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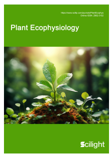

Article

Supplementary Material: Assessment of Plant Responses to Simulated Combination of Heat Wave and Drought

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Supplementary Material S1

Technology

- **Control system**

It is based on an SBC (Single Board Computer) Raspberry Pi Compute Module 4, with a quad-core Cortex-A72 processor at 1.5 GHz, embedded on a Raspberry Pi Compute Module 4 IO (Input/Output) Board. Leveraging its SoM (System on Module) board design, a carrier was designed that included several communication buses: one Modbus RTU (Remote Terminal Unit) bus unit, two 1-Wire bus units, one CAN (Controller Area Network) bus unit, eight digital outputs at 12 V, and eleven GPIO (General Purpose Input/Output) pins.

- **Power switch**

The power switch is based on a solid-state contactor capable of switching a maximum of 25 A on the output, allowing control of up to two heaters of those described in the corresponding section. It has an input connected to the control system that receives a bistable switching command of 0/12 V, with user-programmable hysteresis in the range of 0.25 °C to 2 °C. It also features two type F (commonly known as Schuko) socket outlets according to the CEE 7/4 standard, each protected by a 16 A fuse, where the infrared radiators are connected. Finally, it has a 230 V AC (Alternating Current) power input. It has an IP66 rating (Ingress Protection, as defined by the IEC 60529 standard), which ensures protection against the ingress of foreign objects and allows continuous operation under rainy conditions.

Moreover, although the use of an on/off control presents lower accuracy compared to proportional controls regarding the generated temperature, due to the inherent hysteresis of this type of control and the thermal inertia of the heaters (which continue to emit even after being turned off), the plant is immersed in a thermal environment similar to that during a natural heat wave, as indicated by the curves obtained in each experiment.

- **Infrared heaters**

To effectively reduce cost, widely distributed commercial heaters in Europe (Tristar KA5287, Orbegozo PHF31, Tresko THSL004, Liliana CIPIE2000, and TroniTechnik TT-TH2020), priced between €50 and €100 (all the prices indicated refer to the time of writing the manuscript) were used. These devices are infrared heaters made of metal and plastic, designed with a circular support base 50 cm in diameter, facilitating placement around the plants under study. Their height is adjustable, ranging from 130 cm to 210 cm, and inclination can be adjusted from 0° to −45°. Each heater has a polished aluminium reflector with a 120°

dispersion angle, on which three tubular IR emitters, 10 mm in diameter and 358 mm in length, made of opaque quartz, are mounted. Inside each emitter, there is a 328 mm nickel-chrome resistance with a power of 650 W, capable of reaching surface temperatures of up to 1254 K with a radiation peak at a wavelength (λ) of 2.3 µm, located in the mid-infrared (MIR) range. The assembly of the reflector and tubes is housed in a flattened prolate spheroid-shaped casing measuring 498 × 252 × 68 mm. They have a safety system that only allows operation in a horizontal position with a maximum inclination of −45°. Additionally, they include a mechanism that allows activating one, two, or all three emitters simultaneously, offering power levels of 650 W, 1300 W, and 1950 W. The device is manufactured with an IPX4 protection rating against the ingress of foreign objects and water, meaning it can withstand splashes from any direction. This makes it suitable for simulating heat waves under real field conditions, except during periods of heavy rain and/or strong winds. The device weighs 8.45 kg.

- **Temperature sensors**

Negative temperature coefficient (NTC) resistors were used due to their price/robustness and precision ratio (around €15). Their operating temperature ranges from −30 °C to +105 °C, and they can work in humidity ranges of 5% to 95%. They have an IP67 protection rating against the ingress of foreign objects and water. The resistance value at 25 °C is 10 kΩ, and the beta value is 3435 K. The accuracy at 25 °C is ± 0.5 °C. Their weight, including 0.4 m of cable, is 4 g. The casing material is black epoxy resin, and the cable is also black. Their dimensions are 3 mm in diameter and 10 mm in length.

Supplementary Material S2

The present experiments were carried out by heating small plots using the infrared heaters (IH). These were used to replicate extreme climatic conditions. IH were strategically placed to uniformly cover the treatment plot, adjusting their intensity and emission angle (inclination) to reach specific air temperatures that mimic heat wave events. Temperature regulation was controlled by a Raspberry Pi microcomputer, which, with the help of temperature sensors placed in the control and treatment plots, adjusted the temperature variably depending on the time of day (Figure S2.1).

