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Cooling Effects of a Modular Living Wall System in a Humid Subtropical Climate

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ABSTRACT

Living wall systems can generate multiple human health and environmental benefits. Living wall modules have typically been made from materials such as geotextiles, plastics, and metal. In this pilot study, sheet metal by-products from the automotive industry were transformed into three hundred modular living wall system (MLWS) planters. The cooling effects of four of the twenty-five plant species installed on the southeast facing MLWS were observed during the summer season for microclimate observations. Experimental data were observed at the MLWS and an adjacent concrete wall as a control measure at 8:00, 11:00, 13:00, and 15:00 respectively for 5 days in the month of July. One-way Analysis of Variance tests were conducted to investigate significant differences between experimental parameters of the MLWS and the concrete wall including ambient air temperature, surface temperature, relative humidity, and substrate temperature. Mean ambient air temperatures were 3.4 °C cooler at *Coreopsis lanceolata* 'Sterntaler' compared to the mean ambient air temperatures at the concrete wall. The maximum differential in ambient air temperature was 4.6 °C at 15:00 for *C. lanceolata* 'Sterntaler' and the nearby weather station. The greatest differential in surface temperature was 9.78 °C at the background brick wall which is shaded by the MLWS, compared to the adjacent concrete wall at 11:00 and 13:00 hours. These findings confirm the vegetation's cooling effects on the MLWS compared to typical brick and concrete walls in humid subtropical climates.

Keywords: *microclimates; vegetation; field measurement; vertical greenery system; modular living wall*

INTRODUCTION

There has been an increased interest in façade and vertical greening for sustainable building design, beautification, and ecosystem services (Radić et al., 2019). Green facades consist of climbing or hanging plants growing along the wall covering it directly while living walls use lightweight and permeable screens in which plants are inserted to the system individually (Manso and Castro-Gomes, 2015).

Living walls are a component of urban green infrastructure, and therefore contribute to many ecosystem services (Wolf, 2012). These services include providing habitat for urban biodiversity (Francis and Lorimer, 2011), screening out aerial particulate matter and improving air quality (Köhler, 2008), attenuating noise (Ismail, 2013; Wong et al., 2010), enhancing psychological well-being (Van Herzele and De Vries, 2012), improving the aesthetics of the cityscape (White and Gatersleben, 2011), and reducing ambient air temperatures adjacent to living walls (Tudiwer et al., 2019; Zhang et al., 2019). Living walls also have the potential to reduce urban air temperatures, mitigating urban heat island effects, lowering surface temperatures of buildings, and reducing reliance on mechanized air conditioning (Susorova et al., 2013). Air cavities between living walls and building walls can act as a thermal insulation layer to mitigate heat gains and losses (Perini and Rosasco, 2016). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook of Fundamentals emphasizes that airspaces behind typical cladding materials and installations are not considered airtight, R-values for such airspaces must be determined by an appropriate test methodology representative of the conditions of use (A.S.H.R.A.E., 2013).

Living wall systems in China were shown to reduce exterior wall temperatures by a maximum of 20.8° C. The air layers between the wall and vegetation were on average 3.1 °C cooler than ambient air (Chen et al., 2013). Field studies are important and supply real-world findings to verify simulated thermal performance. Many studies have focused on the surface temperature of walls, investigating the maximum temperature differences between vegetated and non-vegetated surfaces with results of 11.6 °C in Singapore (Wong et al., 2010), 18 °C in Japan (Hoyano, 1988), 1.9 °C and 8.3 °C in Greece (Eumorfopoulou and Kontoleon, 2009), 15.2 °C in Spain (Pérez et al., 2011) and 12 °C to 20 °C in Italy (Mazzali et al., 2013).

In Japan, a study showed that the maximum surface temperature differences between vegetated and non-vegetated walls varied between plant species, with the cooling maximum recorded as 11.3 °C for *Ipomoea tricolor*, 7.9 °C for *Canavalia gladiata*, 6.6 °C for *Pueraria lobata*, 4.1 °C for *Momordica charantia* and 3.7 °C for *Apios americana*. However, some differences were explained by different percentages of canopy cover over the wall, rather than any other trait (Koyama et al., 2013). In humid subtropical Hong Kong during the daytime, a northeast green wall cooled the external surface by 3.5 °C on average (Lee and Jim, 2017).

Living wall planters have typically been made from materials including marine-grade thermoplastic, acrylonitrile butadiene styrene (ABS), and galvanized sheet metal. Several studies observed and tested living wall performances provided living laboratories for educational opportunities, and contributed to ongoing research on living wall systems (Briscoe and Bright 2019; Kio and Ali 2021). The maximum surface temperature differential (MSTD) between living walls fabricated with metal components and other materials in their surrounding environment has been investigated. Zhang et al., (2019) observed that *Pyrostegia venusta* plants grown in plastic-coated wire mesh had the highest temperature difference of 2.7 °C at 16:00. In addition, Wong et al., (2010) conducted a study of eight different vertical greening systems (VGS). Five out of the eight VGS were made with metal components.

The first system in Wong's 2010 study was a grid and MLWS with plant panels embedded within stainless steel mesh panels inserted into fitting frames. This grid and MLWS used small-sized plants including *Hemigraphis repanda*, a red-leaved plant species; and had an MSTD of 11.58 °C at 12:35. The second system was a modular panel with an inorganic substrate which employed a Parabienta system with a substrate (composite peat moss) as a substrate inlay. The peat moss panel was encased in a stainless-steel cage and hung onto supports lined with integrated irrigation. This system had an MSTD of 10.94 °C at 12:40. The third system consisted of framed mini planters with a horizontal interface and substrate and individual mini planters secured onto a stainless-steel frame. The vegetation included *Phyllanthus myrtifolius* with an MSTD of 6.85 °C at 12:45. The fourth living wall was a geotextile membrane system with plants incorporated within pockets secured onto a supporting grating or mesh; its MSTD was 7.13 °C at 13:50. Lastly, a plant cassette used planters to hold a wide variety of plant types and sizes. Plants were secured onto the wall through hinges and a lightweight substrate was used. The MSTD was 9.78 °C at 12:40.

In the presented study, the MLWS was constructed from industrial by-product galvanized sheet metal intended to activate a circular economy approach through industrial symbiosis. The modules were constructed from galvanized sheet metal cut-outs known as "Offal", sourced from the automotive industry. The modules were designed by a team of architecture and landscape architecture faculty and students and were pre-tested for temperatures in four seasons: winter, spring, summer, and fall (Kio and Ali, 2021). Findings presented significant surface temperature differences between the background shaded brick wall, exposed brick wall, and the adjacent concrete wall with similar orientations. However, the cooling effect of vegetation in the MLWS was not measured.

Literature suggests that there is a need for more studies on living walls based on buildings with planar vertical facades (Lee and Jim, 2017). Therefore, this pilot study investigated the cooling effect of four plant species during five summer days in a humid subtropical climate. Subsequent sections include materials and methods, results, discussion, and conclusion.

MATERIALS AND METHODS

The MLWS was fabricated from galvanized sheet metal modules and mounted on a steel frame affixed to a recessed area in front of a brick wall (Figure 1). It was installed on the Langford Building at Texas A&M University in College Station (30.6188° N, 96.3376° W) on a southeast facing wall adjacent to a courtyard and a nearby central weather station (WS) located on the rooftop of an opposite building (Figure 1). The overall dimension of the MLWS is 5.8 m in length by 4.3 m high. Three hundred diamond-shaped modules were supported by a steel frame. The MLWS is offset from the background brick wall creating a 30 cm air cavity.

Figure 1. Overall view of the modular living wall; (a) installed in front of the pre-existing brick wall (arrow). Adjacent concrete courtyard (b) and weather station location (c) on the opposite building; b and c in Google Earth image, camera: 172 m, 30°37’09” N 96°20’18” W 109 m. Access year: 2017.

