THERMAL PERFORMANCE OF AN EXTENSIVE GREEN ROOF UNDER SEMI-ARID CONDITIONS IN CENTRAL ARGENTINA

Lelia Imhof,[1]* Edgardo Suárez,[2] Natalia Cáceres,[1] Federico Robbiati,[3] Cecilia Cáceres,[2] Alejandra Broilo,[2] Lucila Pellizari,[2] Mario Suárez,[1] Emmanuel Hick,[1] Evangelina Matoff,[4] and Leonardo Galetto[3]

ABSTRACT

Extensive green roofs improve the provision of ecosystem services in urban environments, particularly in semiarid regions. The aim of this paper is to compare their thermal performance during six months between two rooms, one with a green roof and the other with a conventional roof, in Córdoba (Argentina). The room with a green (planting) roof showed a lower inside surface temperature since the beginning of the study than the control room (between 5–6°C of difference). During the selected period, the indicators such as temperature amplitude (the difference between the maximum and the average temperature) and the anti-interference characteristics of the layers to the outdoor air temperature are produced a better performance for the green roof compared to the conventional roof. The pattern of a better performance was consistent across the study for the green roof, characterized by a higher cooling and warming of the roof surface during the day and night, respectively. The green roof was more effective at blocking an upward heat flux during the day and suppressing heat loss during the night. Evaporation, conductive flux and climatic conditions seem to dominate the thermal performance of green roofs in areas with semiarid climate conditions.

KEYWORDS

thermal performance, extensive green roofs, semiarid region

INTRODUCTION

Green roofs (GRs) contribute to the development of urban resilience at different scales but also help deal with future environment disturbances (Wilkinson and Dixon, 2016). GRs fulfill multiple social objectives (Mees et al, 2013), offering many eco-systemic services, such as an

1. IRNASUS (Facultad de Ciencias Agropecuarias—Facultad de Arquitectura; Universidad Católica de Córdoba-CONICET)
2. Instituto de Etiquetación Edilicia Urbana, Colegio de Arquitectos de la Provincia de Córdoba
3. Departamento de Diversidad Biológica y Ecología, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba e Instituto Multidisciplinario de Biología Vegetal (CONICET-UNC)
4. AER INTA Agencia de Extensión Rural, Presidente Roca esquina La Coruña, Córdoba
**Corresponding author:* Imhof Lelia, IRNASUS (Facultad de Ciencias Agropecuarias—Facultad de Arquitectura; Universidad Católica de Córdoba-CONICET), Av Armada Argentina 3555 (Córdoba, Argentina); leliaimhof@gmail.com.

increase of biodiversity (Kadas, 2006; Volder and Dvorak, 2013), improvement in air quality (Veisten et al., 2012; Yang et al., 2008), mitigation of the urban heat island effect and thermal regulation (Butler and Orians, 2011; Peng and Jim, 2013; Sharma et al., 2016), aesthetic and social benefits (Fernandez-Cañero et al., 2013), as well as rainwater collection, retention and detention of runoff (Fioretti et al., 2010; Wolf and Lundholm, 2008).

GRs require plant materials growing on a specific medium contained by a series of root barriers and water proofing membranes (Suárez et al. 2019) or mounted on modular trays. GRs can be classified into extensive, semi-extensive and intensive, based on the substrate depth (<15 cm, between 10–20 cm and >20 cm, respectively) and the amount of maintenance expected (following Sutton 2015; p.19). Semi-intensive and intensive green roof solutions are still more competitive leading to 10–45% and 25–60% of energy savings, respectively (Silva et al. 2016).

Timely variation in the outside air temperature would cause the fluctuation of the roof inside slab temperature (Yang et al. 2015). By analyzing the profile of slab temperature fluctuation, the characteristics of the temperature attenuation can be obtained and then used to evaluate the roof´s performance in terms of the inside/outside temperature response (Yang et al. 2015). Temperature amplitude has been defined as the difference between the maximum and average temperature, and the difference between the maximum and the minimum values of temperature used to evaluate the attenuation characteristics of the roof surface temperature (Zhang et al. 2008).

The thermal performance of GRs on non-insulated rooftops diverges from those GRs installed on well-insulated rooftops, mostly under warm and hot climates (Susca, 2019). For low insulation levels, results with extensive GRs with a technically modified substrate (i.e., with a reduced density) proved to save around 20% of the energy compared to conventional black roofs; notwithstanding, GRs do not have great energy benefits when they present higher insulation levels (Silva et al. 2016). The review of Susca (2019) showed that in warm climates—such as Aw, BSk, Cwb and Csa—the deployment on non-insulated rooftops entails a decrease in heating energy demand ranging from 20 to 60%. In general, and for all the investigated climate areas (Aw, Cfa, Cwb, Bwh, Bsk, Bwk), the decrease varies from 10 to 75%. Similarly, insulated GRs decrease heating and cooling energy demand by at most 30% in all the scrutinized climate areas, except BSh and Dfa, where their deployment is uninfluential (Susca, 2019).

For Yang et al. (2015) GRs could help reduce the building´s energy consumption and improve the thermal environment, leading to a reduction in both roof and indoor air temperatures (e.g., Niachou et al. 2001; Xhao and Xue 2006; Zhao, Tan and Tang 2009). In particular, under tropical and subtropical climate conditions, the thermal performance is considerably decreased during rainy days (Lin et al., 2013). When the temperatures of outside and indoor spaces are compared between rooftops covered with thick, dark green vegetation and exposed roofs, lower indoor temperatures were registered for GRs (e.g., Niachou et al. 2001) with values decreasing up to 3°C (0.9–1, 2, and 2–3°C lower in Yang et al., 2015; Jaffal et al., 2015; and Niachou et al., 2001, respectively).

Heat transmission through GRs has been studied in experimental studies but during short periods (Spolek, 2008). To reduce heat flow through the GRs, the components to be considered can be grouped into (i) the vegetation layers (Susca, 2019), (ii) the substrate layers, and (ii) the climatic conditions (Pérez et al, 2015). Situations with low plant cover (usually during the first year after its implementation, where plants provide little shade) indicate that the thermal performance of the GR depends on the characteristics of the substrate layers (Pérez et al., 2015). The thermal insulation provided by the soil layer is crucial for decreasing the building energy demands for warming or cooling, according the climate. The thermal efficiency can be improved through the regulation of evapotranspiration and plant shading (Cascone et al, 2018); moreover, irrigation will be crucial for thermal regulation in dry climates (Lazzarin, 2005; Susca, 2019; Vera et al. 2015). For example, evapotranspiration could be increased in relatively dry substrates because of the limited substrate mass effect (Jim and Peng 2012) with a low efficacy in thermal regulation (Pérez et al., 2015). Results showed lower heat flux in water-limited than in well-watered treatments in both non-vegetated and vegetated roofs. This pattern suggests that the lower heat transfer of the air in comparison to water would counteract the cooling effect of evapotranspiration that is supposed to be higher in the well watered roof, where the volumetric water content is higher. In particular, when comparing a water-limited and a well-watered irrigation treatment, the thermal insulation capacity is increased in the former. A reduction of the total transferred heat between 25% and 71% can be observed during the different seasons of the year, suggesting that the air/water substrate content has a greater effect on insulation as/ than evapotranspiration (Cascone, 2018).

To validated theoretical advances, Fioretti et al. (2010) emphasizes the importance of working with experimental data. This study analyzes the thermal performance comparing an extensive GR with a conventional roof to better understand the behavior of the parameters of different components (vegetation, substrate and climatic conditions). In addition, we have compared GR under real climate conditions in Córdoba city (Argentina) to define efficient and non-efficient days for temperature regulation.

METHODOLOGY

Semi-arid regions of central Argentina (province of Córdoba) are mainly characterized by a wide temperature range (difference between daily maximum and minimum temperatures), by precipitations concentrated during the spring-summer period, and by a dryer and colder autumn-winter period (Torres and Galetto et al., 2011). In particular, the city of Córdoba is placed in the boundary between two latitudinal regions (Derguy et al, 2019), the warm and temperate region (sub-humid) with rainy summers, dry winters and winter frosts (Cwa) and the warm semi-arid region (hot arid steppe) (Bsh) according to Köppen-Geiger climate classification.

The trial was carried out (31°28′ S, 64°13′ W) at the Catholic University of Cordoba campus, in the city of Córdoba (Province of Córdoba, Argentina; climate region corresponding to Cwa and Bsh) comparing two adjacent classrooms of the Faculty of Architecture. The total period of analysis was 200 days, in which both classrooms were occupied by students except during the summer period. One classroom with a conventional roof was used as the control (C, white roof) and the other one was covered by an extensive green roof (GR, green roof) of 80 m^2 each. In order to compare the thermal performance of the GR with respect to C, the thermal conductivity of the construction materials (coefficient of thermal conductivity or k value of walls, roofs and substrate) was determined by ECOTEC analysis. Then, environmental parameters, including ambient air temperature, relative humidity, wind speed, radiation, and slab and indoor temperature were measured. Data of the sensors were obtained with a frequency of fifteen minutes. Details of the instruments and parameters measured are presented in Table 1. The location of the study was at the UCC campus, the orientation and the position of the classrooms with respect the Faculty of Architecture are shown in the Google Earth image (Figure 1). The plan with the view of the design of the classrooms (with and without GR) (Figure 2) and the stratification of the materials used for the wall and for the conventional roof can be

TABLE 1. Instrument type, parameter and number of sensor measured during in the experimental period.

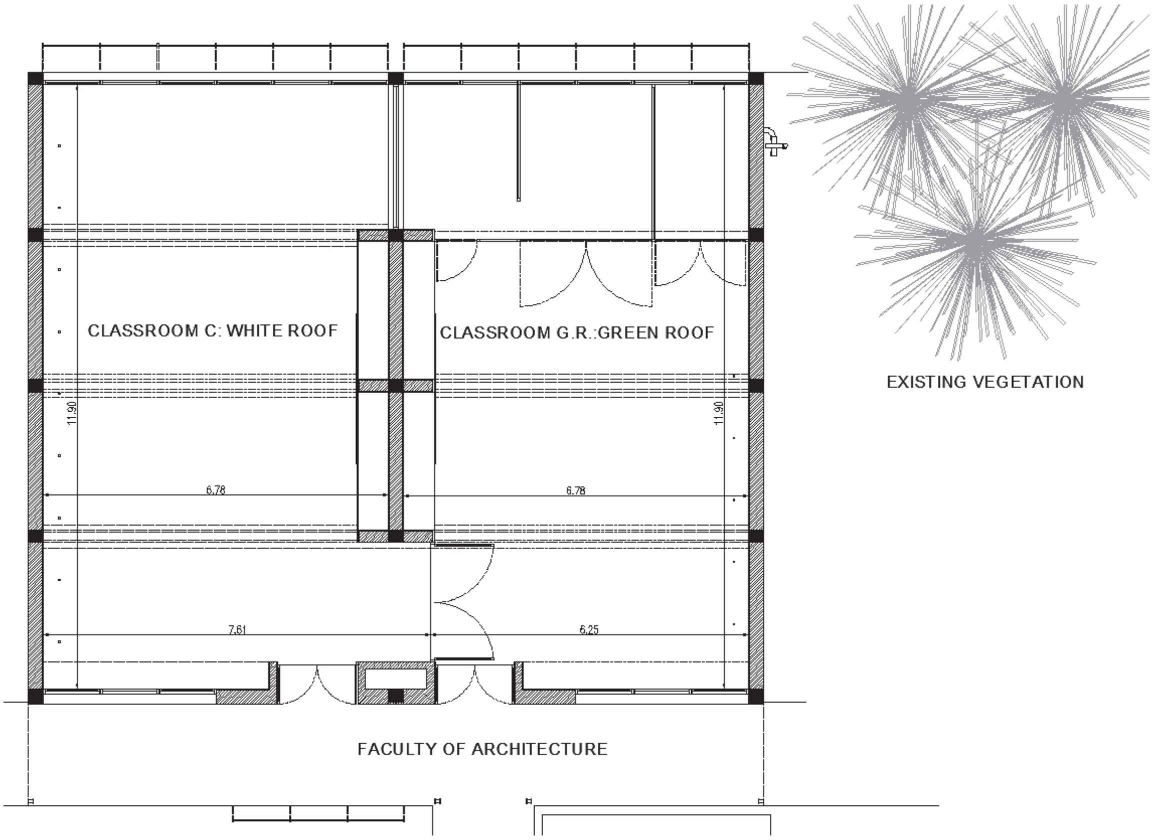
instrument type	parameter	sensors
solar radiation PAR	net radiation	1
anemometer	wind speed	2
pluviometer	rainfall	3
relative humidity sensor	humidity	4
substrate moisture sensor	moisture	5
temperature sensor	temperature	6, 7, 8, 9, 11, 12
thermo-hygrometer	temperature, humidity	10, 13

observed in the Figure 3. The scheme for the location of the instruments used for the study is shown in Figure 4.

