WINTERTIME THERMAL PERFORMANCE OF GREEN FAÇADES IN A MEDITERRANEAN CLIMATE

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ABSTRACT

The increasing environmental issues have afforded opportunities for a widespread application of green systems in urban areas. Greening the building with green roofs and vertical green systems can be a design and retrofitting strategy to improve building energy performance in summer and in winter. Research efforts have been mainly concentrated on their energy saving function during warm periods. Green façades have a great application potential thanks to the space available in urban environment. The effect of green façades on building energy performance has been studied mainly for warm periods. In order to evaluate the effect during cold periods, an experiment was conducted in Bari, Italy, for two years. *Pandorea jasminoides variegated* and *Rhyncospermum jasminoides* were tested as evergreen climbing plants on walls; a third wall was used as control. The night-time temperature of the covered wall was higher than the uncovered wall temperature by up to 3.5°C, thanks to the presence of plants. The thermal barrier function performed by the vegetation layer was analysed. The influence of outdoor air temperature, relative humidity and wind velocity on the façades thermal effect during night-time was investigated. The experimental test demonstrated that both *Pandorea jasminoides variegated* and *Rhyncospermum jasminoides* are suitable for green façades in the Mediterranean climatic area during winter. The use of the green façades allowed increasing the thermal performance of the walls during night-time. They also reduced the surface temperature changes throughout the day.

Keywords: building energy efficiency, energy saving, energy balance, heating effect, vertical greenery systems.

1 INTRODUCTION

The European Council set the goal for Europe and other developed economies of cutting greenhouse gas emissions (GHG) by 80–95% by 2050 below 1990 levels [1]. EU countries succeeded between 1990 and 2017 in decoupling GHG emissions from economic growth by reducing GHG emissions by 22% and at the same time increasing gross domestic product by 58% [2]. Nevertheless, the decarbonisation process is still slow. The reduction of the consumption and environmental impacts of the building sector plays an important role for this objective. One third of global greenhouse gas emissions are attributable to buildings and the heating and cooling buildings energy demands account to about 50% of the final energy consumption in the EU28. Large energy savings can be obtained by improving the building envelope design and construction that affect 20–60% of all energy used in buildings to maintain internal thermal comfort [3], [4].

The ever-rising urban population leads to the replacement of natural vegetation with reinforced concrete buildings and thus to the urban heat island effect, the increase in building energy consumption and GHG emissions. Urban green infrastructures (UGI) are nature-based solutions that can improve urban climate conditions, decrease urban air, surfaces temperature

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level and variation, in particular in the Mediterranean climatic area [5]. UGI include lawns, parks, private gardens, shade trees, remaining native vegetation, and so on, and building greenery systems such as green balconies, sky gardens, green roofs, green walls [6], [7]. The most studied building greenery systems are the green roofs, nevertheless green walls are gaining even more attention. Green walls have potentially more environmental effectiveness in highly urbanized areas because the building vertical surfaces can be also 20 times the area of the roof [8], [9]. Moreover, a very little space for greening results on the rooftop due to the presence of bulky devices, such as solar panels and water tanks.

Green wall systems can be classified into green façades and living walls. Green façades are characterized by climbing plants that grow on a building vertical wall attached directly to it (direct green façades) or on a structural support such as modular trellis, wire, mesh (indirect green façades). The supporting structure is located to a small distance from the wall. Climbers can be rooted in the soil on ground or in pots that can be placed at different heights of the façade. Living walls are characterized by the growing media embedded in panels, modules, bags (modular living walls) or by continuous screen or geotextile felt (continuous living walls) which are fixed to a wall or a free-standing frame [6], [10]. Green façades, when compared to living walls have a wider application potential due to having a simpler composition, easier installation and maintenance, lower operational and installation costs [11].

The use of vertical greenery systems is a passive green technology for improving buildings energy performance by lowering energy demand for air conditioning in summer and by enhancing thermal insulation in winter. Their application can also alleviate urban ecological environment deterioration and provides economic and social benefits [12]–[16]. Thermal effects of green façades on the environment are mainly due to the following mechanisms: shading of the building envelope from solar radiation provided by plants, thermal insulation produced by the different layers composing the greenery system, cooling by evapotranspiration from the vegetation or from the substrate, and protection from wind exposure [15]–[17]. Moreover, the creation of an air gap between the building external wall and the green layer can act as a thermal barrier to the diffusion of longwave radiation from the wall towards external ambient, improving building thermal insulation [6], [8], [18].