Modules

Each module is 305 mm wide, 230 mm deep, and 455 mm high. The modules slope at an angle of 45 degrees to both vertical and horizontal which minimizes direct exposure of the metal surface to solar incident rays (Figures 2 and 3).

Vegetation and Irrigation

The vegetation used in this study included P1- *Coreopsis lanceolata* ‘Sterntaler’, P2- *Achillea millefolium*, P3 - *Liriope muscari*, and P4 - *Oenothera speciosa* (Figures 2 and 3). These pre-established plants were installed into the modules using Rooflite$^{©}$ 700 extensive substrate (Skyland USA LLC, Landenberg, PA), and a 3.1 mm thick nonwoven felt liner (Superior Felt and Filtration, McHenry, IL). Each module had an approximate substrate depth of 215 mm. Plants were irrigated by a multiple-emitter system. A drip irrigation system was installed to deliver potable water to each module through adjustable drip emitters. Each emitter was capable of delivering up to 3.7 lph maximum flow rate (Ali and Dvorak, 2019).

Figure 2. Image of the MLWS at noon, June 22, 2022. Locations of P1, P2, P3, P4, and CW are shown. Vegetation (P1- *C. lanceolata* 'Sterntaler', P2- *A. millefolium*, P3 - *L. muscari*, and P4 - *O. speciosa)* were selected for their moderate water needs, canopy cover, and leaf and floral interests.

Setup and Instrumentation

Environmental conditions were monitored at the MLWS, plants, adjacent concrete wall, and shaded brick wall at 1.2 m height and within 10 mm from the respective surfaces except the thermal images. Observed variables include ambient air temperature, relative humidity, solar radiation, and wind speed. Thermal images of the full MLWS were taken at a 6-meter distance in front of the MLWS while thermal images of the plants were taken at a 1.2-meter distance. Measurements were recorded at 8:00, 11:00, 13:00, and 15:00 and compared to data from the WS on the opposite building from July 9 to July 13 in 2022.

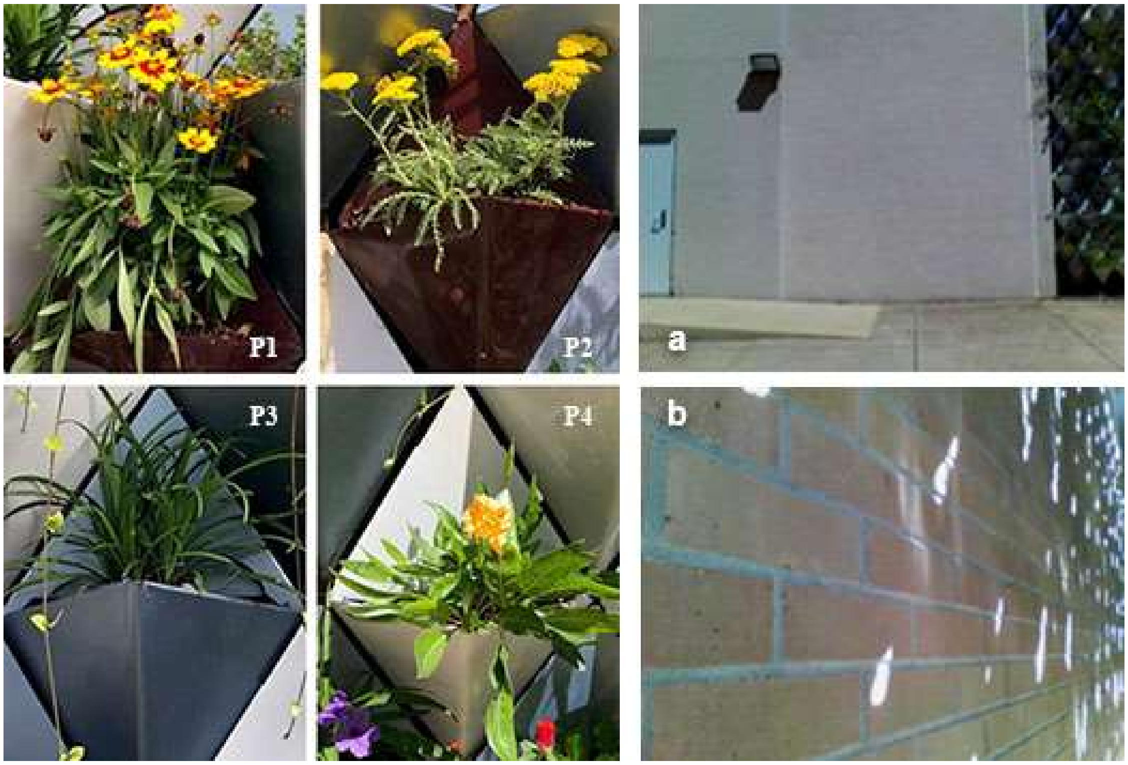


Figure 3. Images of the four modules and plant species P1- *C. lanceolata* 'Sterntaler', P2 - *A. millefolium*, P3 - *L. muscari*, and P4 - *O. speciosa*. Adjacent concrete wall a) measured in this study and b) 300 mm air cavity and background shaded brick wall.

Onsite measurements were carried out for five summer days (July 9, 2022 to July 13, 2022). Air temperatures were recorded at seven locations, namely the brick wall air cavity (AC), concrete wall (CW), plants (P1-P4), and the weather station (WS). Parameters included air temperature, substrate temperature, surface temperature, relative humidity, solar radiation, and wind speed (Table 1). Air temperatures were recorded at the four species P1-P4 located at a height of 1.2 m from the concrete floor. Air temperatures were measured with a Kestrel 5400 WBGT Heat Stress Tracker, and substrate temperatures were measured with a Wireless Leaf & Soil Moisture/Temperature Sensors manufactured by Davis Instruments. Data from the sensors are transmitted through the WeatherLink USB Data Logger to the Vantage Pro2 Wireless Console/Receiver for viewing, (Table 1).

Statistical Analysis

Data gathered from onsite measurements were analyzed for significant differences in microclimate parameters. This analysis is intended to provide direction for potential material choices, plant choices and designs of living wall systems. In the study, the cooling effect of four of the plant species in the MLWS were analyzed with the R programming software analyzing variance (ANOVA) and Tukey honest significant difference test. Data evaluated in the ANOVA tests included air temperatures, substrate temperatures, surface temperatures, relative humidity, solar radiation, and wind speed.

Table 1. Onsite measurement equipment list.

Instrument	Accuracy	Parameter	Manufacturer	Location
FLIR E6 thermal imaging camera	±2% between -20 °C to +250 °C (-4 to +482 °F)	Surface temperature	Teledyne FLIR	Wilsonville, OR, USA
Kestrel 5400 WBGT Heat Stress Tracker	Wind speed | air: larger of 3% of reading, least significant digit or 20ft/min speed: ambient temperature: accuracy: 0.9 °F or 0.5 °C; relative humidity: 2% RH	Ambient air temperature, wind speed, relative humidity	Nielsen-Kellerman Company	Boothwyn, PA, USA
TES 132 data logging solar power meter	: ±0.7dB, ref 94dB@1KHz	Solar radiation	TES Electrical Electronic Corp	Taipei, Taiwan, R.O.C.
Wireless Leaf & Soil Moisture/ Temperature Sensors	Temp range: -40 to +150°F (-40 to +65° C)	Substrate temperature	Davis Instruments	Hayward, California, USA
WeatherLink USB Data Logger		Substrate temperature	Davis Instruments	Hayward, California, USA
Vantage Pro2 Wireless Console/Receiver		Substrate temperature	Davis Instruments	Hayward, California, USA