The substrate was prepared with equal proportions of (i.e. native) soil, peanut shells and perlite (pH = 6.7; soluble salts 0.98 deciSiemmens (dS)). Substrate dry weight was 70 kg/m^3 and the saturated weight was 100 kg/m^3. They were placed with a slope of 10%, allowing excess rain runoff to drain. A mix of plant material of *Sedum acre*, *Sedum lineare*, *Sedum reflexum*, *Glandularia* spp, *Phyla nodiflora*, *Eustachys distichophylla*, and *Grindelia cabrerae* were conditioned and propagated asexually by stem cuttings or mat division and were grown under greenhouse conditions for about 30 days. Once all propagules were rooted, the transplants were carried out to the green roofs. Planting density was 25 rooted stems per m^2 or an equivalent density. At the beginning of the experiment, all modules started with a different number of

FIGURE 1. Spatial location of the study on the Catholic University of Cordoba campus. N: north orientation; 1: classroom (the left is C, white roof; the right is GR, green roof); 2: Faculty of Architecture (at south direction from classroom).

FIGURE 2. Plan view of the classrooms (with a conventional white roof, C; with a green roof, GR); their dimensions (in meters) and the location with respect to the faculty.

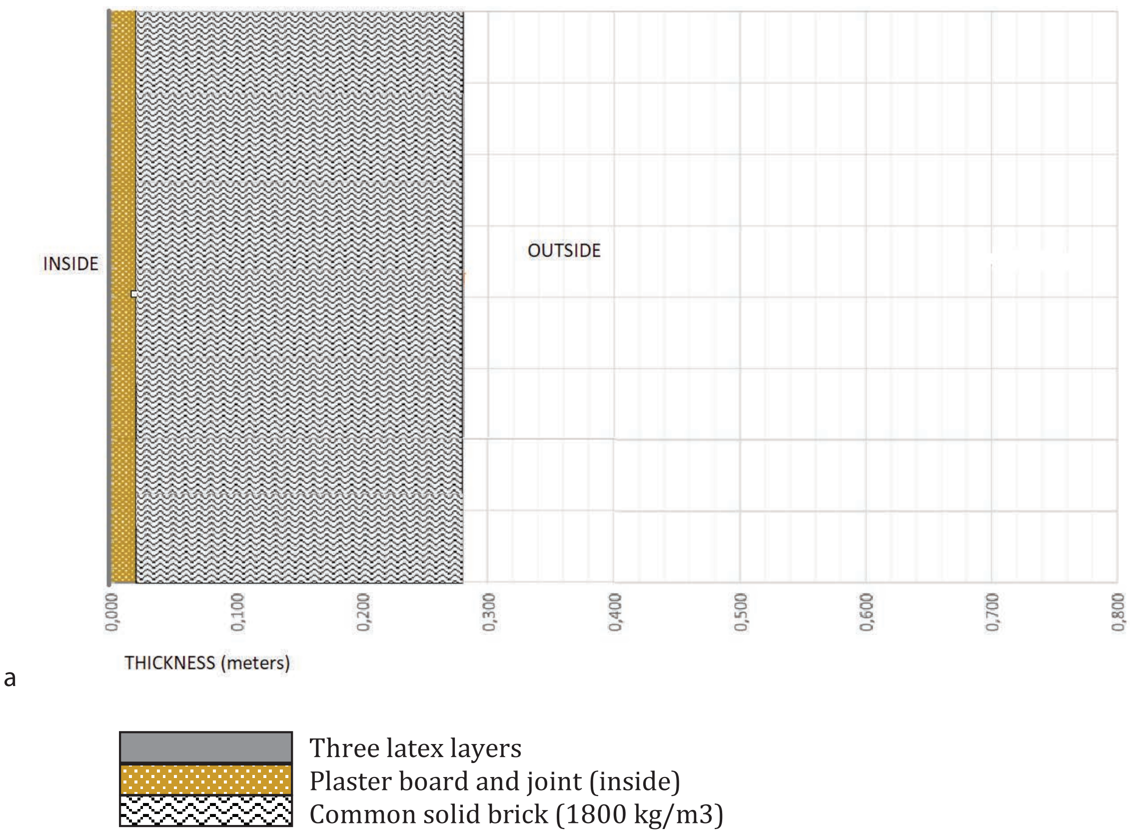


seedlings to reach comparable plant coverage (10 to 15%). Plant material was cultivated on experimental units of extensive green roof modules. The general technical specifications of the modules are: dimensions: 1m x 1m x 0,15m; total area of each module: 10000 cm2; water reservoir: 0,013 m3; material: high density polyethylene; drainage: 94 holes of 8mm each one; water reservoir depth: 35 mm; water substrate weight: 110 kg/m2 (for more details see Súarez et al. 2019). The date of transplant was September 19th. During the first 15 days after implantation, an abundant irrigation was carried out during implantation; thereafter, weekly irrigation contributed to the maintenance of the plants (36 mm/m^2/months). Weed control was carried out every 15 days manually.

Three moments of analysis were determined: 1) at the beginning of the installation of the system, 2) during the period of highest temperature and radiation and 3) during the total period of the study. Moments (M) of analysis were M1 (to 15 days after planting, a 7 days evaluation period, vegetated cover: 20%, LAI: 1, rainfall: 0 mm); M2 (to 75 days after planting, a 50 days evaluation period, vegetated cover: 80%, LAI: 3, rainfall: 120.9 mm); M3 (to 15 days after planting, a 200 days evaluation period, vegetated cover: 90%, LAI: 3, rainfall: 440.9 mm).

Thermal performance was analyzed through the summary of the measures of temperature (Mean value, Standard Deviation, Coefficient of Variation, Minimum and Maximum value of the period,) and the difference between Maximum and Minimum temperature noted as a "peak-to-valley-gap" (PV). Heat flux (H) through the concrete roof slab was calculated based

FIGURE 3. Stratification of the materials of the classroom: a) stratification of the materials used for the walls and their dimensions; b) stratification of the roof materials and their dimensions used for conventional roof.



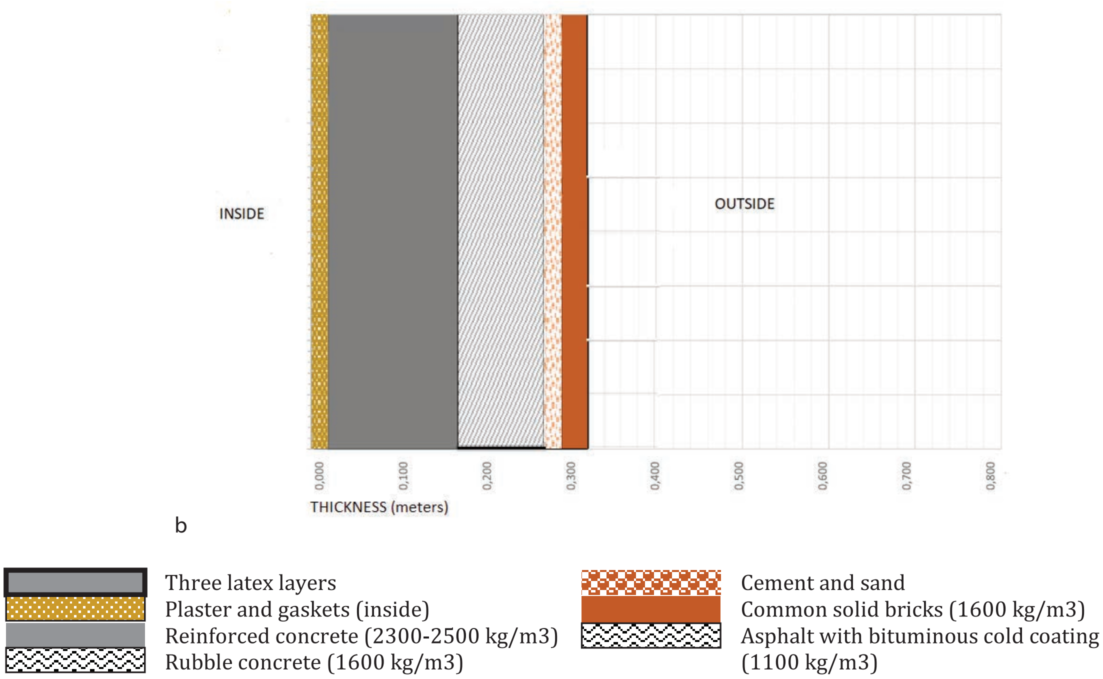
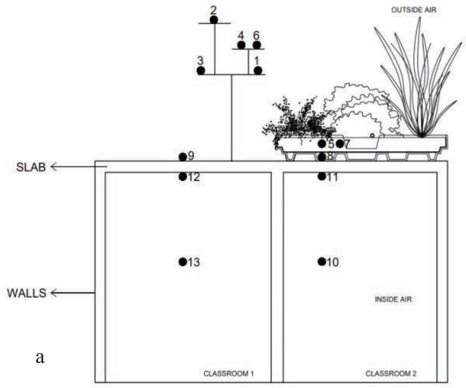


FIGURE 4. The experimental configuration of the conventional roof (C), the green roof (GR) and the associated measurement instrumentation. In the left diagram, a transection of the two experimental classrooms used in the experiment showing the green roof on one of the classrooms (details of the sensors can be seen in Table 1: 1 = solar radiation sensor (PAR), 2 = anemometer, 3 = pluviometer, 4 = relative humidity sensor, 5 = substrate moisture sensor, 6, 7, 8, 9, 11, 12 = temperature sensor, 10, 13 = thermo-hygrometer). In the right photograph, a partial view of the conventional roof (in light grey) and the green roof (behind the meteorological station) are shown.



on the temperature differences between outside roof surface (T_s) and the indoor ceiling (T_c) as suggested by Peng et al. (2019): $H = k\,(T_s - T_c)/d$, where (H) was the heat flux (W/m^2); (k) was the thermal conductivity of the roof slab (W/m k) and (d) was the thickness of the roof slab (m). A positive (H) value indicates incoming heat flux to the inside space (heat gain), whereas a negative value denotes outside heat flux (heat loss).

To understand the efficiency during the non-occupation period, efficient and non-efficient days were chosen as examples to analyze all parameters (variation of the temperature and humidity of the air, radiation, wind speed and rainfall).

RESULTS

This work provides real-time data of the thermal performance for two situations (with and without a green roof, GR and C respectively) that would help designing GRs for improving building applications. In order to compare both situations, materials of the studied rooms and the values of thermal conductivity (k) for exterior walls and the roof of both classrooms (C and GR) are detailed in Table 3, and the thermal conductivity of the substrate at different levels of moisture and seasons of the year are detailed in Table 4.

At this point it should be clarified that due to differences in the use of both classrooms, one differs from the other with a constructive difference: C classroom presents a ceiling and the other one with the GR does not.

INSIDE SLAB TEMPERATURE AND ASSOCIATED THERMAL EFFECT

At the beginning of the investigation, the temperature of the inside roof slab with GR was constant within a value of 2.8°C (difference between maximum and minimum outside temperature

TABLE 3. Characteristics of the materials and thermal conductivity of walls and the roofs of studied rooms before installing the green roof.

	Walls	Roofs
Materials	latex layers (3); plaster and joints; solid bricks	latex layers (3); reinforced concrete; concrete rubble; solid bricks; plaster and joints; asphalt paint; cement and sand
K (W/m^2°C) summer	2.09	1.02
K (W/m^2°C) winter	2.09	1.10

TABLE 4. Thermal conductivity of substrate of the GR with three levels of moisture in winter and summer seasons

	Dry substrate	Mid wet substrate	Wet substrate
Winter	0.54	0.68	0.73
Summer	0.52	0.65	0.69

or termed as the "peak-to-valley-gap" (PV)). Inside roof slab with the conventional roof showed a value of 9.5°C (Table 5).

Reliable temperature measures were obtained during the summer period (from 9th January to 28th February) without student movements. During this specific period, we compared the indoor temperatures between the GR and conventional roof (C: control). As can be seen, the

TABLE 5. Temperature parameters at the beginning of the study: mean, coefficient of variation (CV), minimum value, maximum value and peak-to-valley-gap (PV = the difference between maximum and minimum).

Variable	n	Mean±SD	CV	Min (1)	Max (2)	PV = (2)-(1)
Outside Air	697	13.48±9.68	71.81	-5.1	36.8	**41.9**
Outside slab GR	697	15.15±5.86	38.67	5	29.8	**24.8**
Outside slab control	697	20.76±6.16	29.7	9.2	39	**29.8**
Inside slab GR	697	18.17±0.94	5.2	16.9	19.7	**2.8**
Inside slab control	697	21.04±2.22	10.56	16.5	26	**9.5**
Substrate temperature	697	11.39±7.3	64.06	-2.8	26.9	**29.7**

*Outside air: air temperature at 0.8 m from slab; outside slab GR: air temperature on external face slab under green roof system; outside slab control: air temperature on external face slab (C, white roof); inside slab GR: air temperature on internal face slab under green roof system; inside slab control: air temperature on internal face slab (C, white roof); substrate temperature: temperature measured in the middle of the substrate of the depth of the substrate; n = registered dates (every fifteen minutes); SD; standard deviation; CV: coefficient of variation (%); Min: minimum value of serie of dates; Max: maximum of series of dates; PV: the difference between maximum and minimum temperature

TABLE 6. Temperature parameters during the summer period: mean, coefficient of variation (CV), minimum value, maximum value and peak-to-valley-gap (PV = the difference between maximum and minimum).