Many experimental and theoretical studies have mainly investigated thermal effects of green façades on buildings in summer. A few studies have investigated their energy behaviour throughout the year for evaluating the performance of perennial climbing plants [8], [19].

Winter passive warming may come from the higher temperatures generated in the air-gap and on the wall external surface in indirect green façades [20]. In subtropical climates, where buildings are rarely equipped with air heating systems, a negative temperature difference could be generated by keeping warmth in the air gap and wall external surface, thus a heat flux from them towards indoor ambient could be established [21].

Highest thermal performances of green façades have been assessed by Cameron et al. [22] during extreme weather conditions, i.e. very low temperatures, high wind or heavy rain in temperate oceanic climate. Energy savings up to 50% and wall surface temperatures higher up to 3°C, compared with a bare wall, were recorded using a Hedera helix as green façade component.

Wall temperatures and energy loss on a Hedera helix green façade and on a bare exposed wall, both north-facing, were compared in a maritime temperate climate. Minimum external wall temperatures on the green façade were on average 1.7°C higher than the bare wall, winter heating costs were reduced, and energy losses were lowered by almost 8%, despite the heating effect of short-wave radiation was minimized during daytime [23].

In winter the vegetated systems could create negative thermal effects by reducing the inflow of short-wave solar radiation and thus, their application could lead to an increase in heating systems energy consumptions [24].

Green façades thermal benefits in winter conditions should be assessed and plant species suitable for this application in areas characterized by high levels of solar radiation, such as the Mediterranean regions, should be defined [25].

This study aims to investigating the thermal performance of two different evergreen climbing plants for green façades, experimentally tested at the University of Bari in the winter season. Climatic data and surface temperatures were analysed for defining the influence of the different climatic parameters on the external surface temperatures of the walls equipped with vertical greenery systems. Benefits deriving from the thermal barrier effect provided by the vegetation layer were also evaluated.

2 MATERIALS AND METHODS

A research was performed at the experimental centre of the University of Bari in Valenzano (Bari, Italy) latitude 41° 01' N and longitude 16° 54' E, in the period June 2014–December 2016. The climate at the experimental field is classified as Csa, Mediterranean climate, according to the Köppen–Geiger climate classification [26]. It is a warm temperate climate with a particularly evident variation of solar radiation intensity at seasonal level; the average annual temperature is 16.1°C and the winter months are considerably rainier than the summer months.

A typical Mediterranean building solution was followed for the setup of three experimental walls in open environment, built facing south. The walls are made of perforated bricks, arranged in a single skin, joined with mortar (Fig. 1) with a width of 1.00 m, a height of 1.55 m, and a total thickness of 0.22 m, including 0.02 m of the plaster coating. The masonry is characterized by a thermal conductivity coefficient of 0.28 $Wm^{-1}K^{-1}$ [27] and a heat capacity coefficient of 840 $Jkg^{-1}K^{-1}$. The plaster coating is characterized by a thermal

Figure 1: The three walls at the experimental field of the University of Bari: the uncovered control (the left wall), the *Pandorea jasminoides variegated* green façade (on the central wall), the *Rhyncospermum jasminoides* green façade (on the right wall).

conductivity coefficient of 0.55 $Wm^{-1}K^{-1}$ and a heat capacity coefficient of 1,000 $Jkg^{-1}K^{-1}$. The average density of the walls, taking in consideration also plaster, was equal to 695 kg m^{-3}. The south exposed side of two walls was covered with plants and it simulates the external side of a Mediterranean common building envelope. The other side was shaded and insulated with a sealed structure made of sheets of expanded polystyrene. The incident solar radiation effect on the sealed structure was reduced by the adoption of a shading net, positioned onto the structures.

The radiometric properties of the wall surface were evaluated by laboratory tests [28]. The emissivity coefficient of the wall surface samples in the long wave infrared radiation (LWIR) range (2,500–25,000 nm) was 95.3% and the solar absorption coefficient was 42.1%.