RESULTS

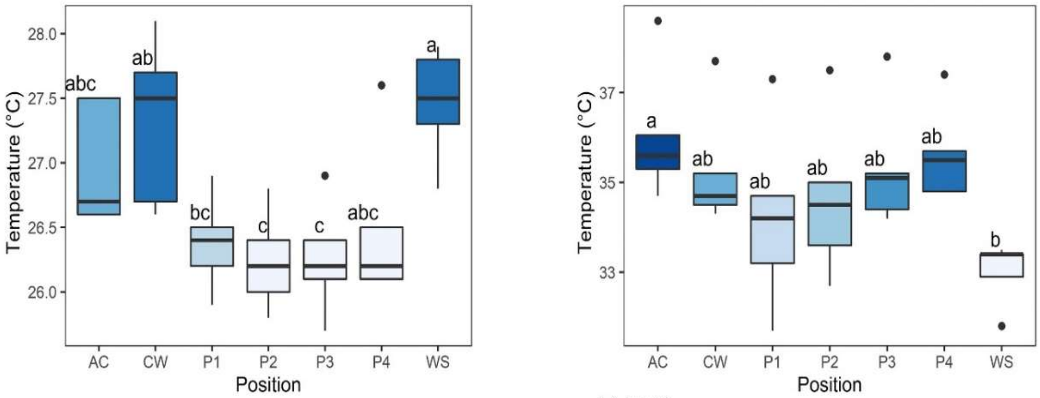
Ambient Air Temperatures

At 8:00, the mean ambient air temperatures demonstrated a differential of 1.3 °C (Table 2) observed between P2 - *A. millefolium* (26.2 °C) and the WS (27.5 °C). At 11:00, the ambient air temperature at the WS was 33.0 °C and was 3.1 °C cooler than the air cavity (36.1 °C) behind the MLWS. By 13:00, the minimum ambient air temperature was observed at P1 - *C. lanceolata* 'Sterntaler', which was 1.7 °C cooler than the air temperature in front of CW. Lastly, at 15:00, the maximum differential was 4.6 °C between P1 - *C. lanceolata* 'Sterntaler' and WS (Table 2).

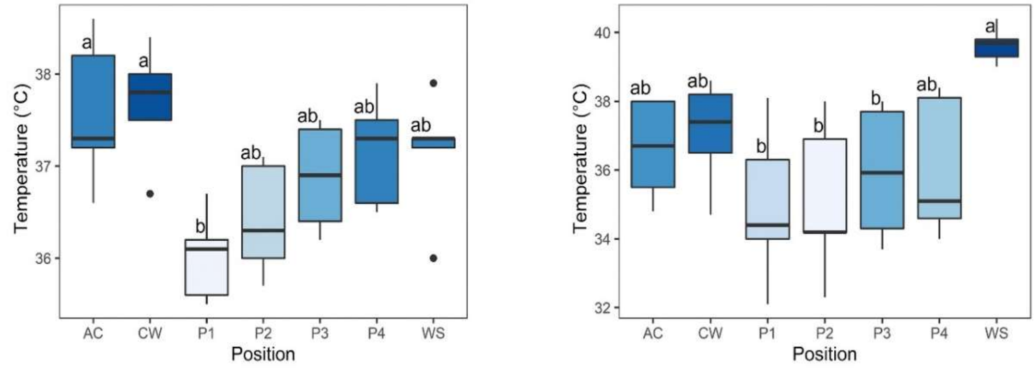
Table 2. Mean ambient air temperatures (° C) at AC, CW, P1, P2, P3, P4, and WS. The bolded numbers in parentheses show the difference between the bolded maximum.

Position	8:00 (°C)	11:00 (°C)	13:00 (°C)	15:00 (°C)
Air Cavity (AC)	27.0	**36.1 (0)**	37.6	36.6
Concrete wall (CW)	27.3	35.3	**37.7 (0)**	37.1
P1 – *C. lanceolata* 'Sterntaler'	26.4	34.2	**36.0 (-1.7)**	**35.0 (-4.6)**
P2 – *A. millefolium*	**26.2 (-1.3)**	34.7	36.4	35.1
P3 – *L. muscari*	26.3	35.3	36.9	35.9
P4 – *O. speciosa*	26.5	35.6	37.2	36.0
Weather station (WS)	**27.5 (0)**	**33.0 (-3.1)**	37.1	**39.6 (0)**

At 8:00 air temperatures had the greatest variance of 1.5 °C at the CW and a variance of 1.2 °C at P3 at 13:00. By 15:00 maximum variances of 4.3 °C and 4.4 °C were observed at P3 and P4. The analysis at different positions showed the significance of the results of pairwise comparison between the parameters recorded at the four different hours of observation. The least variance of 0.9 °C occurred in AC at 8:00. A pairwise comparison was conducted between the air temperatures that were recorded at the different hours of observation (Figure 4). At 8:00, there was a significant difference between mean air temperatures of 26.24 °C and 26.26 °C at P2 and P3 and 27.46 °C at the nearby weather station respectively. By 11:00 the mean air temperature of 36.05 °C in the AC was significantly different from the mean of 33 °C at the WS. At 13:00, the mean air temperature of 37.58 °C in the AC was significantly different from 36.02 °C at P1. Lastly, at 15:00, P1, P2, and P3 air temperatures of 34.98 °C, 35.12 ° C, 35.93 °C were significantly different from 39.64 °C at the WS.



a) 8:00 b) 11:00



c) 13:00 d) 15:00

Figure 4. Boxplots show significant differences between air temperatures at different positions at 8:00, 11:00, 13:00, and 15:00. (AC- air cavity; CW - concrete wall; P1 - *C. lanceolata* 'Sterntaler'; P2 – *A. millefolium*; P3 – *L. muscari*; P4 – *O. speciosa*; WS - weather station.) Using an alpha value of 0.05, the variable with the highest mean (or average) was named "a", if it was statistically different from all the others, otherwise, it was denoted as "ab". Variables with the lowest mean (or average) had the highest letter among the tested variables.

Substrate Temperatures

At 8:00, the substrate temperature at P3 was the coolest, and the temperature differential was 0.6 °C compared to P4. At 11:00, the substrate at P2 was the coolest and the maximum temperature differential was 4.3 °C compared to P3. The substrate at P1 remained the coolest at 13:00 while the maximum differential rose to 5.2 °C for P4; at 15:00 the substrate at P1 remained the coolest and the maximum temperature differential was 1.4 °C for P4. Substrate temperatures of P4 were the warmest throughout the day except during 11:00, where P3 was warmest (Table 3).

Table 3. Mean substrate temperatures (°C) at the four plants by 8:00, 11:00, 13:00, and 15:00. The bolded numbers in parentheses represent the difference compared to the bolded maximum.

Position	8:00 (°C)	11:00 (°C)	13:00 (°C)	15:00 (°C)
P1 – *C. lanceolata* 'Sterntaler'	25.3	**32.1 (-4.3)**	**32.8 (-5.2)**	**33.8 (-1.4)**
P2 – *A. millefolium*	25.3	33.4	34.9	35.1
P3 – *L. muscari*	**25.2 (-0.6)**	**36.4 (0)**	34.7	34.7
P4 – *O. speciosa*	**25.8 (0)**	35.7	**38.0 (0)**	**35.2 (0)**

Substrate temperatures had the greatest variance at P3 at 11:00, and the least variance at P3 at 13:00 (Figure 5). At 8:00, there was no significant difference between the mean substrate temperatures, while at 11:00, P1 and P2 were significantly different from P3 and P4. By 13:00, P1 and P3 became significantly different from P2 and P4. Finally, at 15:00, P1 is significantly different from P2 and P4. Minimum mean substrate temperatures remained constant at P1.

Surface Temperatures

Surface temperatures were obtained by analyzing the thermal images (Figure 6). The average temperatures of the eight surfaces were compared for the four different times of measurement. At 8:00, maximum temperatures (33.18 °C) were observed at the CW and minimum temperatures (28.46 °C) were observed at P3. By 11:00 and 13:00, the CW had the maximum temperature (41.56 °C and 44.04 °C) while the minimum surface temperature (31.78 °C and 34.48 °C) was observed at the BW behind the MLWS. At 15:00, maximum surface temperatures (43.06 °C) were observed at the CW while the BW had the minimum surface temperature (35.88 °C).