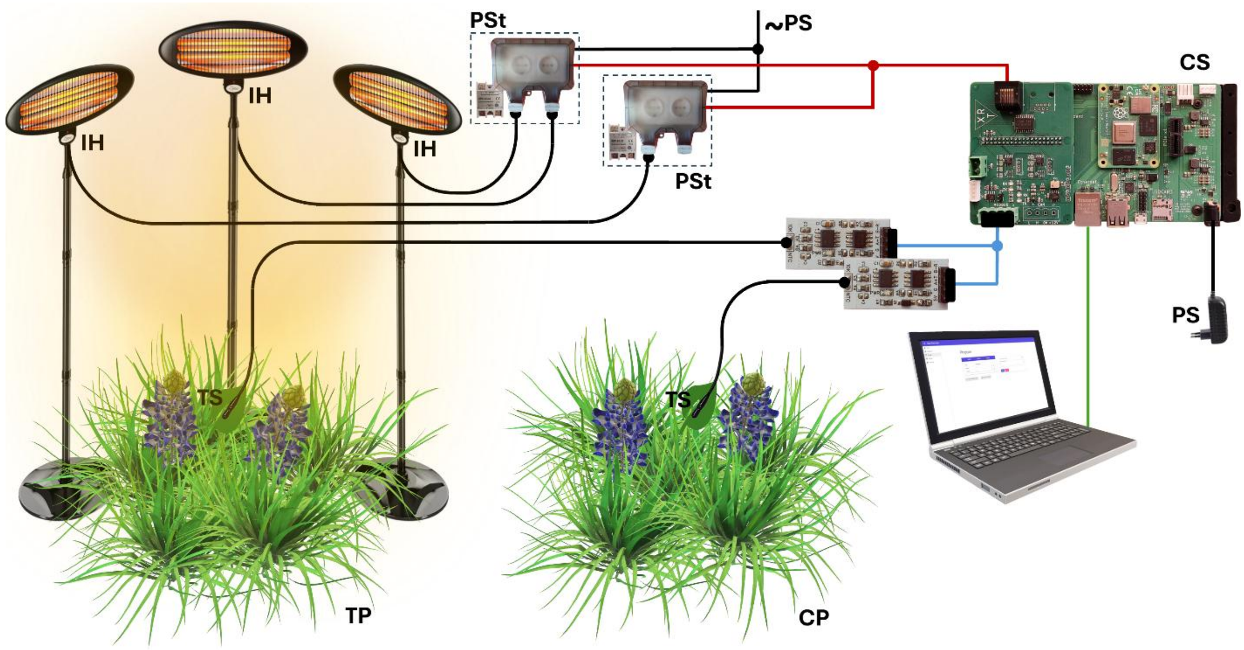

Figure S2.1. Block diagram illustrating a typical heat wave experiment. A Temperature Sensor (TS) located in the Control Plot (CP) sends temperature data to the Control System (CS), which calculates the target temperature for the Treatment Plot (TP) based on the time of day and on the table of thermal increments. Using this temperature data, the Control System (CS) adjusts the Power Switch (PSt), which controls the Infrared Heaters (IH) to heat the Treatment Plot (TP). This process is executed at a programmable frequency. The Power Supply (PS) provides the necessary power for the system.

Supplementary Material S3

Why heat wave simulations should be based on air and not leaf temperature? models and examples based on simulated leaves

The equation governing the thermal balance of an isolated leaf (Campbell and Norman, 1998; Monteith and Unsworth, 2013; Nobel, 2020) can be expressed as:

$$Rn - Q_L - Q_C - Q_{\lambda E} = M + S$$

where:

- Rn is the net incident radiation flux, representing the amount of radiant energy received by the leaf.
- Q_L is the longwave radiation emitted by the leaf to the environment.
- Q_C is the sensible heat flux, corresponding to heat exchange through convection or conduction.
- $Q_{\lambda E}$ is the latent heat flux, associated with energy loss through evapotranspiration. λ is the latent heat of vaporization, and E is the water vapor flux.
- M is the net heat storage in biochemical reactions, including energy generated or absorbed by metabolic processes such as photosynthesis or respiration.
- S is the physical heat storage, corresponding to temperature changes in the leaf. An increase or decrease in temperature results in energy accumulation or loss in the system.