Pandorea jasminoides variegated and *Rhyncospermum jasminoides* were chosen for their capacity to easily climb the wall and to grow vigorously in the climatic conditions of the experimental area. The plants were transplanted on June 18, 2014. The third bare wall was kept for control. As structure supporting plant growing, an iron net was put 15 cm away from the wall. Drip irrigation and fertilization with N:P:K 12:12:12 were performed. Plant leaf surface index (LAI) varied throughout the year in the ranges 1.5–3.5 and 2.0–4.0 for *Pandorea jasminoides variegated* and *Rhyncospermum jasminoides*, respectively. It was measured with an AccuPAR PAR/LAI Ceptometer (model LP-80, Decagon Devices Inc., Pullman, WA, USA).

The external air temperature and relative humidity, the wind speed and direction, the external surface temperature of the wall, the solar radiation on a horizontal and on a vertical plane were measured during the experimental test. The data were measured with a frequency of 60 s averaged every 15 min and recorded on a data logger (CR10X, Campbell, Logan, USA). The external air temperature was measured by a Hygroclip-S3 sensor (Rotronic, Zurich, Switzerland), adequately shielded from solar radiation. The temperature on the external surface of the walls was measured using thermistors (Tecno.EL s.r.l. Formello, Rome, Italy). The solar radiation on a horizontal and on a vertical plane were measured by means of pyranometers (model 8-48, Eppley Laboratory, Newport, RI, USA) in the wavelength range 300–3000 nm.

Analysis of variance (ANOVA), in detail a three-way ANOVA analysis at 95% probability level, was performed for assessing the influence of external air temperature (EAT), wind speed (W) and air relative humidity (RH) of the outdoor environment on the heating effect of the façades. The CoStat software (CoHort Software, Monterey, CA, USA) was used to carry out the ANOVA.

The thermal barrier effect of the vegetation layer and the deriving benefits, in the cold season, were also analysed. The longwave infrared energy balance at the external surface of the bare wall and of the wall covered with *Rhyncospermum jasminoides* was evaluated. Calculations were performed for a representative winter day, according to Convertino et al. [29].

For the external surface of the bare wall, the LWIR radiative balance (RB) is equal to:

$$RB_{bw} = \varepsilon_{ws}\left(R_{sky} + R_g\right) - R_{e,bw}, \tag{1}$$

where: ε_{ws} is the infrared emissivity coefficient of the wall external surface, R_{sky}, R_g and $R_{e,bw}$ (Wm^{-2}) are the LWIR radiative fluxes emitted by the sky, the ground and the external surface of the bare wall, respectively.

RB for the external surface of the covered wall is:

$$RB_{cw} = \varepsilon_{ws}R_{i,gl} - R_{e,cw}, \tag{2}$$

where $R_{i,gl}$ and $R_{e,cw}$ (Wm^{-2}) are the LWIR radiative fluxes emitted by the inner side of the green layer of vegetation and by the external surface of the covered wall, respectively.

3 RESULTS AND DISCUSSION

Air temperatures and monthly values of cumulative solar radiation on the horizontal and vertical planes corresponding to 2015 and 2016 winter months are summarized in Table 1. The minimum and maximum monthly value of cumulative solar radiation on a horizontal plane were recorded respectively in December and February, in 2015, and in January and February, in 2016. The minimum and maximum monthly value of cumulative solar radiation on the vertical wall were recorded respectively in February and January, in 2015, and in January and December, in 2016.

Table 1: Air temperatures and monthly values of cumulative solar radiation on a horizontal and on a vertical plane on the experimental field of the University of Bari in 2015 and 2016 winter months (January, February and December).

	Air temperatures(°C)			Monthly cumulative solar radiation on a horizontal plane (MJ m^{-2})		Monthly cumulative solar radiation on a vertical plane (MJ m^{-2})	
	Mean	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2015	9.6	–0.3	20.9	179	213	254	338
2016	10.9	0.7	22.6	177	238	289	333

The climatic conditions able to mostly influence during night-time the heating effect of the two green façades were examined. The heating effect was assumed as the positive difference between the external surface temperature of the wall behind the vegetation and the temperature of the external surface of the bare wall.

The maximum and average heating effect obtained in the analysed period were equal to 3.5°C and 1.1°C for *Rhyncospermum jasminoides* and to 3.5°C and 1.2°C for *Pandorea jasminoides*, respectively. The maximum cooling effect during daytime was of 8.3°C and 7.7°C for *Rhyncospermum jasminoides* and *Pandorea jasminoides*, respectively. These findings are confirmed by results available in the literature that refer to slightly different climates [22], [23].