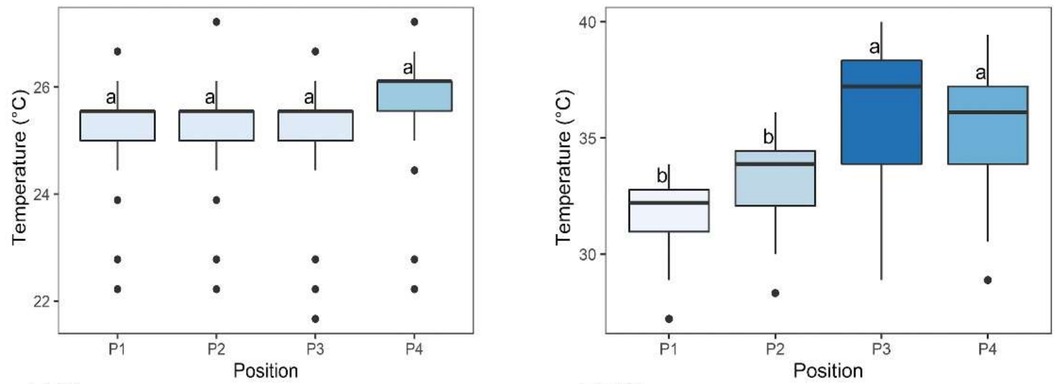
The maximum temperature differentials of 9.78 °C and 9.56 °C were observed between the CW and the BW at 11:00 and 13:00 consecutively (Table 4). Surface temperatures have the highest variance at the CW surface and minimum variation at P2.

The pairwise comparison was conducted between the recorded surface temperatures at the different hours of observation (Figure 7). At 8:00, maximum temperatures were observed at the CW surface, and minimum surface temperatures occurred at P3. The CW surface maintained high temperatures at 11:00, 13:00, and 15:00 while minimum surface temperatures were observed at the BW at the same periods. Maximum surface temperature variance occurred at the CW and P4 at 8:00, P2 by 11:00; behind the MLWS, CW, and P1 at

13:00, and the CW at 15:00. There was a significant difference between the surface temperature at the BW and the CW at all four periods of observation. Also, P1, P2, P3, and P4 were significantly different from the CW. Individual plant mean temperatures were significantly different from the total surface mean temperature at the MLWS at 11:00, 13:00, and 15:00.

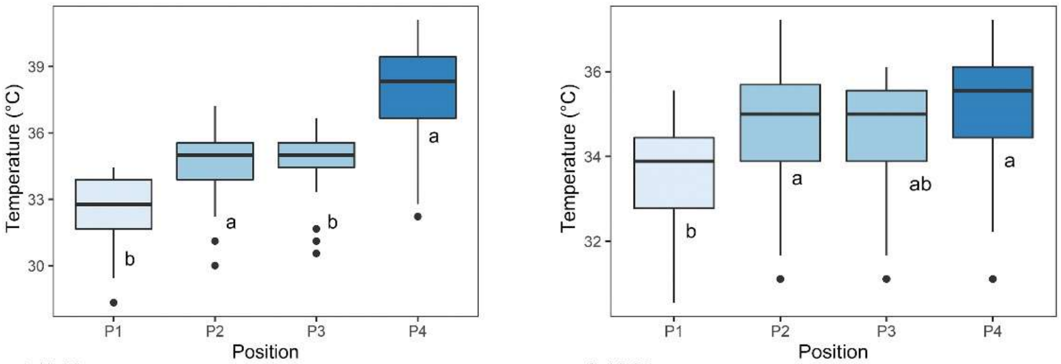
Table 4. Mean surface temperatures (°C) at shaded brick wall, modular living wall, concrete wall, back of MLWS, vegetation, and the nearby weather station. The bolded numbers in parentheses represent the difference compared to the bolded maximum.

Position	8:00 (°C)	11:00 (°C)	13:00 (°C)	15:00 (°C)
Shaded brick wall (BW)	29.1	**31.78 (-9.78)**	**34.5 (-9.5)**	**35.9 (-7.2)**
Modular living wall system (MLWS)	29.5	39.36	42.5	42.0
Concrete wall (CW)	**33.2 (0)**	**41.56 (0)**	**44.0 (0)**	**43.1 (0)**
Back of MLWS (BLMWS)	28.9	36.9	37.8	39.7
P1 – *C. lanceolata* ‘Sterntaler’	29.9	35.48	36.5	36.3
P2 – *A. millefolium*	28.9	37.84	39.8	39.6
P3 – *L. muscari*	**28.5 (-4.7)**	38.54	40.0	39.3
P4 – *O. speciosa*	29.1	37.54	39.4	39.2



a) 8:00

b) 11:00



c) 13:00

d) 15:00

Figure 5. A pairwise comparison was carried out between the substrate temperatures that were recorded at the different hours of observation. Boxplots show significant differences between substrate temperatures at different plants at 8:00, 11:00, 13:00, and 15:00. *C. lanceolata* ‘Sterntaler’- P1; *A. millefolium* - P2; *L. muscari* - P3; *O. speciosa* - P4.

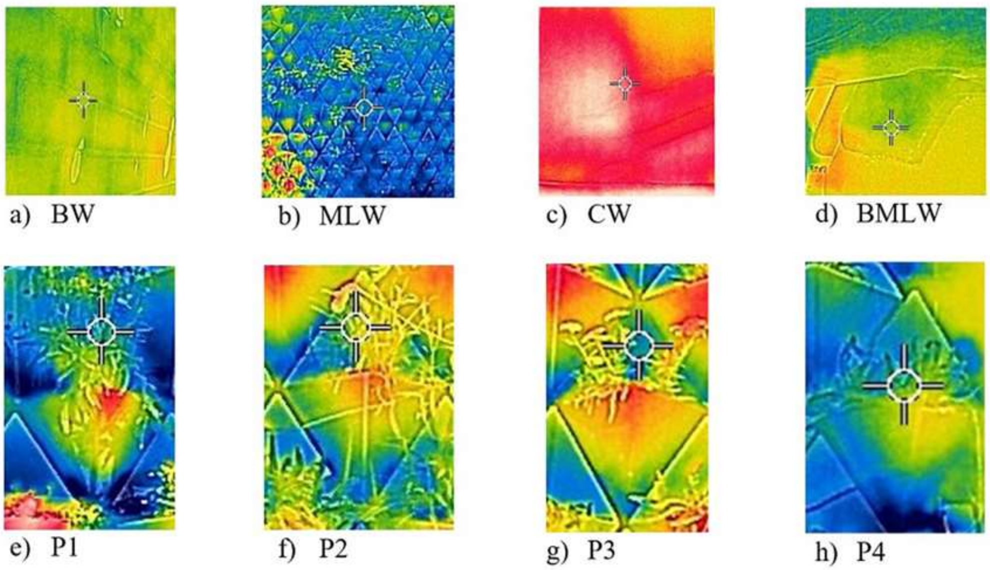
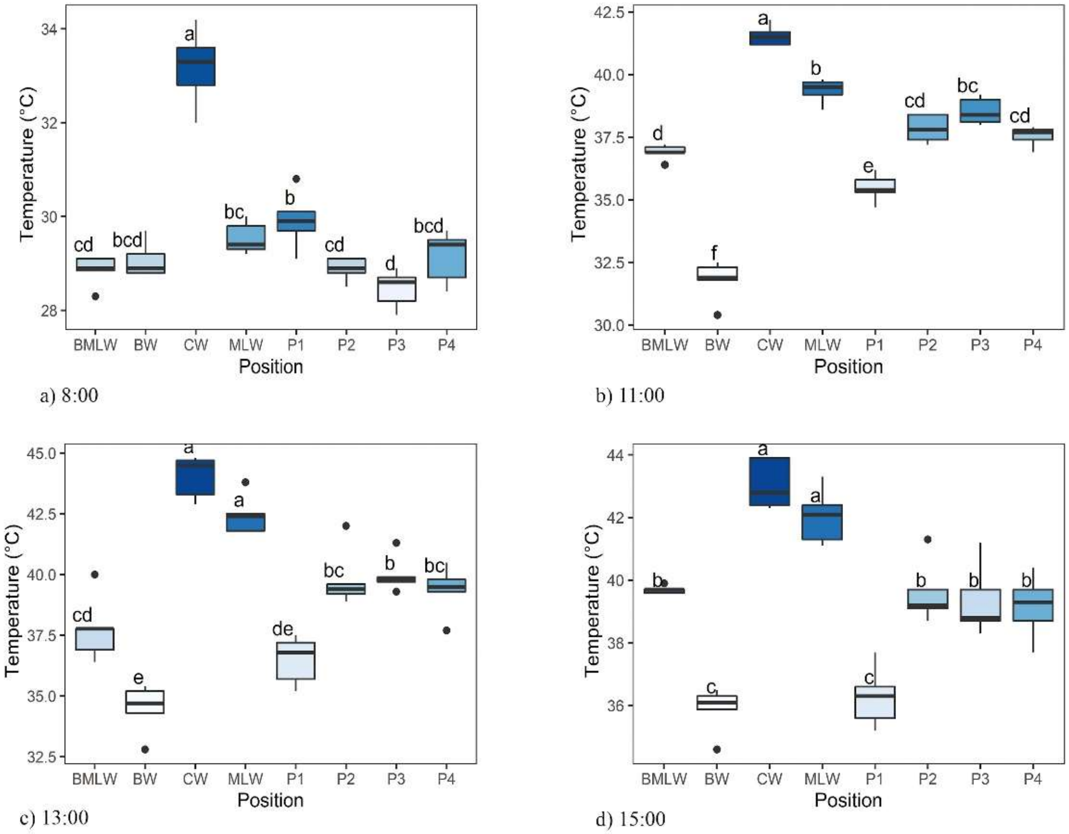

