C average temperature increase was measured for *Hedera* between the reference plants and water-stressed plants.

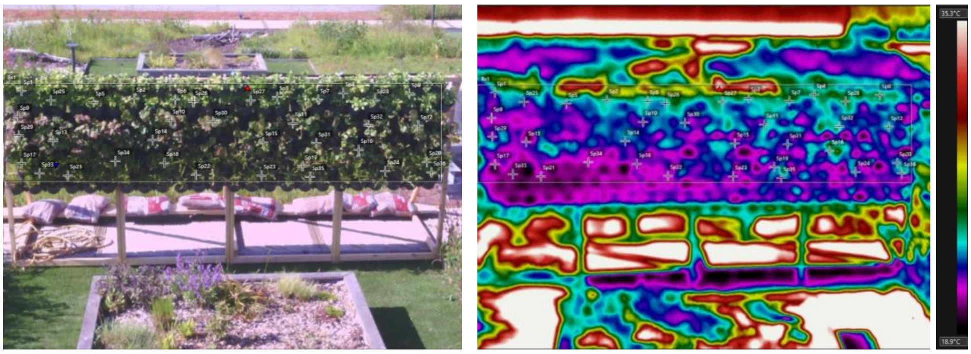


Figure 13. The temporary wall thermal image and marked temperature reading spots.

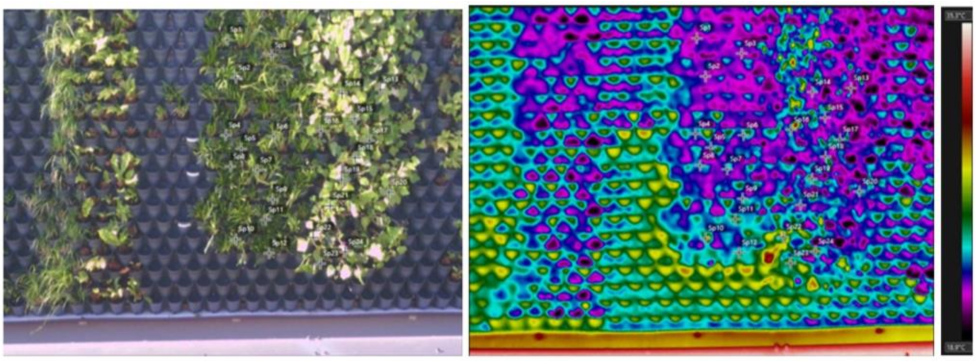


Figure 14. The industrial wall thermal image and marked temperature reading spots.

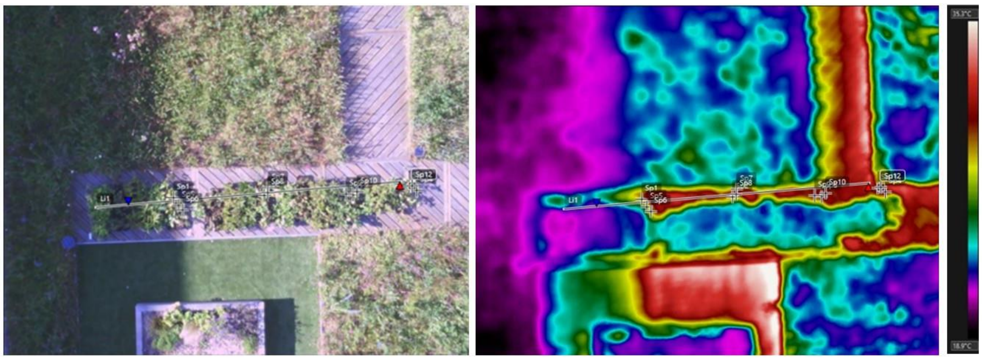


Figure 15. The green roof thermal image and marked temperature reading spots.

Table 5. Delta T between different level of water stress with the reference plants on the temporary wall, industrial wall, and the roof in °C.

	Plant Type	Temperature Difference between Reference and L1–3 Water-Stressed Plants		
		DT L1	DT L2	DT L3
Temporary wall	1	1.17	1.50	2.33
	2	0.93	1.43	2.33
	3	0.87	1.90	2.70
Industrial wall	4	1.26	1.63	2.96
	5	0.87	1.60	3.20
Green roof decking	5	3.10	5.20	6.30

The findings presented in Table 5 show that the average leaf surface temperature differences on the industrial wall are in a similar range to the plants on the temporary wall. The leaf surface temperature differences between levels of water stress and between reference plants and water-stressed plants are minimal. This can be explained due to a fault in the smart irrigation system, resulting in plants being over-watered and very wet plant soils. As a result, the water-stressed plans were taken inside to induce water stress, but the plants did not have enough time to lose much of their soil moisture on the day of thermal imaging. Despite this limitation, leaf surface temperature differences were still detectable.