The ANOVA statistical analysis revealed significant differences at $P<0.001$ (Tables 2 and 3). Subsequently, the effects of the three external climate factors were analysed by means of the Tukey–Kramer's test (Tables 4–6).

It emerges that the variability determined by EAT is greater than those determined singly both by W and by RH, and by the interaction of the climatic parameters, for both *Rhyncospermum jasminoides* and *Pandorea jasminoides* façades.

The Tukey–Kramer's test highlighted the dependence of the magnitude of the heating effect on EAT for both the two green façades (Table 4). The heating effect is more evident when air temperature decreases. Moreover, the analysis showed that for EAT values ≥ 10°C *Rhyncospermum jasminoides* and *Pandorea jasminoides* façades have almost a steady effect on the external surface temperature of the walls. W affected the heating performance with an increasing trend for speed values lower than 3 ms^{-1}; once exceeded this limit the heating effect varies with a slightly decreasing trend. The maximum effect occurs in the range 2–3 ms^{-1} (Table 5). The Tukey–Kramer's test shows the scarce influence of RH on the

Table 2: ANOVA results concerning the external climate conditions influence on the night-time temperature rise of the wall surface behind the *Rhyncospermum jasminoides*.

Source[a]	df	MS	F	P
Main effects				
EAT	7	103.96	398.41	***
W	5	23.65	90.65	***
RH	6	2.30	8.82	***
Interaction				
EAT × W	35	4.42	16.95	***
EAT × RH	37	2.87	10.99	***
W × RH	28	1.01	3.88	***
EAT × W × RH	131	0.82	3.16	***
Error	10,722	0.26		

[a] EAT: external air temperature; W: wind speed; RH: relative humidity.
*** $P \leq 0.001$.

Table 3: ANOVA results concerning the external climate influence on the night-time temperature rise of the wall surface behind the *Pandorea jasminoides*.

Source [a]	df	MS	F	P
Main effects				
EAT	7	59.89	218.84	***
W	5	14.67	53.60	***
RH	6	8.38	30.63	***
Interaction				
EAT × W	35	3.82	13.97	***
EAT × RH	37	3.84	14.02	***
W × RH	28	1.19	4.34	***
EAT × W × RH	131	0.98	3.59	***
Error	10,640	0.27		

[a] EAT: external air temperature; W: wind speed; RH: relative humidity.
*** $P \leq 0.001$.

heating effect. The maximum effect of RH on the heating effect has been achieved for percentage values falling in the range 70–80% for the *Pandorea jasminoides* façade (Table 6). In this façade the heating performance was influenced by RH with an increasing trend from 40 to 80%; once exceeded this limit the heating effect starts decreasing.

The calculation of the LWIR radiative energy budget at the external surface of the bare wall and of the wall behind *Rhyncospermum jasminoides* brought out significant differences in the thermal behaviour of the two solutions (Fig. 2).

The LWIR radiative fluxes were evaluated distinguishing between daytime, night-time and all day (Fig. 2), since they are strongly related to the day period.

During daytime, the bare wall lost a quantity of LWIR energy equal to 1.23 MJm^{-2}, while the covered wall gains 0.05 MJm^{-2}. At night-time, the LWIR energy lost by the bare wall (2.32 MJm^{-2}) was 56% higher than that lost by the covered wall (1.01 MJm^{-2}).

Overall, daily, the bare wall lost 73% more energy than the covered wall (Fig. 2).

Table 4: Mean temperature rise of the wall external surface, during night-time, as related to the external air temperature levels, analysed with Tukey–Kramer's test.

		External air temperature EAT (°C)							
		EAT < 4	4 ≤ EAT < 6	6 ≤ EAT < 8	8 ≤ EAT < 10	10 ≤ EAT < 12	12 ≤ EAT < 14	14 ≤ EAT < 16	EAT ≥ 16
Mean temperature rise (°C)	*Rhyncospermum jasminoides*	1.62^{a}	1.48^{b}	1.34^{c}	1.10^{d}	0.88^{e}	0.87^{ef}	0.84^{ef}	0.79^{f}
	Pandorea jasminoides	1.63^{a}	1.45^{b}	1.35^{c}	1.20^{d}	1.05^{e}	0.95^{e}	0.94^{e}	0.91^{e}

[a-b-c-d-e-ef-f] Mean values of the temperature in a row with a different superscript letter statistically differ at P < 0.05 using Tukey–Kramer's test.