a) BW b) MLW c) CW d) BMLW
e) P1 f) P2 g) P3 h) P4

Figure 6. Thermal images of surfaces at: a) shaded brick wall (BW), b) modular living wall system (MLWS), c) concrete wall (CW), d) back of modular living wall system (BMLWS), e) *C. lanceolata* 'Sterntaler' (P1), f) *A. millefolium* (P2), g) *L. muscari* (P3), h) *O. speciosa* (P4).



a) 8:00 b) 11:00
c) 13:00 d) 15:00

Figure 7. Boxplots show significant differences between surface temperatures at different positions at 8:00, 11:00, 13:00, and 15:00 behind the MLWS - BMLWS; brick wall - BW; concrete wall - CW, modular living wall system - MLWS; *C. lanceolata* 'Sterntaler'- P1; *A. millefolium* - P2; *L. muscari* - P3; *O. speciosa* - P4).

Relative Humidity

Relative humidity (Rh) was recorded in seven areas, namely the AC, CW, P1-P4, and the WS. At 8:00 maximum Rh of 84.88% occurred at the AC space while the minimum Rh of 78.8% was at P1, *C. lanceolata* 'Sterntaler'. At 11:00, a maximum Rh of 61% was at the WS and a minimum Rh of 49.2% occurred at P4. By 13:00, a maximum Rh of 55.26% occurred at P1 and a minimum Rh of 44.02% was observed at the WS. Lastly, at 15:00, a maximum Rh of 54.62% was observed at P1, and a minimum Rh of 35.96% was observed at the weather station (Table 5).

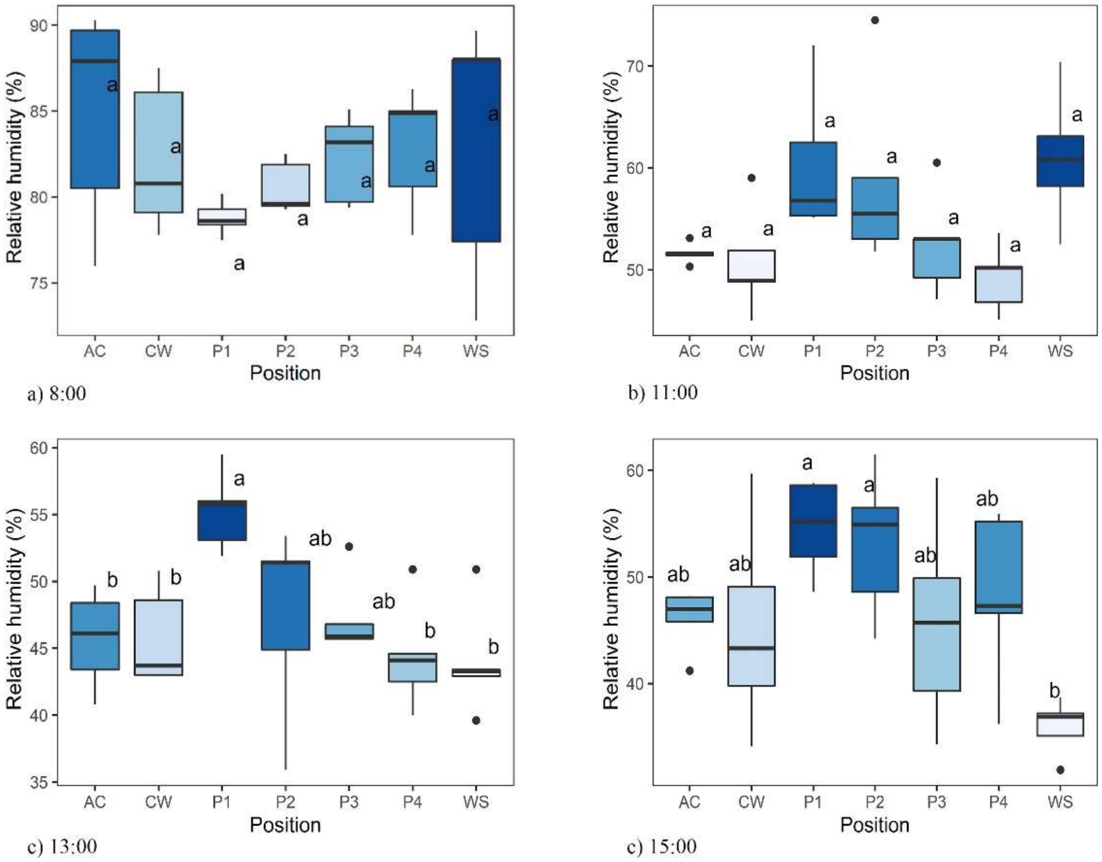
Table 5. Average relative humidity at air cavity, concrete wall, vegetation, and weather station. The bolded numbers in parentheses represent the difference compared to the bolded maximum.

Position	8:00 (% Rh)	11:00 (% Rh)	13:00 (% Rh)	15:00 (% Rh)
Air Cavity (AC)	**84.9**	51.6	45.7	46.1
Concrete wall (CW)	82.3	50.7	45.8	45.2
P1 – *C. lanceolata* 'Sterntaler'	**78.8 (-6.1)**	**60.3**	**55.3**	**54.6**
P2 – *A. millefolium*	80.6	58.8	47.4	53.1
P3 – *L. muscari*	82.3	52.6	47.3	45.7
P4 – *O. speciosa*	82.9	**49.2 (-11.1)**	44.4	48.2
Weather station (WS)	83.2	61.0	**44.0 (-11.3)**	**36.0 (-18.6)**

Likewise, the pairwise comparison was carried out between the Rh that were recorded at the different hours of observation (Figure 8). At 8:00 maximum Rh of 84.9% occurred in the air cavity behind the MLWS, and a minimum Rh occurred at P1. The weather station had the largest variation while the minimum variation occurred at P1. The maximum difference of mean Rh of 18.6% was between the weather station and P1 at 15:00. At 8:00 and 11:00 there was no significant difference between the means. By 13:00 AC was different from P1 and at 15:00 WS was different from P1 and P2.