The term Rn can be broken down into the terms $Q_{IR} + Q_{SW} + Q_{LW}$

where:

- Q_{IR} is the radiant energy emitted by the heaters that strikes the leaf.
- Q_{SW} is the shortwave radiant energy emitted by the sun that strikes the leaf.
- Q_{LW} is the longwave radiant energy emitted by the environment that strikes the leaf.

The development of each of these terms leads to the following energy balance equation:

$$M + S = 6\eta \frac{P_{IR}}{2\pi A_l \left(1 - cos\left(\alpha/_2\right)\right) x^2} \varepsilon_{IR}\, \alpha_{IR}\, A_l + \varepsilon_S\, I_{SW}\, A_l\, \alpha_{SW} + \varepsilon_a\, \sigma\, A_l\, \alpha_{LW}\, T_a^4$$
$$- 2\, \varepsilon_l\, \sigma\, A_l\, T_l^4 - 2\, A_l \frac{k(T_l - T_a)}{\delta^{bl}} - A_l\, \lambda\, \frac{g_w(e_{sl} - e_a)}{P_a}$$

where:

- 6 is because there were 6 heaters around the leaf.
- η is the efficiency of the heaters.
- x is the distance from the heater to the leaf.
- A_l is the leaf area.
- P_{IR} is the power of the heater.
- α_{IR} is the absorptance of the leaf for IR radiation emitted by the heater.
- ε_{IR} is the heater emissivity. Given that the heaters have a reflector that modifies the radiation, emitting it at a certain dispersion angle α, the radiation is modified according to the solid angle $\Omega = 2\pi(1 - \cos(\alpha/2))$.
- I_{SW} is the shortwave solar irradiance.
- α_{SW} is the leaf's absorptance for shortwave radiation from the sun. Another way to express the leaf's absorptance, especially in the case of a plant canopy, is by using the albedo or reflection of the vegetation cover, $\alpha_{SW} = (1 - \alpha)$.
- α is the albedo.
- ε_S is the sun emissivity (approximately 0.99).
- σ is the Stefan-Boltzmann constant (5.67×10^{-8} W·m^{-2}·K^{-4}).
- α_{LW} is the leaf's absorptance for longwave radiation.
- T_a is the air temperature.
- ε_a is the atmospheric emissivity.
- T_l is the leaf temperature.
- ε_l is the leaf emissivity.
- k is the thermal air conductivity (0.026 W·m^{-1}·K^{-1} at 25 °C)
- λ is the latent heat of vaporization of water (2.45×10^6 J·kg^{-1}).
- g_w is the stomatal conductance to water vapor.
- e_{sl} is the saturated water vapor pressure inside the leaf.
- e_a is the water vapor pressure in the surrounding air.
- P_a is the atmospheric pressure.
- δ^{bl} is the boundary layer thickness.

Considering a practical simplification applied to plant leaves, derived from the relationships developed from dimensionless numbers such as the Nusselt number and others related, such as the Reynolds number and the Grashof number, the boundary layer thickness δ^{bl} for a flat leaf can be calculated as:

$$\delta^{bl}(\mathrm{mm}) = 4.0 \times 10^{-3} \sqrt{\frac{l\ (\mathrm{m})}{v\ (\mathrm{m/s})}}$$

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where l is the average length of the leaf in the wind direction and v is the wind speed.

Since photosynthesis generally represents less than 5% of Rn, and nighttime respiration causes a slight energy loss, the term M can be considered negligible compared to the other energy fluxes and can thus be eliminated. Likewise, since artificial leaves do not have transpiration, the term $Q_{\lambda E}$ can also be omitted. In this context, the radiation from IR heaters adds to the solar radiation, allowing the model to be simplified by treating the total irradiance as augmented solar irradiance. Under these as sumptions, the thermal balance equation simplifies to:

$$S = \varepsilon_S \, I_{SW} \, A_l \, \alpha_{SW} + \varepsilon_a \, \sigma \, A_l \, \alpha_{LW} \, T_a^4 - 2 \, \varepsilon_l \, \sigma \, A_l \, T_l^4 - 2 \, A_l \frac{k(T_l - T_a)}{\delta^{bl}}$$

Assuming that the simulated leaves are in thermal equilibrium (i.e., $S = 0$), the equation can be solved to study the leaf temperature T_l, focusing on how it varies as a function of leaf length, wind speed, and net radiation incident on the leaf:

$$\varepsilon_l \, \sigma \, T_l^4 + \frac{kT_l}{4{,}0 \times 10^{-3}\sqrt{\frac{l}{v}}} = \frac{1}{2}\left(\varepsilon_S \, I_{SW} \, \alpha_{SW} + \varepsilon_a \, \sigma \, \alpha_{LW} \, T_a^4 + 2 \, \frac{kT_a}{4{,}0 \times 10^{-3}\sqrt{\frac{l}{v}}}\right)$$