Variable	n	Mean±SD	CV	Min (1)	Max (2)	PV = (2)-(1)
Outside temp	4849	20.38±7.15	35.08	0.2	36.1	**35.9**
Outside slab GR	4849	21.36±4.46	20.42	7.8	32.2	**24.4**
Outside slab control	4849	27.01±9.59	35.51	10.9	52.4	**41.5**
Inside slab GR	4849	24.34±1.59	6.52	21.1	27.3	**6.2**
Inside slab control	4849	25.96±2.5	9.61	19.4	32.2	**12.8**
Substrate temperature	4849	21.21±5.08	23.97	5.1	33.3	**28.2**

* Outside air: air temperature at 0.8 m from slab; outside slab GR: air temperature on external face slab under green roof system; outside slab control: air temperature on external face slab (C, white roof); inside slab GR: air temperature on internal face slab under green roof system; inside slab control: air temperature on internal face slab (C, white roof); substrate temperature: temperature measured in the middle of the substrate of the depth of the substrate; n = registered dates (every fifteen minutes); SD; standard deviation; CV: coefficient of variation (%); Min: minimum value of series of dates; Max: maximum of series of dates; PV: the difference between maximum and minimum temperature.

differences in these periods of analysis between the GR and the C were comparable to the initial moment. The peak-to-valley-gap (PV) was observed with less value for inside the roof slab temperature with GR of about 6.2°C of C. By comparison, the amplitude in the outside slab was more pronounced (with a difference of 24.4°C below the green roof and 41.5°C without one) (Table 6).

Temperatures at slab on the GR (outside and inside) were more stable than C throughout the entire period (200 days). By observing the pattern through the slab roof temperature fluctuation, an attenuation and delay temperature relative to the outside temperature can be observed (Table 5). During this period, the values for the peak-to-valley-gap temperature were noticeably diminished towards inside space, especially under the GR (Table 7).

TEMPERATURE ATTENUATION CHARACTERISTICS OF THE INSIDE SLAB TEMPERATURE

In order to analyze the pattern of the fluctuations in the roof´s inside slab temperature, the attenuation characteristics was evaluated as: the temperature amplitude, the peak to valley gap and the anti-interference ratio (φ) (Table 8). The ratio of attenuation (anti-interference ratio, φ) is defined as the relation between the peak-to-valley-gap of inside temperature slab and the peak-to-valley-gap of outside temperature (Yang et al., 2015). GR showed lower (i) peak-to-valley-gap (10.8°C), (ii) temperature amplitude (4.82° C) and (iii) ratio φ (0.2) respect control (C) roof with 16.8°C, 8.67°C and φ 0.31 respectively. GR showed better anti-interference performance compared to the control roof (i.e., at the beginning of the trial, during the summer with highest temperatures, and throughout the entire period).

TABLE 7. Temperature parameters during the all essay period: mean, coefficient of variation (CV), minimum value, maximum value and peak-to-valley-gap (PV = the difference between maximum and minimum).

Variable	n	Mean±SD	CV	Min (1)	Max (2)	PV = (2)-(1)
Outside air	17432	17.5±8.48	48.47	-5.1	45	**54**
Outside slab GR	17432	19.52±5.7	29.22	0	37.5	**37.5**
Outside slab control	17432	24.86±9.35	37.62	8.6	57.6	**49**
Inside slab GR	17342	22.88±2.47	10.80	16.9	27.7	**10.8**
Inside slab control	17342	24.13±3.26	13.50	16	32.8	**16.8**
Substrate temperature	17342	18.27±6.33	34.65	0	40.9	**40.9**

* Outside air: air temperature at 0.8 m from slab; outside slab GR: air temperature on external face slab under green roof system; outside slab control: air temperature on external face slab (C, white roof); inside slab GR: air temperature on internal face slab under green roof system; inside slab control: air temperature on internal face slab (C, white roof); substrate temperature: temperature measured in the middle of the substrate of the depth of the substrate; n = registered dates (every fifteen minutes); SD; standard deviation; CV: coefficient of variation (%); Min: minimum value of series of dates; Max: maximum of series of dates; PV: the difference between maximum and minimum temperature.

TABLE 8. Characteristics of the inside slab temperatures for M1, M2 and M3 of the essay showing the temperature attenuation.

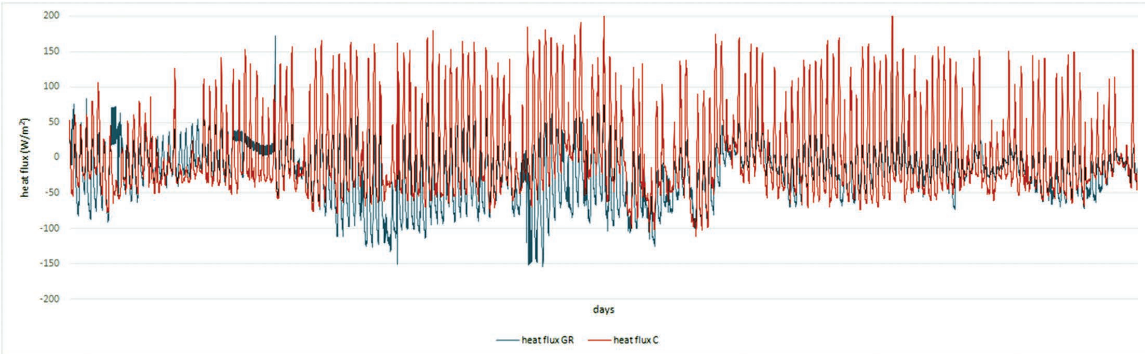
	Moment 1		Moment 2		Moment 3	
	Green roof	Control	Green roof	Control	Green roof	Control
Peak to valley gap for inside slab	2.8°C	9.5°C	6.2°C	12.8°C	10.8°C	16.8°C
Temperature amplitude for inside slab	1°C	4.96°C	2.96°C	6.24°C	4.82°C	8.67°C
Ratio of attenuation (φ)	0.07	0.22	0.17	0.35	0.2	0.31

*φ = peak-to-valley-gap of inside slab/peak-to-valley-gap of outside temperature

HEAT FLUX PATTERN

During the study, the inside space under the control roof experienced heat gain due to the highly heated roof surface during the day resulting from strong solar radiation (Figure 5). Particularly, the higher C roof surface temperature during the day resulted in constant heat penetration to the indoor space, with scarce outgoing heat loss reaching an input heat flux over than 200 W/m^2. At the same time, GR inhibited night-time heat loss and blocked daytime heat gain throughout the evaluated period, except during the first 30 days from plantation where cooling of the inside space occurred at night, and warming during the day.

FIGURE 5. Heat flux patterns of green roof (GR in blue) and control roof (C in red) during the essay.



COMPARISON OF VARIATION IN THETEMPERATURE DIFFERENCE FOR INSIDE ROOM AIR BETWEEN GREEN ROOF AND CONTROL

Environmental Parameters during the Student Non-Occupation Period

The environmental parameters, including ambient air, relative humidity, wind speed, radiation and precipitation for this period are presented in Figure 6.

COMPARISON OF THEVARIATION IN THE INSIDE-ROOM AIR TEMPERATURE DIFFERENCE BETWEEN GREEN ROOF AND CONVENTIONAL ROOF DURING THE NONSTUDENT OCCUPATION PERIOD

The differences in temperature (i.e., as relative thermal performance of GR against C) of this study were expressed in the equation: Indoor temperature difference between classrooms (C and GR) (ID) = (C air indoor temperature – outside temperature; D1) – (GR air indoor temperature – outside temperature; D2). In Figure 4, D2 is expressed as the orange area, and D1 as the blue area. "Efficient days" are those where orange areas have covered the blue bars; at the same time, "non-efficient days" are those where blue areas have covered orange bars (Figure 7).

During the summer period, GR enhanced thermal performance inside of the room with a difference (ID) up to 1.6°C lower than the C roof during the heating period of the day, and up to 4.2°C during the cooling period of the day (Figure 7). These thermal differences in favor of the indoor space under GR, are more meritorious given that the control classroom (C) has a ceiling to increase thermal isolation whereas the other room with GR does not (see M&M section). Moreover, we could observe a dynamic process during the experimental period with variations in these differences according the weather conditions. In order to better understand the thermal performance under the GR, we selected an efficient day (Figure 8 where two other examples are presented in supplementary materials. SFigure 10) and one non-efficient day (Figure 9 where two other examples are presented in supplementary materials SFigure 11) to compare the parameters throughout 24 hours between days with contrasting weather conditions. On the first of the efficient days presented (example 1, E1), the outside temperature reached 25° C with a relative humidity of the environment that did not exceed 75% (Figure 8

FIGURE 6. Environmental parameters of the non-student occupation period: a. Outside air temperature: air temperature at 0.8 m from slab and Air humidity (relative humidity of the air, %); b. Net radiation and Wind speed; c. Rainfall

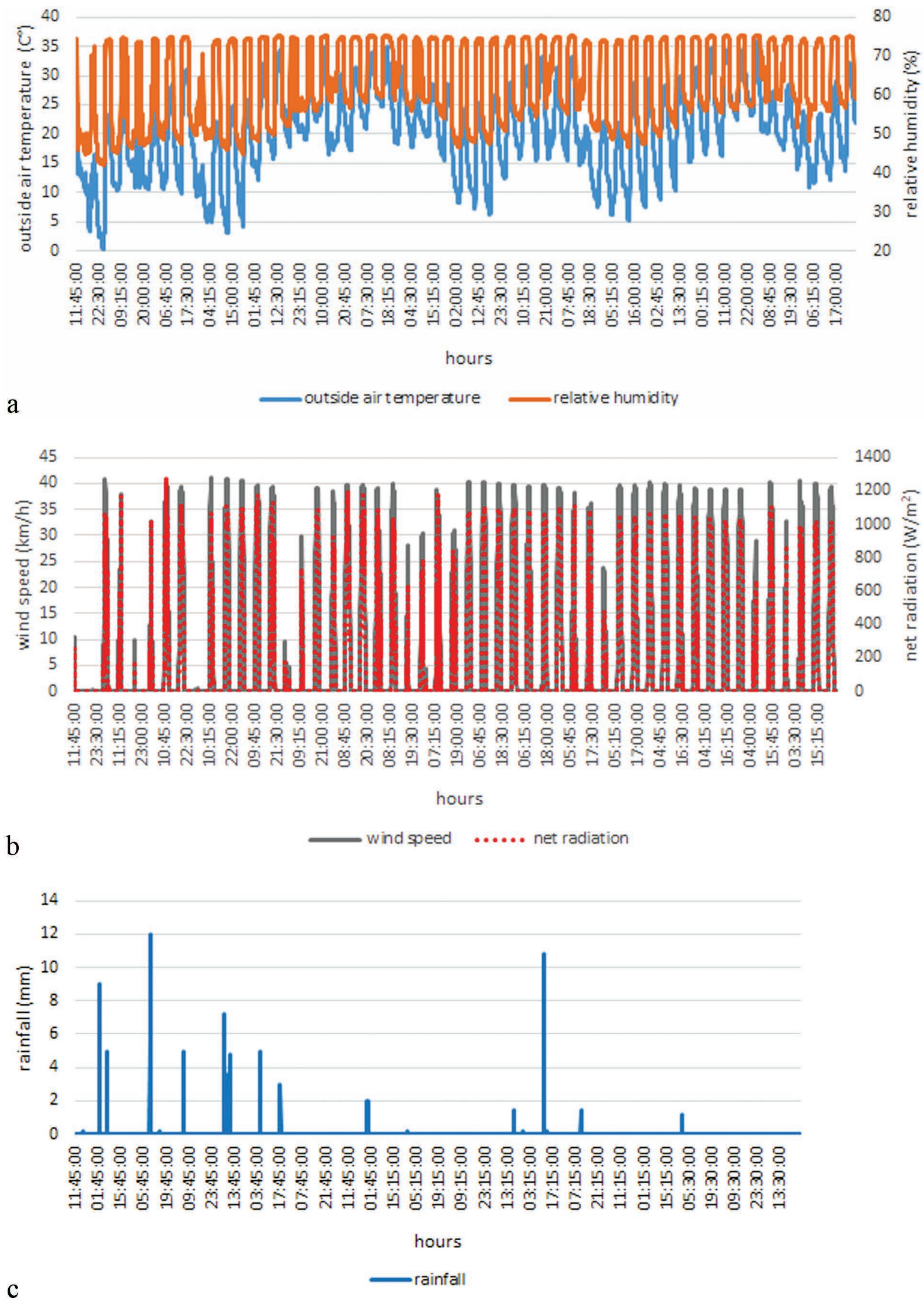


FIGURE 7. Comparative illustration between the outside and inside air temperatures under GR (in orange) and control roof (in blue) during moment 2 of the analysis (see M&M for details).