4. Discussion

The study provides valuable insights into the thermal variations observed under different water availability levels in green wall and green roof plant species using leaf surface temperature measurements. To the best of the authors' knowledge, this study is the first to detect drought stress on multiple green infrastructure systems in an uncontrolled, real-time setting exposed to varying weather conditions. The findings, derived from an uncontrolled, real-time environment, align with those of previous studies conducted in controlled settings, validating the methodology and the reliability of the results [11]. Further research could explore other plant physiological responses to water stress, such as stomatal conductivity and chlorophyll content in leaves [11–14]. Studies such as Gräf et al. [11] were carried out in a greenhouse environment where light and water conditions were controlled and thus report a significant difference between well-watered and water-stressed plants. Furthermore, the findings also contribute to our understanding of how weather conditions and shade can have a notable impact on the recorded temperatures of plants, especially in the context of water stress. While the formal experiment was carried out under favorable weather conditions that did not affect our research outcomes, it is important to acknowledge that real-world situations may not always be as accommodating. Unfavorable weather conditions in humidity, wind, and rain could alter the leaf surface temperature differences through convective cooling and wind chill effect [43]. During periods of high temperatures and intense sunlight, plants may experience elevated leaf surface temperatures due to increased solar radiation and heat [34,54]. Conversely, shaded areas and cooler weather conditions can contribute to lower leaf surface temperatures by reducing the direct impact of solar radiation and providing a cooler microclimate for the plants. In the presence of water scarcity and climate change, the interaction between weather conditions, shade, and plant temperatures becomes even more critical [55]. By examining the impact of weather conditions and shade on observed plant temperatures, researchers can gain insights into the varying degrees of thermal stress experienced by plants in different microclimates.

Thermal imaging with drones has proven to be a successful method for detecting drought stress in plants on green walls and green roofs, showcasing their potential even in high or difficult-to-access urban roof tops. The thermal images reveal temperature variations of around 3 °C between green walls and non-vegetated walls, and approximately 13 °C between green roofs and non-vegetated roofs [20,56]. This underscores the effectiveness of green roofs in reducing heat absorption. The presence of vegetation facilitates a cooling mechanism, primarily through evapotranspiration, which helps regulate temperatures. While the smaller temperature differences between green walls and non-vegetated walls were expected, as vertical surfaces receive less direct sunlight compared to horizontal roofs [39,57,58]. The modest temperature difference still demonstrates the positive impact of green walls in mitigating the urban heat island effect and improving quality of life. This emphasizes the value of green infrastructure in urban environments.

Plant species display a wide range of responses to water scarcity and these variations in leaf surface temperature provide insights into their adaptive strategies [28,33]. This research will contribute to a better understanding of plant–water interactions and facilitate the development of sustainable vegetation management practices in water-limited conditions. The plant species *Pachysandra terminalis*, *Lonicera nit.* Hohenheimer, and *Rubus tricolor* maintained lower leaf surface temperatures even under water conditions, indicating a greater resilience to water scarcity. This capability may be linked to characteristics such as efficient water-use strategies, changes in leaf structure, or enhanced osmotic regulation [59,60]. These physiological and morphological adaptations contribute significantly to the plant's ability to thrive in water-limited environments. Conversely, *Liriope muscari* Big Blue and *Hedera algeriensis* Belleceour exhibited higher leaf surface temperatures when facing water stress. This increase in temperature may result from reduced transpiration due to stomatal closure, leading to heat accumulation on the leaf surface [11]. Understanding the differences in the leaf surface temperature responses of various plant species is essential for identifying water-tolerant varieties and implementing appropriate plant selection for green walls and green roofs. It is important to note that leaf surface temperatures alone may not provide a comprehensive understanding of plant's responses to water stress. Future research should consider including additional physiological parameters such as stomatal conductance and osmotic adjustments to obtain a more holistic understanding of plant responses to water stress [61,62].

Limitations and Future Work

The experiment encountered two limitations that must be addressed in future research. First, a fault in the smart irrigation system on the industrial wall led to smaller-than-expected differences in soil moisture between water stress levels, resulting in overwatering and very wet plant soils. However, differences in average moisture levels were still observed, as shown in Table 3. Second, the timing of the thermal imaging experiment in the late afternoon caused shading from the parapet, leading to a decrease in temperature for the reference plants. Future research should position the plants more towards the center of the roof to mitigate the presence of shade.

Further research could (1) explore the effectiveness of various UGI maintenance techniques such as irrigation methods and substrate composition; (2) use thermal imaging technology and integrate thermal imaging with remote sensing for UGI monitoring; (3) use other plant species with various plant morphologies.

5. Conclusions

This study revealed the significance of detecting early stage drought stress for managing the longevity and sustainability of UGI in cities. Climate change intensifies the challenges cities face, with rising temperatures, altered precipitation patterns, and more frequent droughts threatening the capacity of green roofs and walls to improve urban living conditions. As cities expand, green roofs and walls are critical for mitigating the urban heat island effect in dense urban areas. However, drought stress can undermine this cooling ability with stressed or dying vegetation reducing the potential of green roofs and walls. Thermography analysis has provided valuable insights into the thermal responses of green wall and green roof plants under varying levels of water stress. Using innovative methods like thermographic imaging to detect early drought stress can be vital for urban planners and building managers. This can help them better prepare their UGIs for climate extremes ahead by optimizing water use and choose more drought-resistant plant species. Future research on imaging and monitoring technologies could focus on incorporating machine learning and AI for the real-time analysis of thermographic data. This would enable the predictive modeling of drought stress impacts and support the development of better maintenance strategies.

The findings inform the creation of targeted strategies for managing and mitigating water stress in urban plant ecosystems, contributing to the advancement of sustainable plant cultivation practices in varied environmental conditions. Future research could focus on investigating a wider variety of plant species and mixes, such as succulents, native grasses, or climate-adapted species, to assess which vegetation types show the best thermographic performance under the varying levels of drought stress. Additional research directions could include exploring the effectiveness of water management techniques, like rainwater harvesting and greywater reuse, in supporting vegetation under varying climate conditions. Expanding the research to multiple climate zones beyond Salford and similar temperate regions could also provide valuable insights into how vegetation on green roofs and walls performs thermally under drought stress in hot, arid, or tropical climates. Integrating resilient vegetation and smart water management systems will be essential to ensure the long-term success of green infrastructure in the face of climate change.

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