Evaluating the equation for different wind speeds (0.5, 1, 2, 4, 6, 8, 10, 15, and 20 m/s), leaf lengths (0.02, 0.04, 0.08, 0 .16, and 0.32 m), and two solar irradiance values (500 and 1000 W/m^2), with the leaf's absorptance for shortwave radiation from the sun (α_{SW}) as 0.8; solar emissivity (ε_S) as 1; Stefan-Boltzmann constant (σ) as 5.67 × 10^{-8} W·m^{-2}·K^{-4}; leaf's absorptance for longwave radiation (α_{LW}) as 0.96; atmospheric emissivity (ε_a) as 0.79; leaf emissivity (ε_l) as 0.96; and thermal conductivity of air (k) as 0.026 W·m^{-1}·K^{-1} at 25 °C, yields lines such as those shown in Figure S3.1. The slopes of this lines vary slightly with leaf size and wind speed, as summarized in Table S3.1.

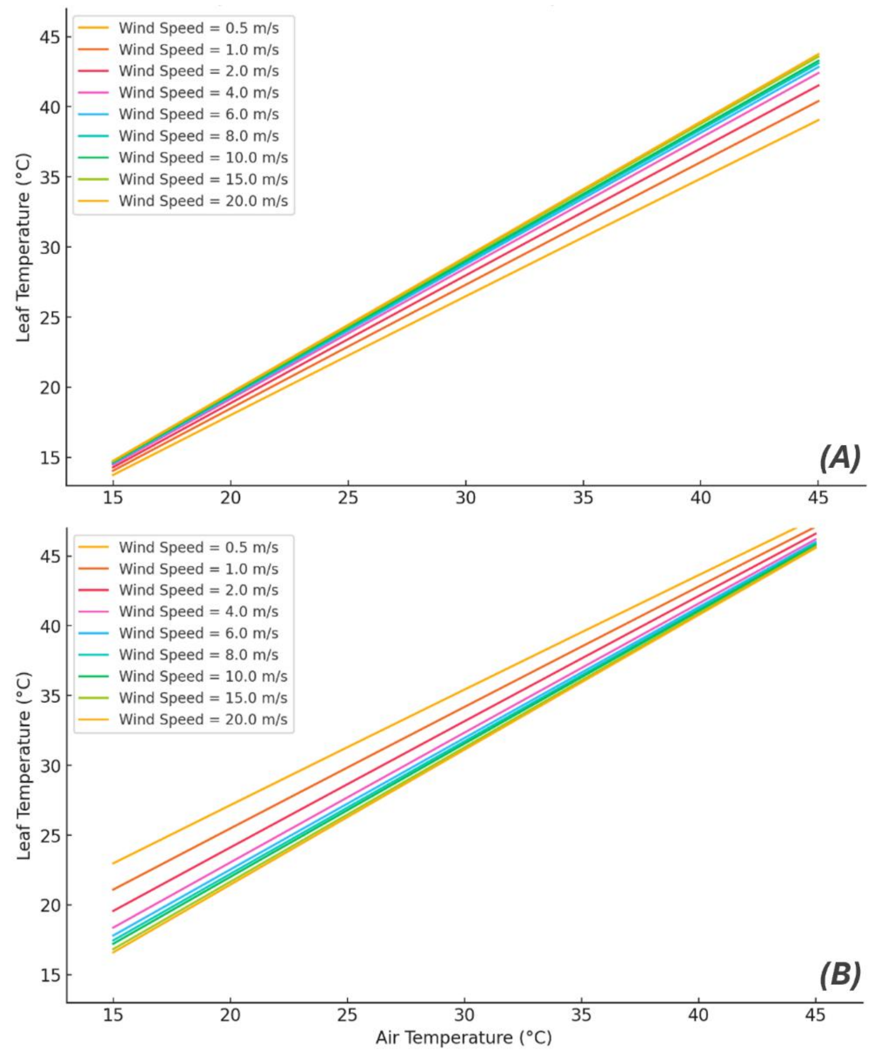

Figure S3.1. Temperature of an isolated leaf as a function of air temperature for various wind speeds. Behaviour of the temperature of an isolated leaf with a characteristic length of 0.08 m in response to wind speed for an irradiance of 500 W/m^2 (Figure 1A) and 1000 W/m^2 (Figure 1B).