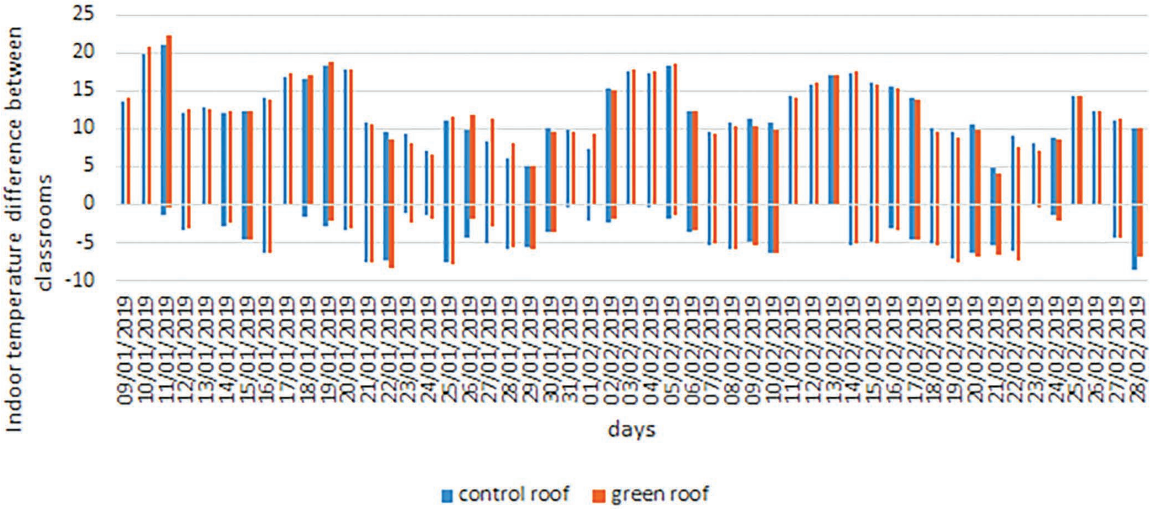
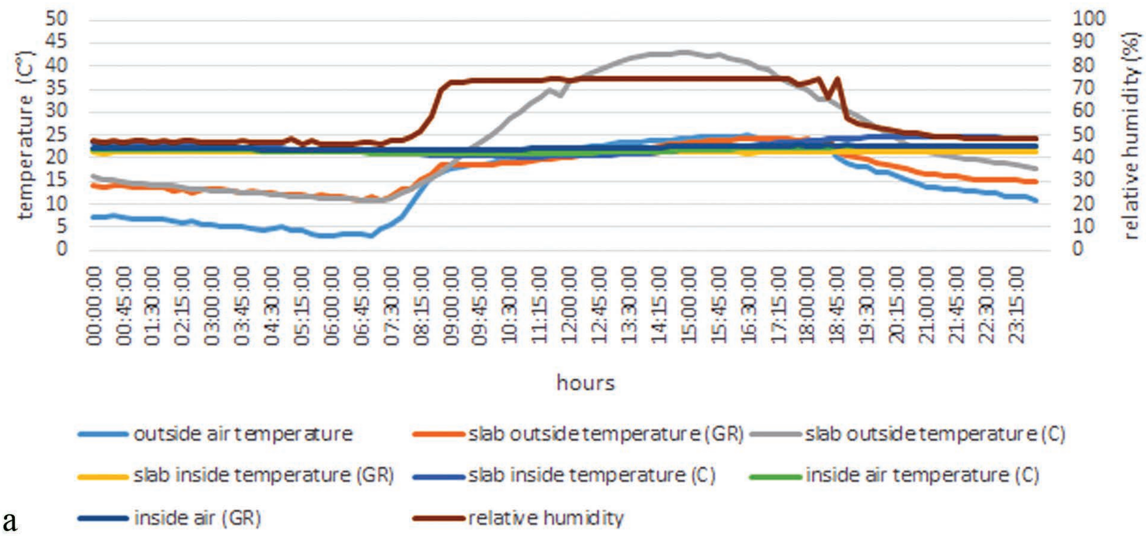


FIGURE 8. Parameters for an efficient day. a. Outside air: air temperature at 0.8 m from slab; outside slab GR: air temperature on external face slab under green roof system; outside slab control: air temperature on external face slab (C, white roof); inside slab GR: air temperature on internal face slab under green roof system; inside slab control: air temperature on internal face slab (C, white roof); air C: temperature of the air at the middle of the classroom under control roof; air green roof: temperature of the air at the middle of the classroom under green roof; b. substrate temperature: temperature measured in the middle of the substrate of the depth of the substrate and substrate moisture; c, Net radiation and wind speed; d, difference of temperature across the layer; for E1.



a

FIGURE 8. *(Continued)*

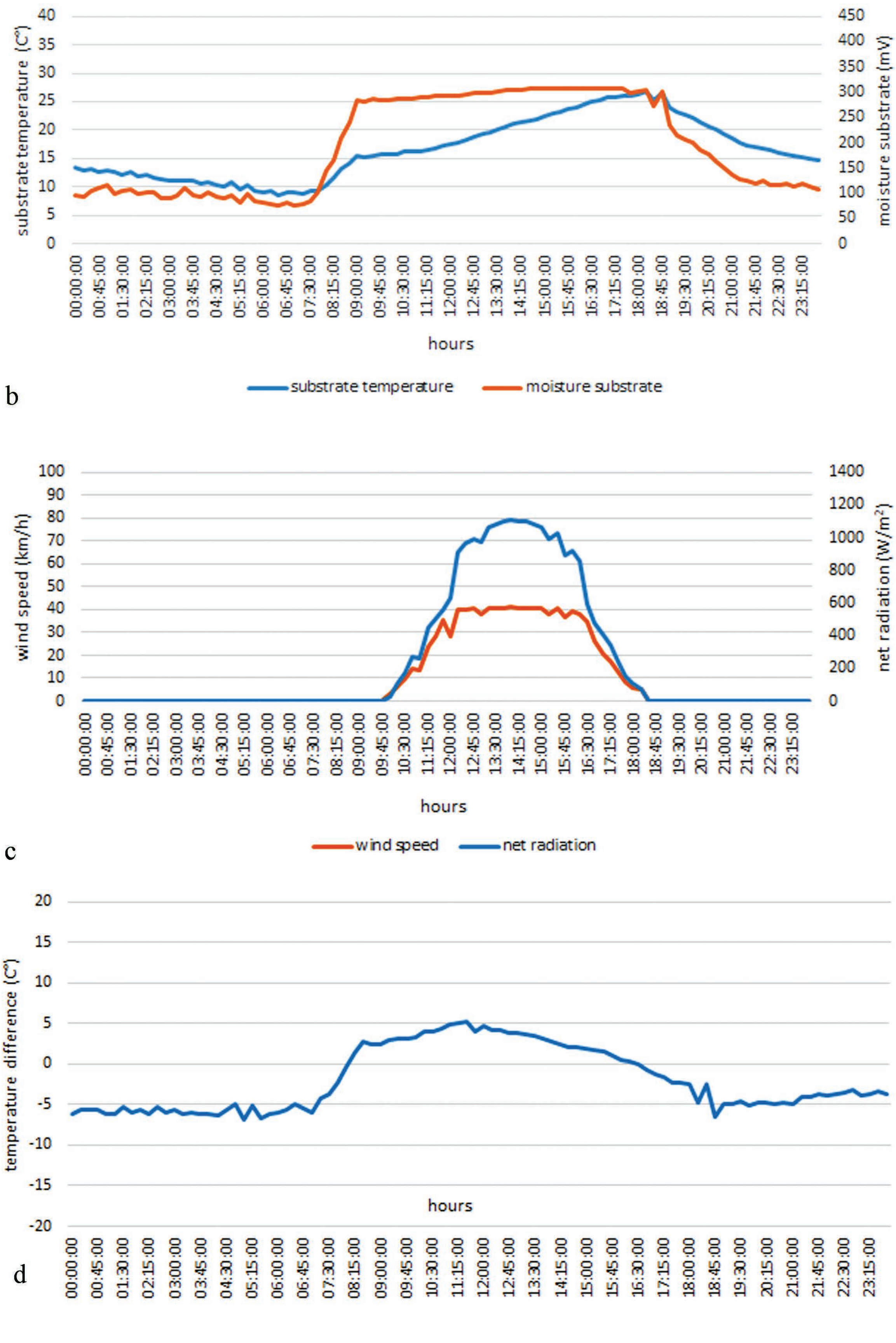
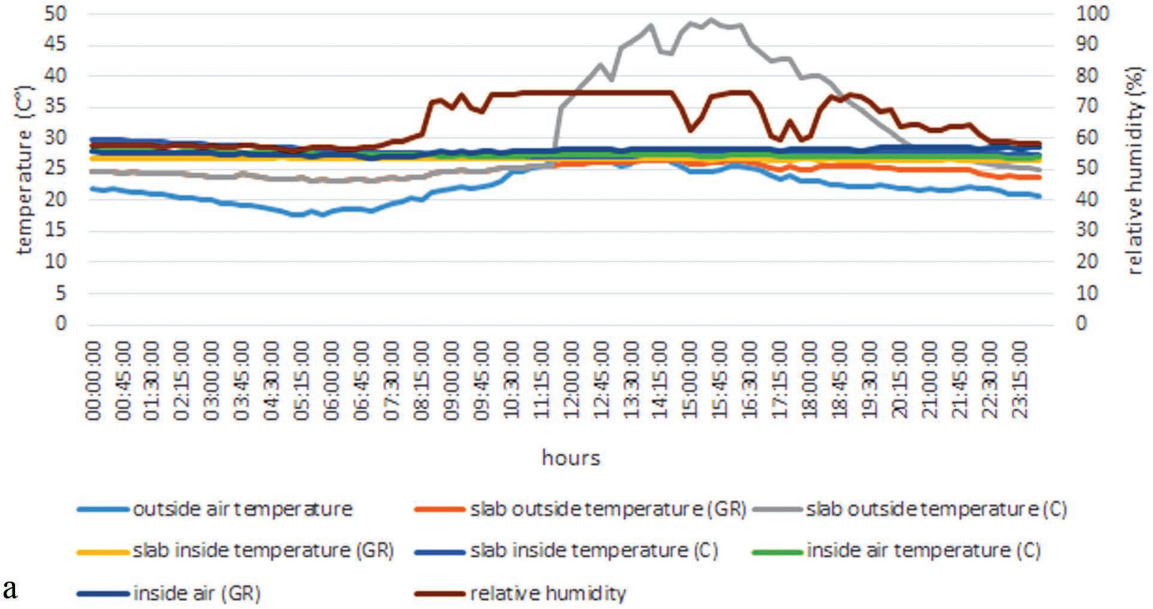
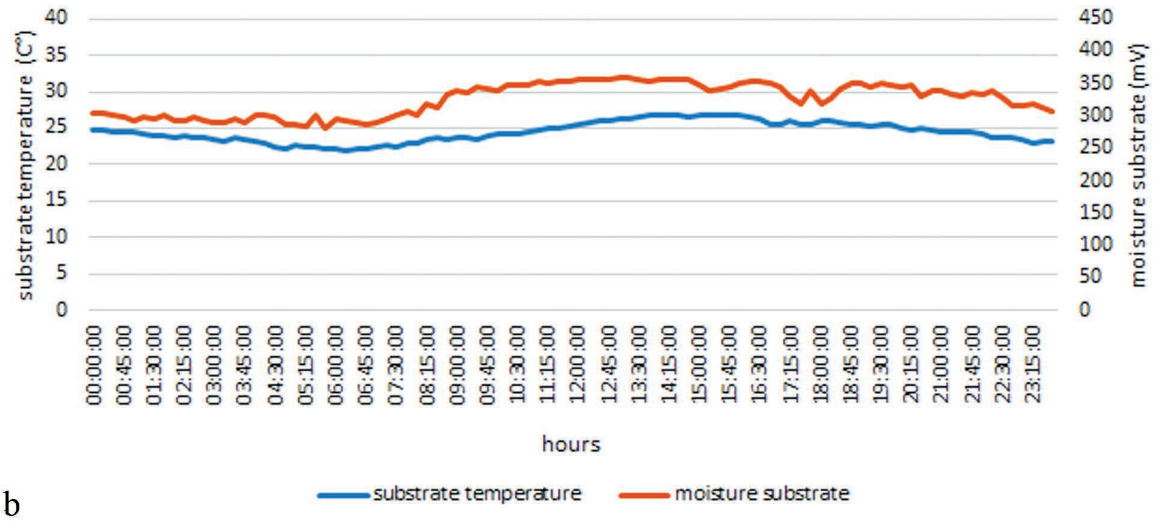


FIGURE 9. Parameters for a non-efficient day: a. Outside air: air temperature at 0.8 m from slab; outside slab GR: air temperature on external face slab under green roof system; outside slab control: air temperature on external face slab (C, white roof); inside slab GR: air temperature on internal face slab under green roof system; inside slab control: air temperature on internal face slab (C, white roof); air C: temperature of the air at the middle of the classroom under control roof; air green roof: temperature of the air at the middle of the classroom under green roof; b. substrate temperature: temperature measured in the middle of the substrate of the depth of the substrate and substrate moisture; c, Net radiation and wind speed; d, difference of temperature across the layer; for E1.