Solar Radiation

Solar radiation was measured at the AC, CW, P1-P4, and the WS. At 8:00, a maximum solar radiation of 121.72 W/m^2 was recorded at the weather station, and a minimum reading of 0.34 W/m^2 was observed in the air cavity. By 11:00, a maximum solar radiation of 693.68 W/m^2 was observed at the WS and a minimum of 2.54 W/m^2 was observed at the AC. At 13:00, a maximum solar radiation of 926.82 W/m^2 was observed at the WS, and a minimum solar radiation of 2.76 W/m^2 was recorded at the AC. Lastly, at 15:00, a maximum solar radiation of 889.96 W/m^2 was observed at the weather station, and a minimum solar radiation of 0.78 W/m^2 was observed at the air cavity, (Table 6).


a) 8:00

b) 11:00

c) 13:00

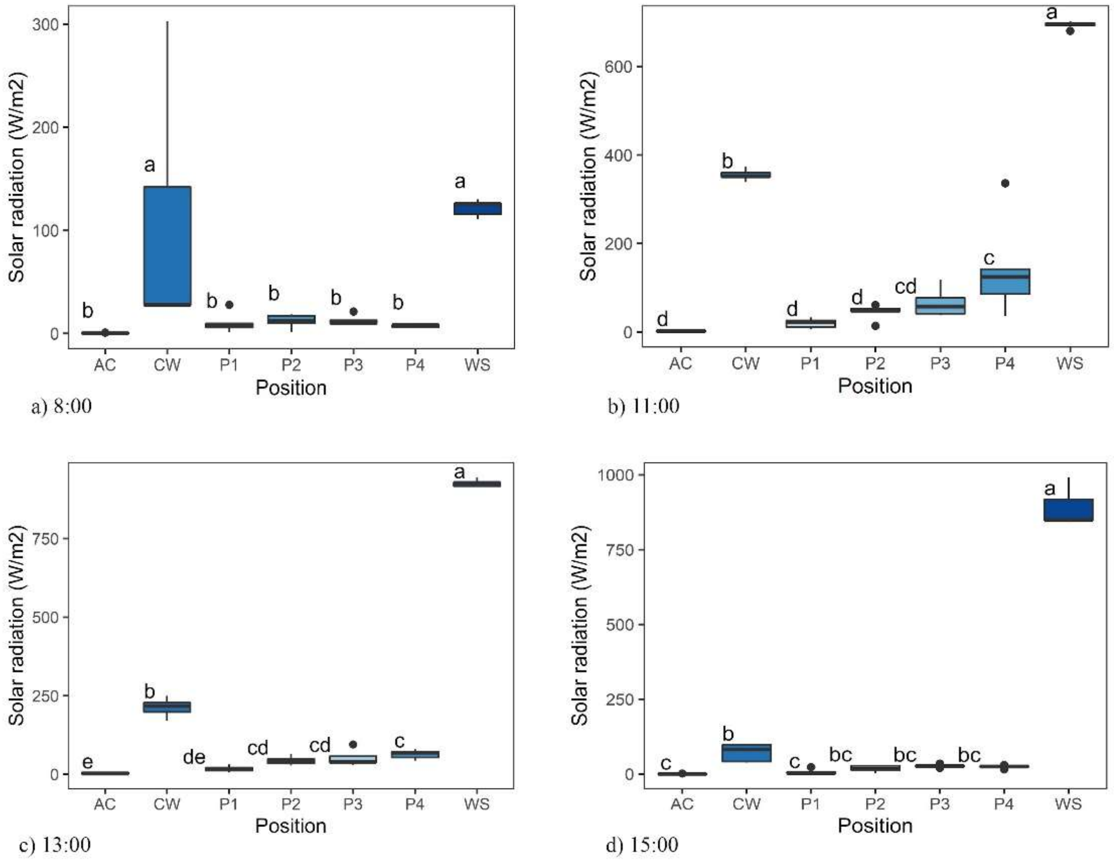
c) 15:00

Figure 8. Boxplots showing significant differences in relative humidity at different positions at 8:00, 11:00, 13:00, and 15:00 (Air cavity - AC, Concrete wall - CW, *C. lanceolata* 'Sterntaler'- P1, *A. millefolium* - P2, *L. muscari* - P3, *O. speciosa* - P4, Weather station - WS).

Table 6. Solar radiation at air cavity, concrete wall, vegetation, and weather station. The bolded numbers in parentheses represent the difference compared to the bolded maximum.

Position	8:00 (W/m^2)	11:00 (W/m^2)	13:00 (W/m^2)	15:00 (W/m^2)
Air Cavity (AC)	**0.3 (-121.4)**	**2.5 (-691.2)**	**2.8 (-924)**	**0.8 (-889.2)**
Concrete wall (CW)	105.7	355.0	212.6	72.3
P1 – *C. lanceolata* 'Sterntaler'	10.7	19.8	17.4	7.9
P2 – *A. millefolium*	11.9	44.7	43.0	17.9
P3 – *L. muscari*	12.7	66.4	51.9	26.8
P4 – *O. speciosa*	7.5	144.9	63.4	24.2
Weather station (WS)	**121.7**	**693.7**	**926.8**	**890.0**

The pairwise comparison was conducted between all the solar radiation recorded at the different hours of observation (Figure 9). Solar radiation was minimum at the AC and maximum at the WS at all the recorded times. At 8:00 maximum variation in solar radiation was observed at the CW by 8:00, at P4 by 11:00, at the CW by 13:00, and at the weather station by 15:00. At 8:00 the CW and the WS had significantly different means from the AC and P1-4. By 11:00, four levels of means occur at the WS, CW, P4, and P1. It increases to five levels at 13:00 with an additional level at the AC. Finally, at 15:00, the means are different for the WS, CW, and AC.



a) 8:00 b) 11:00 c) 13:00 d) 15:00

Figure 9. Boxplots show significant differences in solar radiation at different positions at 8:00, 11:00, 13:00, and 15:00. (Air cavity - AC, Concrete wall - CW, *C. lanceolata* 'Sterntaler'- P1, *A. millefolium* - P2, *L. muscari* - P3, *O. speciosa* - P4, Weather station - WS).

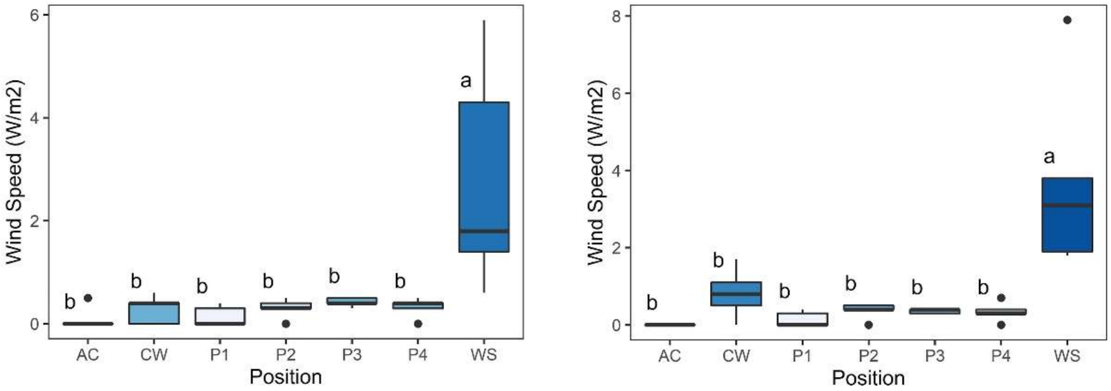
Wind Speed

Wind speeds were recorded at the AC, CW, P1-P4, and the WS. At 8:00 maximum wind speeds were observed at the weather station (up to 5.9 m/s^2) and minimum wind speeds (0) were observed at the air cavity. By 11:00, maximum wind speeds (up to 7.9 m/s^2) were observed at the weather station and zero at the air cavity, and P1. At 13:00, maximum wind speed of up to 2.6 m/s^2, and minimum wind speeds of zero were observed at the air cavity, concrete wall, and P1. Lastly, at 15:00, there was a maximum wind speed of up to 3.7 m/s^2 at the weather station and a minimum wind speed of zero at the air cavity (Table 7).