Table 5: Mean temperature rise of the wall external surface, during night-time, as related to the wind speed levels, analysed with Tukey–Kramer's test.

		Wind speed W (ms^{-1})					
		W < 2	2 ≤ W < 3	3 ≤ W < 4	4 ≤ W < 5	5 ≤ W < 6	W ≥ 6
Mean temperature rise (°C)	*Rhyncospermum jasminoides*	1.02^{c}	1.33^{a}	1.22^{b}	0.99^{cd}	0.90^{de}	0.88^{e}
	Pandorea jasminoides	1.18^{c}	1.36^{a}	1.25^{b}	1.01^{d}	0.95^{de}	0.87^{e}

[a-b-c-cd-de-e] Mean values of the temperature in a row with a different superscript letter statistically differ at P < 0.05 using Tukey–Kramer's test.

Table 6: Mean temperature rise of the wall external surface, during night-time, as related to the relative humidity levels, analysed with Tukey–Kramer's test.

		Relative humidity RH (%)						
		RH < 40	40 ≤ RH < 50	50 ≤ RH < 60	60 ≤ RH < 70	70 ≤ RH < 80	80 ≤ RH < 90	RH ≥ 90
Mean temperature rise (°C)	*Rhyncospermum jasminoides*	0.98^{a}	1.15^{a}	1.27^{a}	1.16^{a}	1.25^{a}	1.20^{a}	1.14^{a}
	Pandorea jasminoides	0.90^{c}	1.08^{c}	1.21^{bc}	1.28^{b}	1.39^{a}	1.28^{b}	1.19^{c}

[a-b-bc-c] Mean values of the temperature in a row with a different superscript letter statistically differ at P < 0.05 using Tukey–Kramer's test.

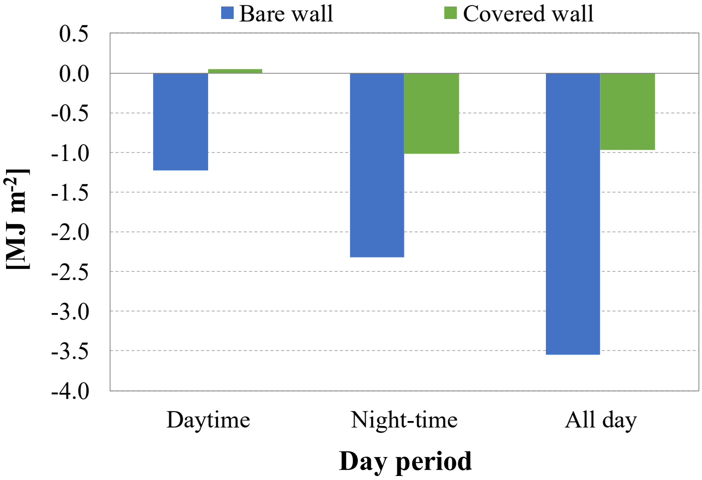

Figure 2: Longwave radiative energy budget at the external surface of the bare wall and of the wall covered with *Rhyncospermum jasminoides*: daytime, night-time and all day.

These findings demonstrated the thermal barrier effect of the vegetation layer in winter. Indeed, the presence of the green façade reduced the energy losses caused by LWIR radiation.

4 CONCLUSIONS

The experimental test allowed quantifying and deepening the heating effect performed by the green layers during winter months of 2015–2016. The application of the vegetation allowed maintaining the temperature of the external facade of the walls covered with vegetation at higher values than the bare wall during night-time periods. A direct consequence is that the thermal losses, especially by longwave infrared radiation, decreased. It was found that the covered wall lost significantly less LWIR energy than the bare wall, during a representative winter day. The statistical analysis allowed understanding that the heating effect of the two green façades was mainly driven by the external air temperature with a greater increase as the temperature drops. Secondly, the heating effect magnitude resulted sensible to wind speed values, in particular to values in the range 2–3 ms^{-1}. Based on the climatic conditions, the findings of the research allow to define the sites where the green walls could have greater potential in terms of winter heating effect. Air relative humidity showed a scarce influence. Further future research should be addressed at quantifying the possible reduction of energy loss throughout the heating season.

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