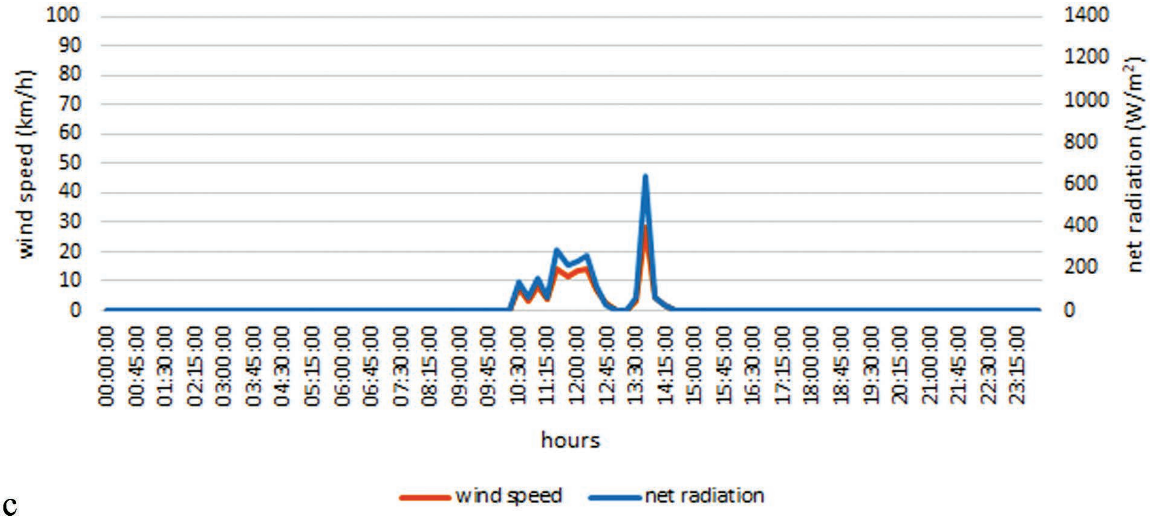


a

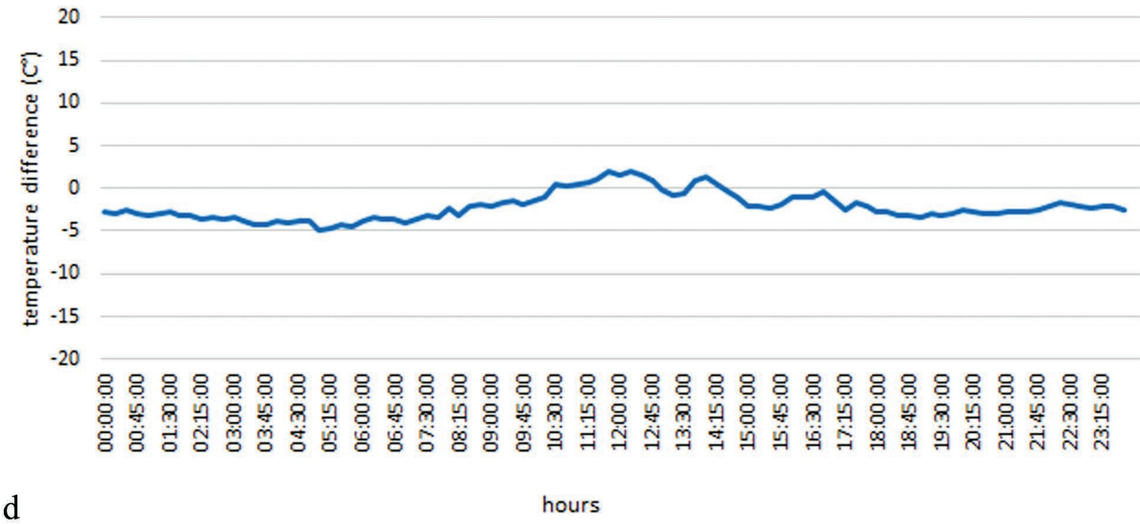


b

FIGURE 9. *(Continued)*



c



d

a). The temperature of the substrate accompanied the outside temperature with a temporary delay and moisture of the substrate decreased despite reaching a high value after 18:45 p.m. (between nearly zero to 300 mV) (Figure 8 b). The radiation and wind speed were high which should cause evapotranspiration and decreasing substrate moisture. It was a sunny and windy day (Figure 8 c). At the same time, the difference between the substrate temperature and the outside temperature (ΔT) remained low, with a peak of (–5°) and 5° C (Figure 8 d). In example 2 (E2), could observe lower values of radiation and wind speed, in spite of which were able to reduce the moisture of the substrate, decreasing the temperature of the substrate accordingly. The value of m (ΔT) was lower (Figure 10 a, b, c, d). Finally, the most noticeable difference of example 3 (E3) was the low substrate moisture throughout the day, allowing evapotranspiration so that the substrate temperature decreased towards the end of the day (Figure 10 e, f, g, h), although (ΔT) reached 5°C. On the first non-efficient days presented (example 4, E4), the outside temperature reached 25°C with a relative humidity of the environment that did not exceed 80% (Figure 9 a). Radiation remained low during the day as was the wind speed, accordingly moisture of substrate stayed high (Figure 9 b, c). The difference between the substrate temperature and the outside temperature (ΔT) has a not so high value (Figure 9 d). On the other hand, example 5 (E5) and example 6 (E6) the difference between substrate temperature and the outside temperature (ΔT) was higher (Figure 11 a, b, c d, e, f, g, h).

DISCUSSION

A green roof is a sustainable choice with ecological benefits that save energy for cooling and heating purposes (Saadatian et al, 2013). The experimental results reported through this study to analyze the thermal performance comparing an extensive GR with a conventional roof (C) in a long-term experimental essay will help to better understand those mechanisms associated with temperature variations between the green and conventional roofs. Although this study needs to verify the consistency of the evidenced thermal trends, these data would also help to design better building structures with improved thermal performance for semiarid regions.

According to literature, GRs can reduce the maximum roof surface temperature, with reported reductions ranging from 15 to 25°C (Peng et al., 2019). Our results obtained in a semiarid region (with Bsh and Cwa Koppen-Geiger climate classification) showed the improvement of the room thermal performance with the installation of a modular extensive GR on a low-insulated rooftop. A reduction of the maximum roof surface temperature of about 5°C was obtained at the beginning of installation of the GR (i.e., during autumn-winter period, with a low green coverage area) and up to 17.1°C during the summer period (i.e., with a high green coverage area). Compared to the exposed control roof, the temperature inside the GR slab surface was 5–6°C less than the control classroom. This temperature range diminished by a GR agreed with previous field and laboratory studies where a significant decrease in the heat flux was reported (Tabares Velasco and Srebric, 2011). For example, a temperature reduction of 2–3.3°C in the inside slab was reported when comparing GR vs conventional roofs (Niachou et al 2001, Zhao, Tan and Tang 2009, Xhao and Xue 2006).

The GR could also reduce the temperature fluctuations in the indoor environment, as was previously reported (Yang et al 2015), Pandey et al 2013, Qin et al 2012). The room with the exposed roof (control) has a lower anti-interference performance to the outdoor air temperature compared to the GR thermal performance during the experimental period. In that case, the thermal inertia of the substrate became very useful to regulate the high thermal amplitude between day and night, particularly during summer weather conditions (Coma et al. 2016).

Our study showed two periods in the pattern of heat flux through the GR. One of these periods was during the first days after plantation, when cooling primarily occurred during the night, warming during the day, and GR coverage was low: Peng et al. (2019) explained this pattern through different factors, (1) exposure of bare soil due to incomplete vegetation coverage; (2) lower albedos of the GR plant canopies with relatively dark colors compared to the conventional white roof; (3) limited soil water content to sustain an adequate evapotranspiration level, among others. The second period occurred during the rest of the essay, when plants grew up and reached a large index of leaf area (LAI). Peng and their collaborators (2019) explained the GR thermal performance as a function of the diurnal and seasonal varying shading, insulation and evapotranspiration effects of the vegetation and soil. He et al. (2017) have suggested two ways to improve thermal performance of a GR: through the relative improvement of roof thermal resistance degree (realized by substrate layer) or through a reduction of the outdoor temperature (by evapotranspiration effect of both the substrate and plant layers). A GR does not always function in favorable ways all the time (Peng et al. 2019). As Tabares Velasco and Sebric (2011) pointed out, wind speed should be a relevant factor favoring passive cooling by evapotranspiration on efficient days. Wind blowing over GRs might enhance evapotranspiration cooling and could facilitate advection to cool the surroundings (Peng et al. 2019). At the same time, solar radiation determines the amount of solar energy received by the roof surface and drives the thermal process of the building-vegetation-atmosphere microclimate system. This process is maximized in semiarid climates during the summer, when conventional roofs are heated by higher solar radiation. In contrast, GRs could improve the balance in thermal differences through evapotranspiration and sustaining cooling effect for the inside air room. Our results showed that evapotranspiration occurred in the presence of net radiation energy, with high wind speeds, and with dry and wet substrates.

The substrate water content is known to be a key factor determining the soil thermal property with diverse effects on thermal performance (Peng et al. 2019). Soil thermal capacity can be enhanced by the substrate water content because it stores heat and suppresses soil thermal fluctuations (Peng et al., 2019). Soil moisture also determines the water availability for evapotranspiration and, in consequence, the cooling of surface and air temperatures are allowed. In addition, water can increase soil thermal conductivity and downward heat transmission to the interior of the building space. These complex effects were previously reported (Tabares Velasco and Srebric, 2011; Peng et al. 2019) and confirmed by the analysis of the results in this study. The results for the efficient days can be explained by the low temperature difference across the layer (ΔT), following the Fourier equation (Tabares-Velasco and Srebric, 2011). This is, heat fluxes through the substrate increase as the substrate becomes drier. Lower heat fluxes are due to the lower temperature differences allowed by higher evapotranspiration fluxes. The latter leads to a temperature decrease due to the latent heat used during evaporation, which leads to a lower temperature difference across the substrate. Thus, it appears that the higher evapotranspiration rates overcome the changes in the thermal conductivity (Tabares-Velasco and Srebric, 2011).

A GR was not always beneficial to reduce building energy demands. Climate and GR features may determine the success or the failure of the thermal efficiency in the use of building energy (Susca, 2019). This study represents the first study for our Argentina region, which is located within a zone between sub-humid and semiarid climate (City of Córdoba, Argentina). The results of this comparison was performed between two adjacent classrooms, one with a low insulated building and the other with a modular GR system, with 15 cm of substrate height, plant stratum with LAI 3 and minimal artificial irrigation. According to the survey of GRs for Córdoba city made in 2016, it has 6504 m^2 of GRs, of which 45% of them had less than 20cm of substrate height and infrequent artificial irrigation (Suárez et al., 2016). It is important to repeat the experimental essay to confirm our main findings, especially in the center of Córdoba city (urban heat island) to be able to extrapolate these trends to other cities located in semiarid regions.

CONCLUSION

Experimental data revealed interesting information about thermal performance of GR on temperature regulation for semiarid regions as the study was performed within the climate Bsh and Cwa Koppen-Geiger classification. Compared to an exposed roof (control), the GR had significantly enhanced the cooling inside the slab surface and also had reduced the influence of the outside air temperature fluctuation to the indoor environment. These effects are observed from the beginning of the GR installation. The increases in the evapotranspiration rate of the substrate and in the complexity of plant layers imply the improvement in the conductive heat fluxes (low moisture of the substrate or a reduction of the temperature difference across the layers) which would favor the thermal regulation and energetic efficiency of the GR. A limitation of this study is that the length of the essay period can be extended in the future (i.e., more than a year). At the same time, a new experimental essay should be carried out comparing the center of the city of Córdoba and the periphery to analyze if the differences in both locations with different environmental conditions affect the performance of the GR. It is expected that in the near future we will have answers to these two questions, as well as more thermal details when comparing GR performance of varying vegetal layers.

REFERENCES

Butler, C., Orians, C.M. (2011). "Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof." *Ecol Eng*, 37 (11), 1796–1803.