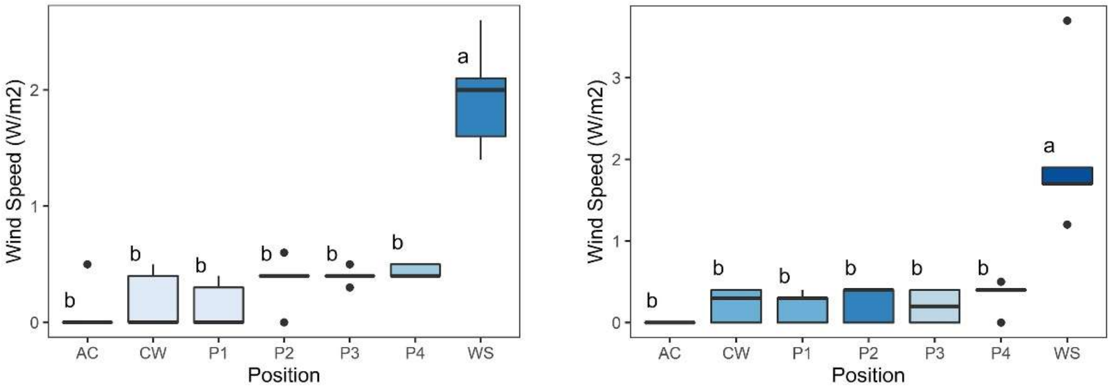
In addition, a pairwise comparison was conducted between the wind speeds recorded at the different hours of observation (Figure 10). Maximum wind speeds occurred at the weather station while minimum wind speeds occurred at the air cavity. Variance in wind speeds was highest at the weather station and least at the air cavity. At all periods of observation, the means of wind speeds were significantly different at WS.

Table 7. Mean wind speeds (m/s) at air cavity, concrete wall, vegetation, and weather station. The bolded numbers in parentheses represent the difference compared to the bolded maximum.

Position	8:00 (W/m^2)	11:00 (W/m^2)	13:00 (W/m^2)	15:00 (W/m^2)
Air Cavity (AC)	**0.1 (-2.7)**	**0.0 (-3.7)**	**0.1 (-1.8)**	**0.0 (-2)**
Concrete wall (CW)	0.3	0.8	0.2	0.2
P1 – *C. lanceolata* 'Sterntaler'	0.1	0.1	**0.1**	0.2
P2 – *A. millefolium*	0.3	0.4	0.4	0.2
P3 – *L. muscari*	0.4	0.4	0.4	0.2
P4 – *O. speciosa*	0.3	0.3	0.4	0.3
Weather station (WS)	**2.8**	**3.7**	**1.9**	**2.0**



a) 8:00 b) 11:00



c) 13:00 d) 15:00

Figure 10. Boxplots showing significant differences in wind speeds at different positions at 8:00, 11:00, 13:00, and 15:00. (Air cavity - AC, Concrete wall - CW, *C. lanceolata* 'Sterntaler'- P1, *A. millefolium* - P2, *L. muscari* - P3, *O. speciosa* - P4, Weather station - WS).

The maximum surface temperature difference (MSTD) from this study was compared to the MSTD in similar studies with metallic living wall materials (Figure 11). The MSTD from other studies ranged from 2.7 °C to 11.58 °C between the hours of 11:00 and 14:00. Vegetation in other studies included *Pyrostegia venusta* grown in plastic-coated wire mesh had an MSTD of 2.7 °C at 16:00 for study 1; *Hemigraphis repanda*, a red-leaved plant species; with a maximum MSTD of 11.58 °C at 12:35 at study 2a; the peat moss panel with

MSTD of 10.94 °C at 12:40 in study 2b; *Phyllanthus myrtifolius* with MSTD of 6.85 °C at 12:45 in study 2c.

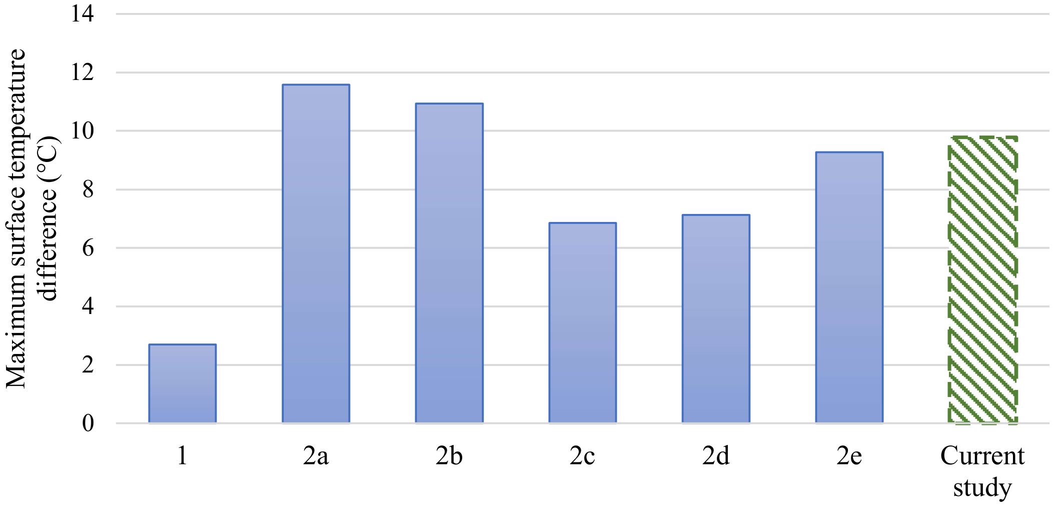


Figure 11. A comparison of the maximum surface temperature differentials of other living wall systems compared to the current study (green hatched). Key: 1= (Zhang et al., 2019), 2a-e (Wong, Kwang Tan, et al., 2010).

DISCUSSION

In the presented study, an MSTD of 9.78 °C was observed between the adjacent concrete wall (CW) and the background shaded brick wall (BW) at 11:00. In addition, a range of MSTDs of 3.02 - 7.5 °C was observed between the four plants and the CW. A minimum variation in air temperatures was observed in the air cavity between the MLWS and the background brick wall. This study demonstrates how living wall systems, even those constructed entirely from metal, contrary to public perception about metal surfaces, can contribute to the significant cooling of air and surface temperatures near buildings in climates with extremely hot summers. The results of this study, including thermal images of the MLWS demonstrate that the metal points of the modules take on the most heat, however, the backside of the metal module that is shaded by the plant is the coolest part of the module. Compared to the CW (Figure 8c), the MLWS surfaces (Figure 8b) were cooler and contributed to shading the background brick wall.

The plant species used in this study were only four of twenty-five trialed (Dvorak and Woodfin, 2022) and represent broadleaf forms of perennial vegetation that drop their leaves during the winter. Additional research on different species of plants and their characteristics during different seasons of the year is needed to better understand how living wall systems affects the performance of building facades during other seasons. This study did not investigate the energy savings potential of living wall systems made from by-products sheet metal through the by-passing of raw materials, but the results indicated that living walls made of metals could potentially reduce energy loads on south-facing building facades compared to findings from living walls not made from metal located in other climates (Tudiwer et al., 2019; Zhang et al., 2019).

CONCLUSIONS

The capacity of MLWS to mitigate microclimates in warm and humid climates is comparable to findings in other climates. The results of the study demonstrate that the maximum temperature differential for ambient air observed between the nearby weather station and the plant *C. lanceolata* 'Sterntaler' was up to 4.6 °C cooler at 15:00. While the maximum surface temperatures differential between surfaces was 9.78 °C cooler between the background shaded brick wall and adjacent concrete wall at 11:00. Individual mean temperatures between plant species were significantly different from the total surface mean temperature at MLWS at 11:00, 13:00, and 15:00. *C. lanceolata* 'Sterntaler' was the most advantageous plant for surface temperature reduction. This study shows the relationship between microclimate parameters at the custom MLWS made from by-product sheet metal during the hot summer season and evaluates the cooling effect of the MLWS plants. Further microclimatic cooling effect evaluations are needed especially for the use of other plant species present at the MLWS, or species not yet trialed.