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Table S3.1 shows the slopes obtained for each of the examined graphs, allowing a refinement of the response of the leaves to temperature changes. The application of the slopes obtained to control the temperature of the heated plot versus the reference plot allows us to determine the expected leaf temperature according to the following relationship:

$$T_{lHW} \simeq T_{lR} + m\,\Delta T_a$$

where:

- T_{lHW} is the simulated leaf temperature in the treated (heated) plot.
- T_{lR} is the simulated leaf temperature in the reference plot.
- m is the slope of the curve that characterizes the simulated leaf temperature as a function of air temperature, leaf size, and wind speed.
- ΔT_a is the desired air temperature increment in the heated plot relative to the reference plot.

Table S3.1. Characteristic slope *m* of leaf temperature *vs* air temperature. Table of variations in the slope *m* according to experimental conditions, particularly according to wind speed and the characteristic leaf length, including variations in solar irradiance. Colours represent data blocks that result from similar slopes, whose arithmetic mean and standard deviation have been represented in Table S3.2 with the same colour.

		Characteristic Leaf Length (CLL) (m)/Solar Irradiance (I_{SW}) ($W \cdot m^{-2}$)													
Wind speed		**0.64**		**0.32**		**0.16**		**0.08**		**0.04**		**0.02**		**0.01**	
$m \cdot s^{-1}$	**$Km \cdot h^{-1}$**	**500**	**1000**	**500**	**1000**	**500**	**1000**	**500**	**1000**	**500**	**1000**	**500**	**1000**	**500**	**1000**
0.5	**1.8**	0.71	0.65	0.76	0.72	0.80	0.77	0.84	0.82	0.88	0.87	0.91	0.90	0.93	0.93
1	**3.6**	0.76	0.72	0.80	0.77	0.84	0.82	0.88	0.87	0.91	0.90	0.93	0.93	0.95	0.95
2	**7.2**	0.80	0.77	0.84	0.82	0.88	0.87	0.91	0.90	0.93	0.93	0.95	0.95	0.96	0.96
4	**14.4**	0.84	0.82	0.88	0.87	0.91	0.90	0.93	0.93	0.95	0.95	0.96	0.96	0.97	0.97
6	**21.6**	0.86	0.85	0.9	0.89	0.92	0.92	0.94	0.94	0.96	0.96	0.97	0.97	0.98	0.98
8	**28.8**	0.88	0.87	0.91	0.90	0.93	0.93	0.95	0.95	0.96	0.96	0.97	0.97	0.98	0.98
10	**36**	0.89	0.88	0.92	0.91	0.94	0.93	0.95	0.95	0.97	0.97	0.98	0.98	0.98	0.98
15	**54**	0.91	0.90	0.93	0.92	0.95	0.95	0.96	0.96	0.97	0.97	0.98	0.98	0.99	0.99
20	**72**	0.92	0.91	0.94	0.93	0.95	0.95	0.97	0.97	0.98	0.98	0.98	0.98	0.99	0.99

Thus, for a programmed increase of n °C in air temperature, the difference to be measured in the simulated leaf temperature in the heated plot should be:

$$T_{lHW} \simeq T_{lR} + m \times n$$

where:

T_{lHW} is the simulated leaf temperature in the treated (heated) plot.

T_{lR} is the simulated leaf temperature in the reference plot.

m is the slope of the curve that characterizes the simulated leaf temperature as a function of air temperature, leaf size, and wind speed.

The slope m varies according to the experimental conditions, particularly with wind speed and the characteristic leaf length. Although individual slopes obtained for each characteristic length and wind speed could be used for greater accuracy, this would require exhaustive control over the parameters in the experimental plots. To avoid this complexity and allow for leaves of different sizes in the same experiment, the results are summarized in Table S3.2, which provides a slope valid for a wide range of conditions without a significant risk of errors.

Table S3.2. Characteristic slope of leaf temperature vs. air temperature. Summary table of variations in the slope m according to experimental conditions, particularly according to wind speed and the characteristic leaf length, including variations in solar irradiance. Data are means ± standard deviation. Colours represent data blocks that result from similar slopes (See table S3.1 for details).