Cascone, S., Coma, J., Gagliano, A., Pérez, G. (2018). "The evapotranspiration process in green roofs: A review." *Build and Environ*, doi:10.1016/j.buildenv.2018.10.024

Coma, J., Pérez, G., Solé, C., Castell, A., Cabeza, L. F. (2016). "Thermal assessment of extensive green roofs as passive tool for energy savings in buildings." *Renew energ*, 85, 1106–1115.

Derguy, M.R., Frangi, J.L., Drozd, A.A., Arturi, M.F., Martinuzzi, S. (2019). "Holdridge life zone map Republic of Argentina." USDA Forest Service, International Institute of Tropical Forestry General Technical Report.

Fernandez-Cañero, R., Emilsson, T., Fernandez-Barba, C., Machuca, M.Á.H. (2013). "Green roof systems: A study of public attitudes and preferences in southern Spain." *J of Environ Manage*, 128: 106115.

Fioretti, R., Palla, A., Lanza, L.G., Principi, P. (2010). "Green roof energy and water related performance in the Mediterranean climate." *Build and Environ*, 45 (8): 1890–1904.

He, Y., Yu, H., Ozaki, A., Dong, N., Zheng, S. (2017). "Long-term thermal performance evaluation of green roof system based on two new indexes: A case study in Shanghai area." *Build and Environ*, 120, 13–28.

Jaffal, I., Ouldboukhitine S.E, Belarbi, R. (2012). "A comprehensive study of the impact of green roofs on building energy performance." *Renew energ*, 43: 157–164.

Jim, C.Y., Peng, L.L. (2012). Substrate moisture effect on water balance and thermal regime of a tropical extensive green roof. *Ecol Eng*, 47, 9–23.

Kadas, G. (2006). "Rare invertebrates colonizing green roofs in London." *Urban Habitats*, 4(1), 66–73.

Lazzarin, R.M., Castellotti, F., Busato, F. (2005). "Experimental measurements and numerical modelling of a green roof." *Energ Buildings*, 37, 1260–7.

Lin, B.S., Yu, C.C, Su, A.T., Lin, Y.J. (2013). "Impact of climatic conditions on the thermal effectiveness of an extensive green roof." *Build and Environ*, 67(0), 26–33.

Mees, H.L., Driessen, P.P., Runhaar, H.A., Stamatelos, J. (2013). "Who governs climate adaptation? Getting green roofs for stormwater retention off the ground." *J of Environ Plann Man*, 56(6), 802–825.

Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., Mihalakakou, G. (2001). "Analysis of the green roof thermal properties and investigation of its energy performance," *Energ Buildings*, 33, 719–729.

Pandey, S., Hindoliya, D.A., Mod, R. (2013). "Experimental investigation on green roofs over buildings." *Int J Low-Carbon Technol*, 8:37–42.

Peng, L. L., Yang, X., He, Y., Hu, Z., Xu, T., Jiang, Z., Yao, L. (2019). "Thermal and energy performance of two distinct green roofs: Temporal pattern and underlying factors in a subtropical climate." *Energ Buildings*, 185, 247–258.

Pérez, G., Vila, A., Solé, C., Coma, J., Castell, A., Cabeza, L. F. (2015). "The thermal behaviour of extensive green roofs under low plant coverage conditions." *Energ efficiency*, 8(5), 881–894.

Saadatian, O., Sopian, K., Salleh, E., Lim, C.H., Riffat, S., Saadatian, E., A. Toudeshki, A., Sulaiman, M.Y. (2013). "A review of energy aspects of green roofs." *Renew Sust Energ Rev*, 23(0), 155–168.

Qin, X., Wu, X., Chiew, Y.M., Li Y. (2012). "A green roof test bed for stormwater management and reduction of urban heat island effect in Singapore." *Brit J Environ Clim Change*, 2(4), 410–20.

Sharma, A., Conry, P., Fernando, H.J.S., Hamlet, A.F., Hellmann, J.J., Chen, F. (2016). "Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model." *Environ Res Lett*, 11(6), 064004.

Silva, C. M., Gomes, M. G., Silva, M. (2016). "Green roofs energy performance in Mediterranean climate." *Energ Buildings*, 116, 318–325.

Spolek, G. (2008). "Performance monitoring of three eco-roofs in Portland, Oregon." *Urban Ecosyst*. 11, 349–359.

Suarez M., Caceres N., Imhof L., Hick E., Fenoglio M.S., Ivancovich G., Romero S., Cortadi M., Wulff E. (2016). Survey of green roofs of the city of Córdoba. First diagnosis. Catholic University of Córdoba Editorial. 20p. ISBN 978-987-626-332-0.

Suárez, M., Galetto, L., Cáceres, N., Hick, E., Matoff, E., Imhof, L. (2019). "Performance of native plant genotypes (*Glandularia*-Verbenaceae) on semi-intensive green roofs with low maintenance requirements." *Cities and the Environment* (CATE): 12(2), 1–17.

Susca, T. (2019). "Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate." *Building and Environment*, (162), 106–273.

Sutton, R. (2015). "Introduction to Green Roof Ecosystems. Ecological Studies (Analysis and Synthesis)," In: *Green roof ecosystems*. Springer, Cham Heidelberg New York Dordrecht London. ISSN 0070-8356.

Tabares-Velasco, P. C., Srebric, J. (2011). "Experimental quantification of heat and mass transfer process through vegetated roof samples in a new laboratory setup." *Int J Heat Mass Tran*, 54 (25–26), 5149–5162.

Tang, M., Wang, K., Jiang. L. (2010). "Study on thermal parameters of green roof for energy saving." *China Building Waterproofing*, 23, 18–21.

Torres, C. Galetto, L. (2011). "Flowering phenology of co-occurring Asteraceae: a matter of climate, ecological interactions, plant attributes or of evolutionary relationships among species?" *Org Divers Evol*, 11, 9–19.

Veisten K., Smyrnova Y., Klæboe R., Hornikx M., Mosslemi M., Kang J. (2012). "Valuation of green walls and green roofs as soundscape measures: Including monetised amenity values together with noise attenuation values in a cost-benefit analysis of a green wall affecting courtyards." *Int J of Env Res Pu He*, 9(11), 3770–3788.

Vera, S., Pinto, C., Victorero, F., Bustamante, W., Bonilla, C., Gironás, J., Rojas, V. (2015). "Influence of plant and substrate characteristics of vegetated roofs on a supermarket energy performance located in a semiarid climate." *Energy Procedia*, (78), 1171–1176.

Volder A., Dvorak B. (2013). "Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in Central Texas." *Sustain Cities Soc*, 10, 59–64.

Wilkinson S.J., Dixon T. (2016). Green Roof Retrofit: building urban resilience. John Wiley & Sons.

Wolf D., Lundholm J. (2008). "Water uptake in green roof microcosms: effects of plant species and water availability." *Ecol Eng*, 33, 179–186.

Yang J., Yu Q., Gong P. (2008). "Quantifying air pollution removal by green roofs in Chicago." *Atmos environ*, 42(31), 7266–7273.

Yang, W., Wang, Z., Cui, J., Zhu, Z., Zhao, X. (2015). "Comparative study of the thermal performance of the novel green (planting) roofs against other existing roofs." *Sustain Cities Soc*, 16, 1–12.

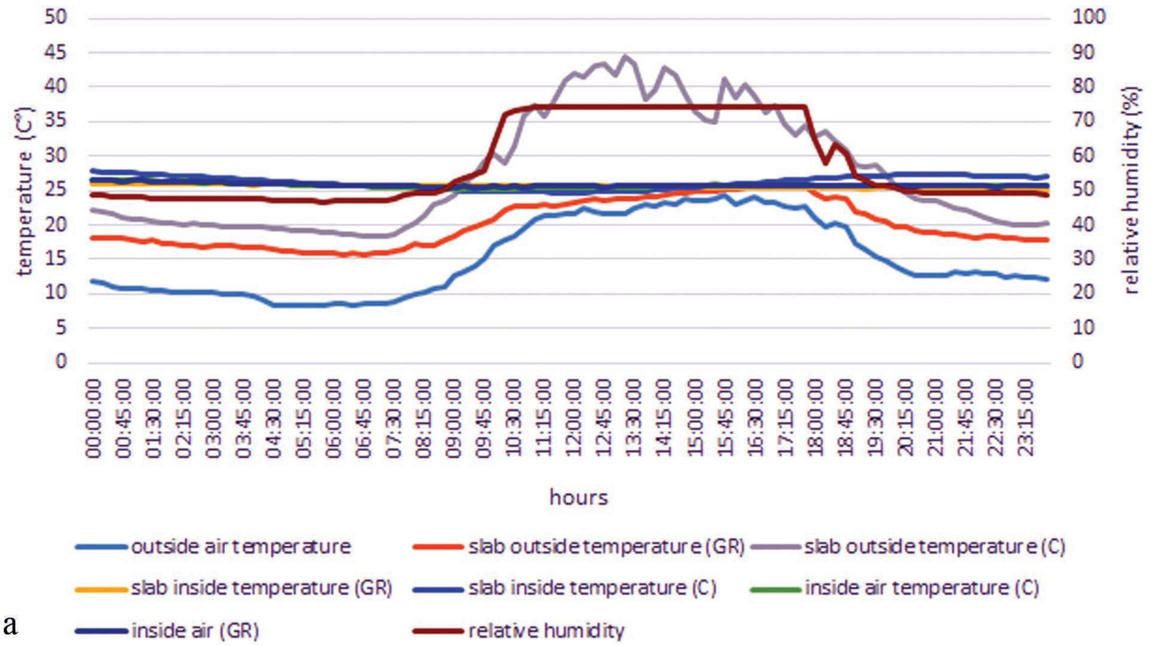
Zhao, D., Tan, Y., & Tang, M. (2009). Quantitative analysis of energy saving green roofs. *Chinese Horticultural Abstract*, 12(2), 27–30.

Zhao, D., Xue, W. (2006). Effect of greening on light roofing on lowering temperature. *Acta Agriculturae Shanghai*, 22(1), 53.

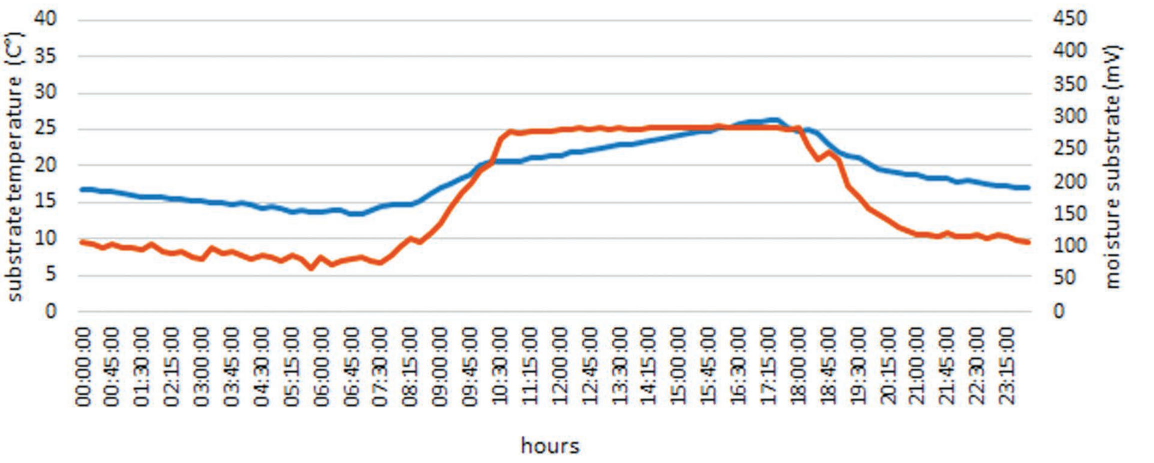
Zhang, X., Ren, Z., Mei, F. (2008). Heat transfer Beijing: Chinese Building Industry Press.

SUPPLEMENTARY MATERIALS

SFIGURE 10. For efficient days; a, e. Outside air: air temperature at 0.8 m from slab; outside slab GR: air temperature on external face slab under green roof system; outside slab control: air temperature on external face slab (C, white roof); inside slab GR: air temperature on internal face slab under green roof system; inside slab control: air temperature on internal face slab (C, white roof); air C: temperature of the air at the middle of the classroom under control roof; air green roof: temperature of the air at the middle of the classroom under green roof; b, f. substrate temperature: temperature measured in the middle of the substrate of the depth of the substrate and substrate moisture; c, g, Net radiation and wind speed; d, h, difference of temperature across the layer; for E2 and 3.