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LITERATURE CITED

Ali, A., and Dvorak, B. 2019. "Cultivating research: resource-based design as an activating agent for energy and water conservation." Paper presented at the ARCC Conference Repository. https://arcc-journal.org/index.php/repository/article/view/610.

Briscoe, D. and Bright, M., 2019. "Modular living wall: collaborative, regional design on an urban campus in Texas." *Journal of Living Architecture*, 6(1):1-13. https://livingarchitecturemonitor.com/s/JLIVModularLivingWall2019.pdf.

Cameron, R. W., Taylor, J. E., and Emmett, M. R. 2014. "What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls." *Building and environment,* 73: 198-207. https://doi.org/10.1016/j.buildenv.2013.12.005.

Chen, Q., Li, B., and Liu, X. 2013. "An experimental evaluation of the living wall system in hot and humid climate." *Energy and Buildings,* 61: 298-307. https://doi.org/10.1016/j.enbuild.2013.02.030.

Dvorak, B. and Woodfin, T. 2022. "Replanting a custom living wall system," Cities Alive: The Home Coming: Philadelphia, Pennsylvania, October 16-18. https://static1.squarespace.com/static/58890829b3db2bd1e52cb6bd/t/634d6be9e8c25f155cdd487d/1666018283718/8.2+Dvorak+and+Woodfin.pdf.

Dunnett, N., and Kingsbury, N. 2008. "Planting green roofs and living walls." *Portland, OR: Timber press.* https://library.wur.nl/WebQuery/titel/1939498.

Eumorfopoulou, E., and Kontoleon, K. 2009. “Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes.” *Building and Environment,* 44(5): 1024-1038. https://doi.org/10.1016/j.buildenv.2008.07.004.

Francis, R. A., and Lorimer, J. 2011. “Urban reconciliation ecology: The potential of living roofs and walls.” *Journal of Environmental Management,* 92(6): 1429-1437. https://doi.org/10.1016/j.jenvman.2011.01.012.

Fridlyander, I., Sister, V., Grushko, O., Berstenev, V., Sheveleva, L., and Ivanova, L. 2002. “Aluminum alloys: promising materials in the automotive industry.” *Metal science and heat treatment, 44*(9): 365-370. https://doi.org/10.1023/A:1021901715578.

Handbook, A. S. H. R. A. E. 2013. “Fundamentals-2013 American Society of Heating. Refrigerating and Air Conditioning Engineers, Atlanta.”

Hoyano, A. 1988. “Climatological uses of plants for solar control and the effects on the thermal environment of a building.” *Energy and Buildings,* 11(1): 181-199. https://doi.org/10.1016/0378-7788(88)90035-7.

Ismail, M. R. 2013. “Quiet environment: Acoustics of vertical green wall systems of the Islamic urban form.” *Frontiers of Architectural Research,* 2(2): 162-177. https://www.sciencedirect.com/science/article/pii/S2095263513000174.

Kio, P., and Ali, A. K. 2021. “In situ experimental evaluation of a novel modular living wall system for industrial symbiosis.” *Energy and Buildings,* 252: 111405. https://doi.org/10.1016/j.enbuild.2021.111405.

Köhler, M. 2008. “Green facades—a view back and some visions.” *Urban Ecosystems,* 11(4): 423. https://doi.org/10.1007/s11252-008-0063-x.

Koyama, T., Yoshinaga, M., Hayashi, H., Maeda, K.-i., and Yamauchi, A. 2013. “Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls.” *Building and Environment,* 66: 96-103. https://doi.org/10.1016/j.buildenv.2013.04.020.

Louis S. H. L. and Jim C. Y. 2017. “Subtropical summer thermal effects of wirerope climber green walls with different air-gap depths.” *Building and Environment*, 126: 1-12. https://doi.org/10.1016/j.buildenv.2017.09.021.

Manso, M. and Castro-Gomes, J. 2015. “Green wall systems: A review of their characteristics.” *Renewable and sustainable energy reviews*, 41: 863-871. https://doi.org/10.1016/j.rser.2014.07.203.

Mazzali, U., Peron, F., Romagnoni, P., Pulselli, R. M., and Bastianoni, S. 2013. “Experimental investigation on the energy performance of Living Walls in a temperate climate.” *Building and Environment,* 64: 57-66. http://dx.doi.org/10.1016/j.buildenv.2013.03.005.

Nori, C., Olivieri, F., and Bedoya Frutos, C. 2013. “Testing the performance of a green wall system on an experimental building in the summer.” https://oa.upm.es/29898.

Pérez, G., Rincón, L., Vila, A., González, J. M., and Cabeza, L. F. 2011. “Green vertical systems for buildings as passive systems for energy savings.” *Applied Energy,* 88(12): 4854-4859. https://doi.org/10.1016/j.apenergy.2011.06.032.

Perini, K. and Rosasco, P. 2016. “Is greening the building envelope economically sustainable? An analysis to evaluate the advantages of economy of scope of vertical greening systems and green roofs.” *Urban Forestry & Urban Greening*, 20: 328-337. https://doi.org/10.1016/j.ufug.2016.08.002.

Radić, M., Brković Dodig, M. and Auer, T. 2019. “Green facades and living walls—a review establishing the classification of construction types and mapping the benefits.” *Sustainability*, 11(17): 4579. https://doi.org/10.3390/su11174579.

Susorova, I., Angulo, M., Bahrami, P., and Brent, S. 2013. “A model of vegetated exterior facades for evaluation of wall thermal performance.” *Building and Environment,* 67: 1-13. https://doi.org/10.1016/j.buildenv.2013.04.027.

Takuya K., Mika Y., Hideki H., Kei-ichiro M., Akira Y. 2013. “Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls.” *Building and Environment,* 66: 96-103. https://doi.org/10.1016/j.buildenv.2013.04.020.

Tudiwer, D., Teichmann, F., and Korjenic, A. 2019. “Thermal bridges of living wall systems.” *Energy and Buildings,* 205: 109522. https://doi.org/10.1016/j.enbuild.2019.109522.

Van Herzele, A., and De Vries, S. 2012. “Linking green space to health: A comparative study of two urban neighbourhoods in Ghent, Belgium.” *Population and environment,* 34(2): 171-193. https://doi.org/10.1007/s11111-011-0153-1.

White, E. V., and Gatersleben, B. 2011. “Greenery on residential buildings: Does it affect preferences and perceptions of beauty?” *Journal of environmental psychology, 31*(1): 89-98. https://doi.org/10.1016/j.jenvp.2010.11.002.

Wolf, K. L. 2012. “The changing importance of ecosystem services across the landscape gradient.” *Urban–rural interfaces: Linking people and nature*, 127-146. https://doi.org/10.2136/2012.urban-rural.c8.

Wong, N. H., Kwang Tan, A. Y., Chen, Y., Sekar, K., Tan, P. Y., Chan, D., Wong, N. C. 2010. “Thermal evaluation of vertical greenery systems for building walls.” *Building and Environment, 45*(3): 663-672. https://doi.org/10.1016/j.buildenv.2009.08.005.

Wong, N.H., Tan, A.Y.K., Tan, P.Y., Chiang, K. and Wong, N.C. 2010. “Acoustics evaluation of vertical greenery systems for building walls.” *Building and environment*, 45(2): 411-420. https://doi.org/10.1016/j.buildenv.2009.06.017.

Zhang, L., Deng, Z., Liang, L., Zhang, Y., Meng, Q., Wang, J. and Santamouris, M. 2019. “Thermal behavior of a vertical green facade and its impact on the indoor and outdoor thermal environment.” *Energy and buildings*, 204:109502. https://doi.org/10.1016/j.enbuild.2019.109502.