Wind Speed ($m \cdot s^{-1}$)	**Characteristic Leaf Length (m)**	***m***
0.5–4	0.01–0.16	0.908 ± 0.049
6–20	0.01–0.16	0.969 ± 0.019
0.5–6	0.32–0.64	0.760 ± 0.068
8–20	0.32–0.64	0.908 ± 0.020

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Supplementary Material S4

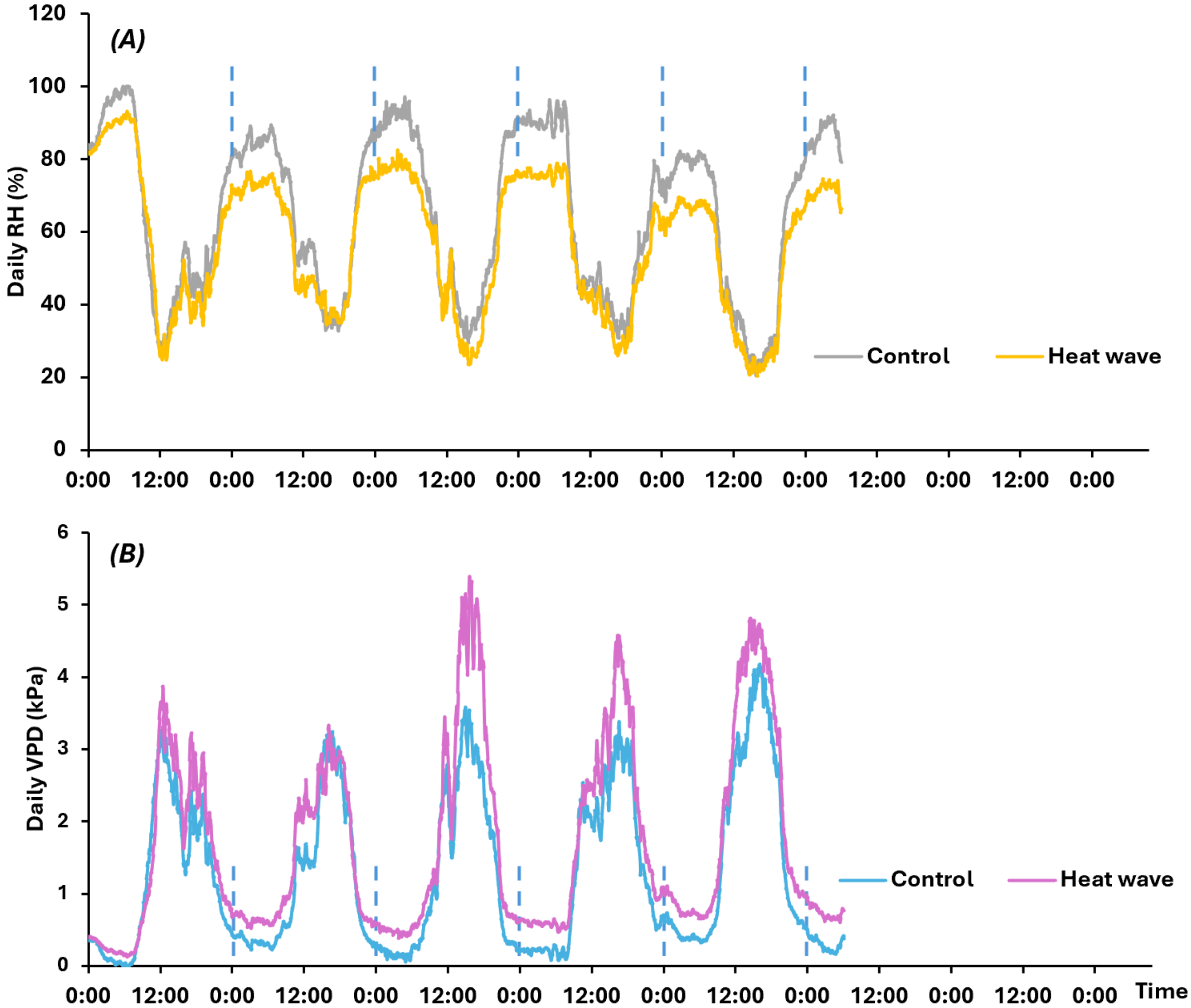

Figure S4.1. Daily of Relative Humidity (RH) and vapor pressure deficit (VPD) courses during experiment 2. Figure S4.1 **A**, illustrates daily RH courses, and Figure S4.1 **B** illustrates daily VPD courses.