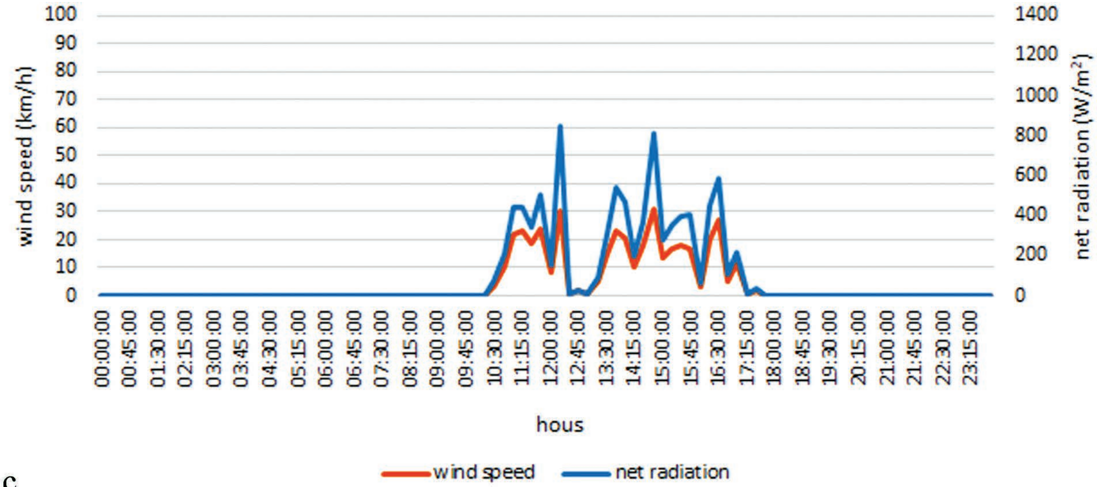


a

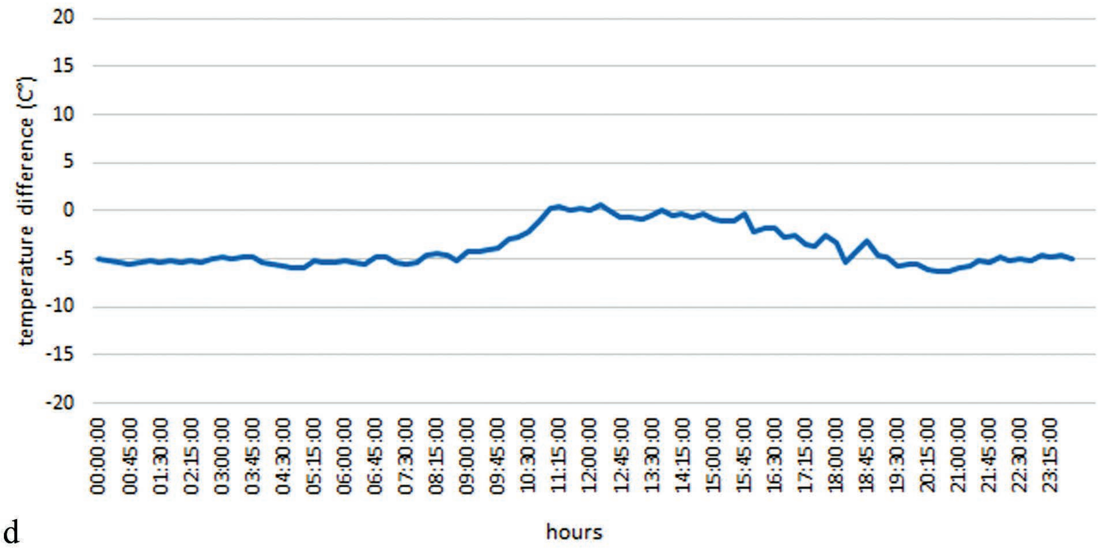


b

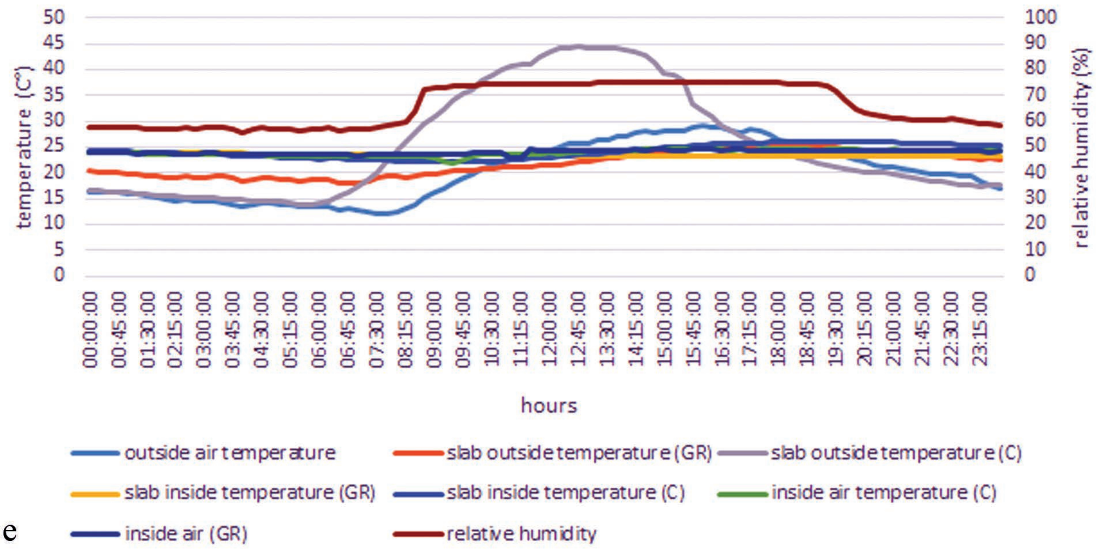
SFIGURE 10. *(Continued)*



c

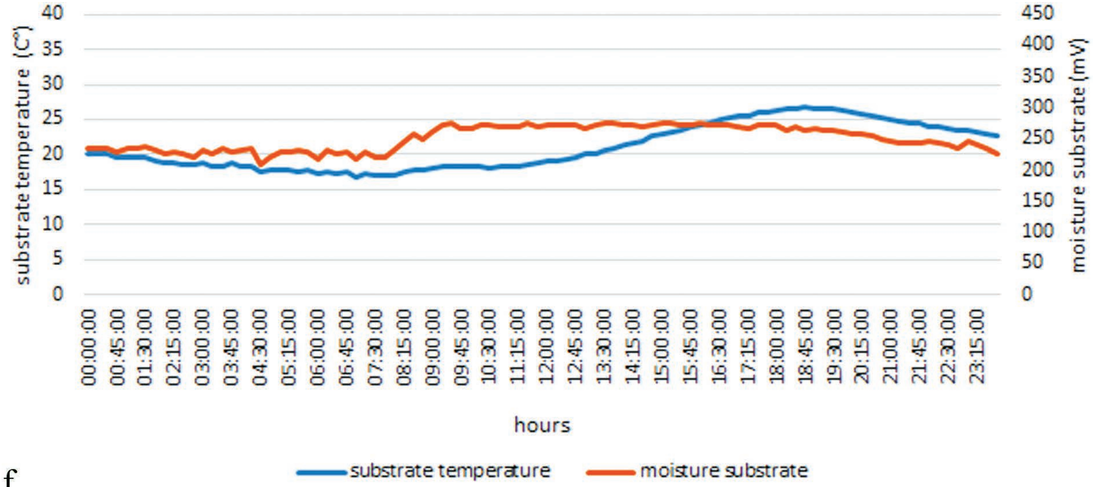


d

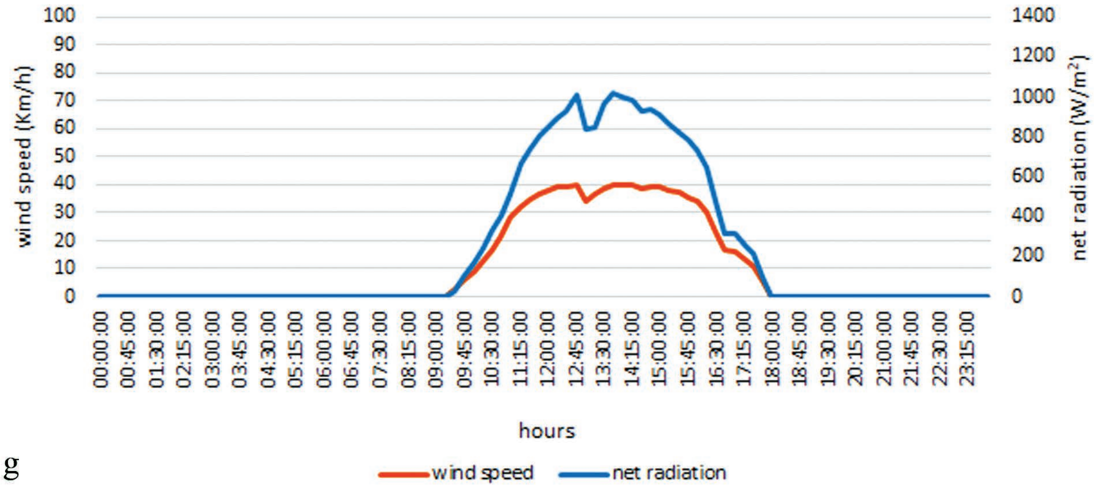


e

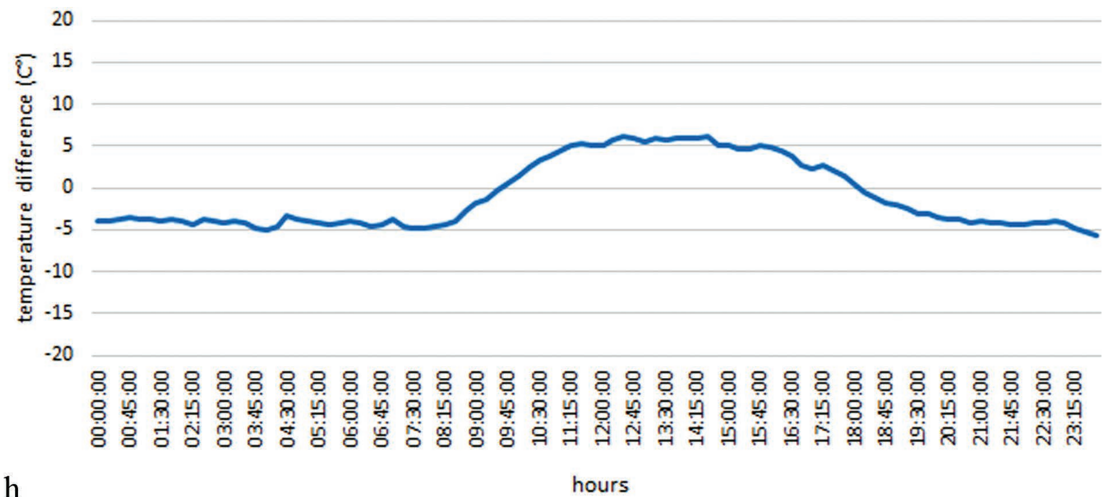
SFIGURE 10. *(Continued)*



f

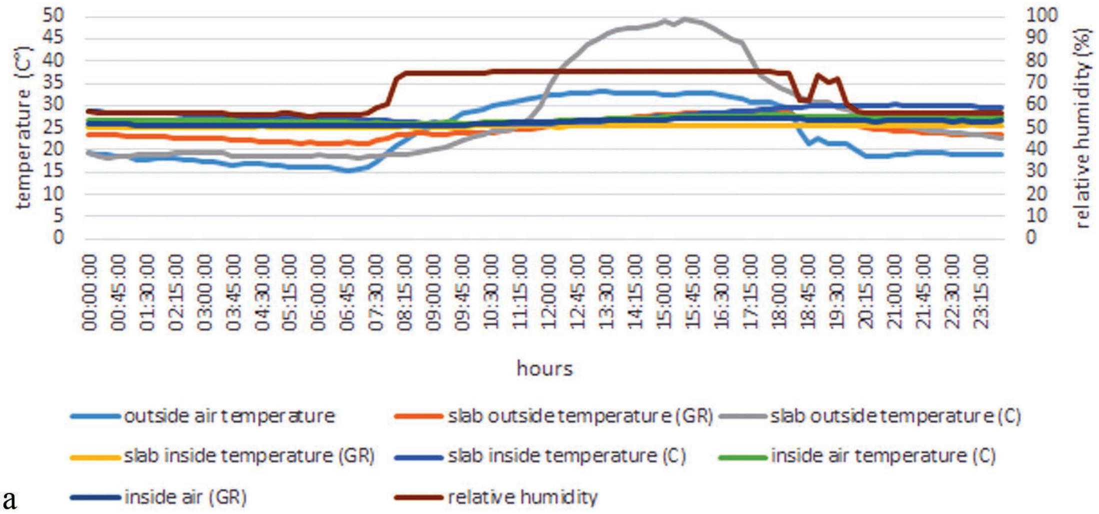


g

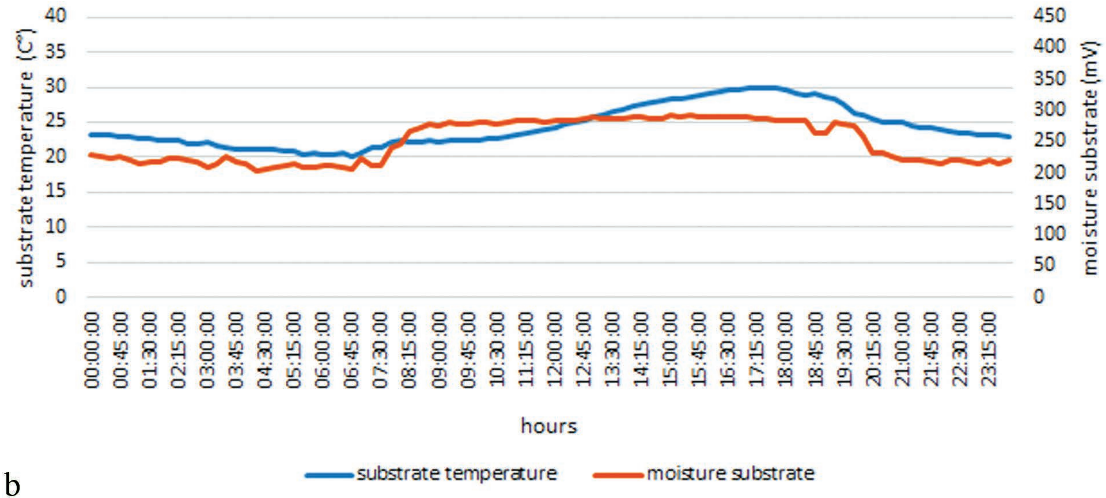


h

SFIGURE 11. For non-efficient days; a, e. Outside air: air temperature at 0.8 m from slab; outside slab GR: air temperature on external face slab under green roof system; outside slab control: air temperature on external face slab (C, white roof); inside slab GR: air temperature on internal face slab under green roof system; inside slab control: air temperature on internal face slab (C, white roof); air C: temperature of the air at the middle of the classroom under control roof; air green roof: temperature of the air at the middle of the classroom under green roof; b, f. substrate temperature: temperature measured in the middle of the substrate of the depth of the substrate and substrate moisture; c, g, Net radiation and wind speed; d, h difference of temperature across the layer; for E2 and E3.

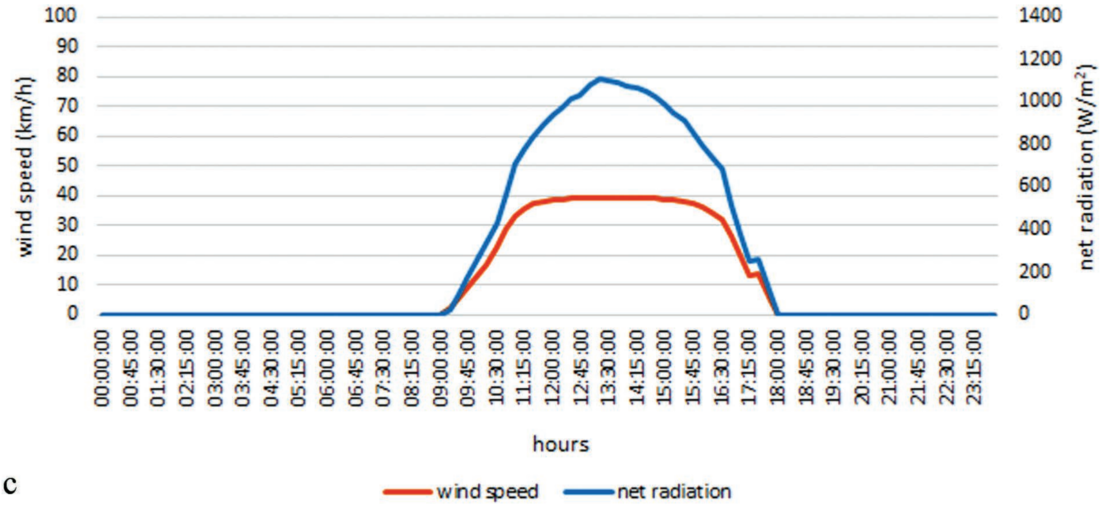


a

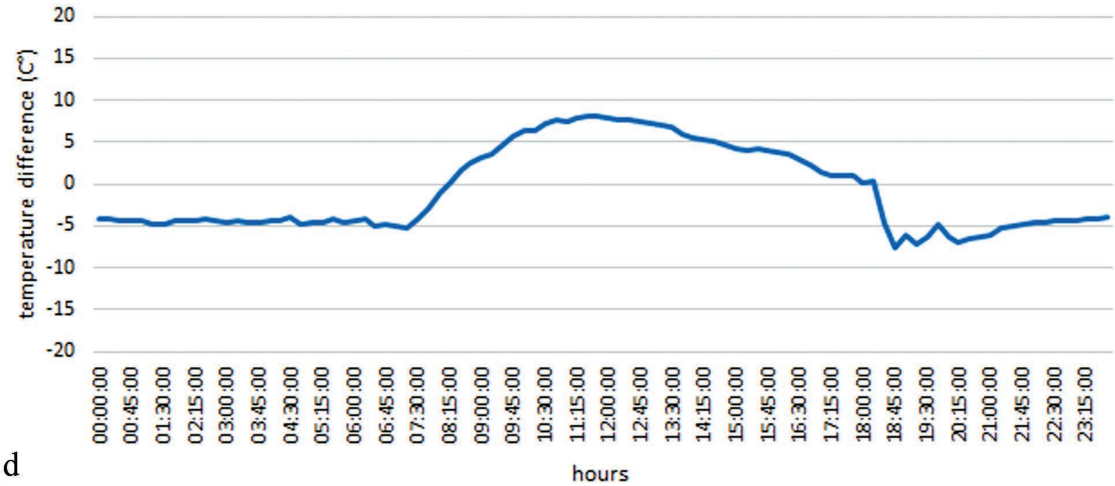


b

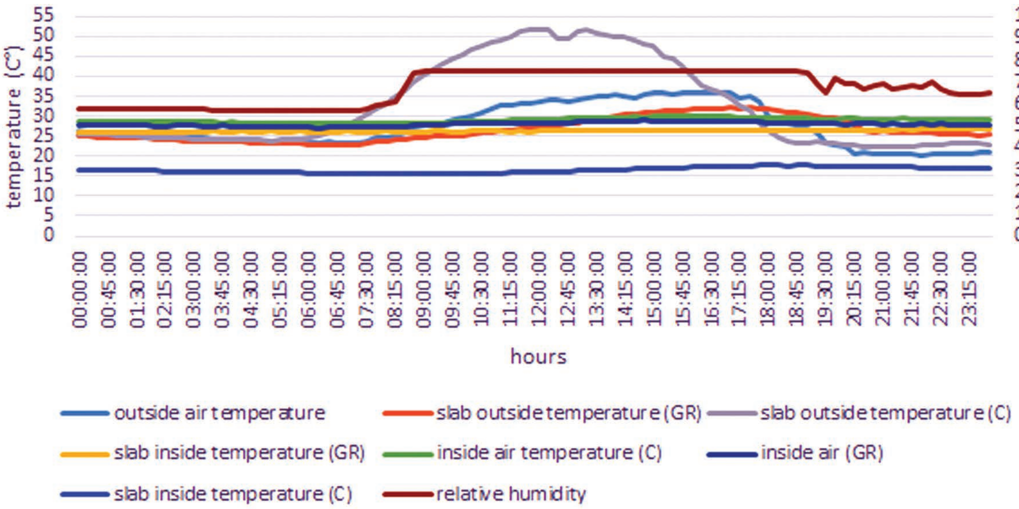
SFIGURE 11. *(Continued)*



c

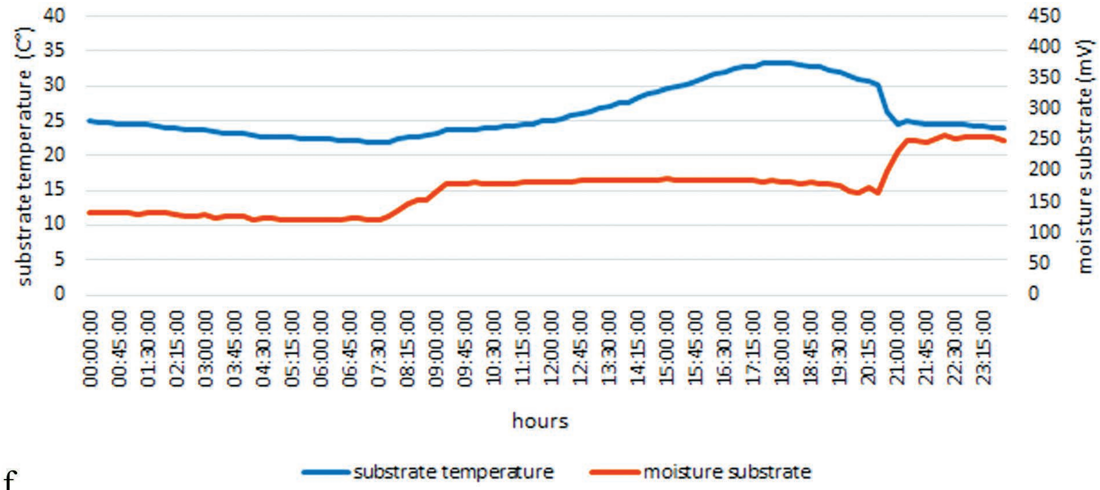


d

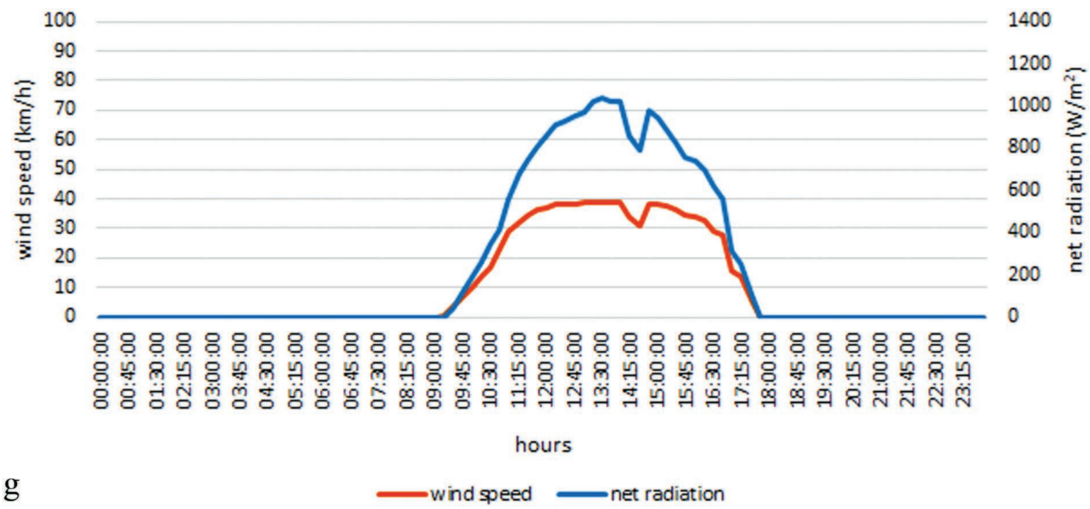


e

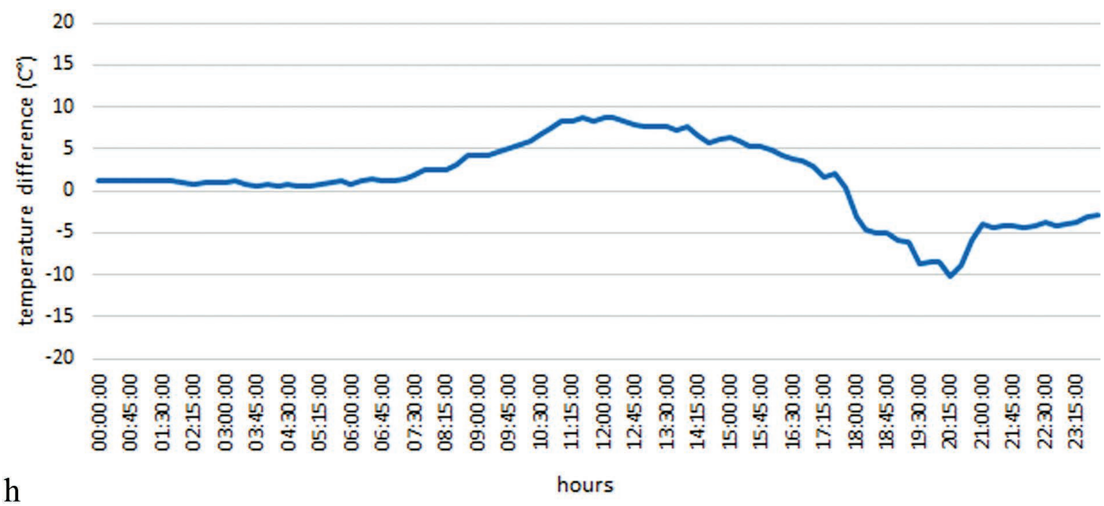
SFIGURE 11. *(Continued)*



f



g



h