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Assessing the Impact of Vertical Greenery Systems on the Thermal Performance of Walls in Mediterranean Climates

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Abstract: This study investigates the impact of vertical greenery systems (VGSs) applied to several typical wall configurations on indoor thermal conditions in a building module situated in the Mediterranean climate of Catania, Italy. By means of dynamic simulations in TRNSYS vers.18, the research compares the thermal behavior of walls made of either hollow clay blocks (Poroton) or lava stone blocks against a lightweight wall setup already in place at the University of Catania. The primary focus is on evaluating the VGSs' capability of reducing peak inner surface temperatures and moderating heat flux fluctuations entering the building. The findings indicate that adding an outer vertical greenery layer to heavyweight walls can decrease the peak inner surface temperature by up to 1.0 °C compared to the same bare wall. However, the greenery's positive impact is less pronounced than in the case of the lightweight wall. This research underscores the potential of green facades in enhancing the indoor thermal environment in buildings in regions with climates like the Mediterranean one, providing valuable insights for sustainable building design and urban planning.

Keywords: green façade; dynamic simulations; thermal inertia; indoor thermal comfort; TRNSYS; heavyweight wall

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1. Introduction

The architectural landscape of the Mediterranean basin is characterized by a significant presence of traditional buildings constructed from local stones. These structures, prevalent in various urban residential areas across European cities, only occasionally gain recognition as part of the valuable historical heritage [1]. Typically, these buildings are built with load-bearing massive masonry walls, known for their considerable thermal mass. This feature allows them significant thermal inertia, which aids in regulating indoor temperatures. However, the main drawback of this construction technique is the lack of adequate thermal insulation, leading to substantial thermal losses and thus diminishing the buildings' energy efficiency [2]. Considering modern energy efficiency standards, especially those detailed in the latest European Directive on Energy Performance of Buildings (EPBD) [3], contemporary Italian construction practices have shifted towards using lightweight alveolar hollow clay blocks for creating opaque vertical enclosures in new developments. This shift is driven by the material's advantageous properties, including reduced thermal conductivity and greater density compared to conventional hollow bricks [4], thereby enhancing both stationary and dynamic thermal performance and contributing to overall building energy efficiency.

In recent decades, there has also been a growing interest in vertical greenery systems (VGSs) as an architectural strategy to enhance building-scale thermal comfort and energy efficiency [5]. These benefits mainly stem from the shading effect provided by the foliage layer and from the evapotranspiration process in the leaves, which concur in cooling down the building surfaces [6]. VGSs, encompassing direct and indirect green facades and living walls, offer numerous further environmental benefits, such as improved air quality,

enhanced biodiversity, and aesthetic value [7]. The primary focus, however, remains their ability to mitigate urban heat island effects and improve building energy performance [8]. The direct green façade is a traditional vertical greenery system consisting of climber plants attached directly to the building and rooted directly in the ground [5–7]. On the other hand, indirect green facades include a vertical structure such as cables, mesh, or trellis to support the climber plants [5–7]. An indirect greenery system thus functions like a double skin façade that creates an air gap between the surface and the vegetation [5–7,9]. Studies focusing on indirect green facades, particularly those using alveolar and hollow brick constructions, have emphasized their effectiveness in improving thermal performance under free-running conditions [10–13]. Such studies often measure the outer wall surface temperature behind the vegetation to quantify the shading benefits provided by the green facade [14]. A comprehensive review by Pérez et al. [15] highlighted that indirect green facades could reduce wall temperatures by 5 °C to 20 °C, depending on the plant species and local climate conditions.

Despite these advancements, the literature contains relatively few papers that employ dynamic energy simulations to explore the indoor thermal conditions ensured by massive masonry equipped with green facades. This gap presents an opportunity for further research: in particular, the Mediterranean climate—marked by hot, dry summers and mild, wet winters—poses unique challenges for building design. High solar radiation and temperature fluctuations require a building capable of dissipating heat effectively. Research by Gagliano et al. [2] demonstrated that Mediterranean buildings with heavyweight walls exhibit better thermal inertia, aiding in stabilizing indoor temperatures. However, the traditional heavyweight walls' lack of insulation often results in high thermal losses, necessitating supplementary strategies like VGSs to improve their thermal performance.

Dynamic thermal simulations are essential for understanding the performance of VGSs under varying climatic conditions [16]. Software tools like TRNSYS and EnergyPlus vers. 24 are widely used for such analyses. In this context, one notable study in the literature dealt with the numerical analysis of green facades installed on the southern and western facades of a brick masonry house in Lille, France. This study used TRNSYS simulations [17] to assess their impact and found that green facades could lower peak indoor temperatures by over 1.3 °C compared to non-vegetated walls [18]. Another interesting study by Perini [19] employed EnergyPlus to simulate the impact of green facades on the thermal performance of buildings in different European climates, demonstrating that green facades could lead to significant energy savings for cooling in the summer, particularly in the Mediterranean area.

Recent studies have also explored various configurations and plant species for VGSs to maximize their thermal benefits, such as the research by Sternberg et al. [20], who investigated the impact of VGSs on thermal performance and energy savings in Mediterranean climates, emphasizing the importance of plant selection and maintenance. Experimental setups and case studies provide valuable data for validating simulation models, such as that of Detommaso et al. [21] at the University of Catania, which involved an experimental setup of insulated lightweight sandwich panels with and without green facades.

As a follow-up of this work, the present paper aims to explore the effects of an indirect green façade on the indoor thermal environment of a cubical room by comparing three distinct wall types: insulated lightweight sandwich panels (the actual configuration of the experimental setup), Poroton blocks, and lava stone blocks (the latter chosen for its emblematic representation of local construction traditions). The primary focus is on evaluating the VGSs' impact in reducing peak inner surface temperatures and moderating heat flux fluctuations entering the building. By comparing the thermal behavior of these different wall types, the study aims to provide a comprehensive understanding of how VGSs can enhance indoor thermal comfort and contribute to sustainable building design in Mediterranean climates. The paper is then structured as follows:

- Section 2 explains the research methodology, detailing the green facade's characteristics, the thermal simulation model employed, and the specific wall configurations under investigation.
- Section 3 presents the study's findings, offering recommendations and highlighting the limitations encountered, thereby setting the stage for future research directions in this field.

2. Materials and Methods

This methodology section outlines the comprehensive approach adopted to evaluate the potential of vertical greenery systems (VGSs) in enhancing a building's thermal performance. By examining various wall materials and configurations, this study aims to provide valuable insights into sustainable architectural practices suited for Mediterranean climates.

2.1. Case Study

The experimental framework for this study involves two full-scale mock-ups, each consisting of prefabricated modules. One module is equipped with a green facade, while the other serves as a control without the greenery. These modules are installed at the University Campus of Catania, located at latitude 37°30′ N and longitude 15°04′ E. Catania's position in Southern Italy implies a Mediterranean climate that experiences hot, dry summers and mild, wet winters, classified as Csa according to the Köppen–Geiger climate categorization. The winters are characterized by low rainfall, while the summers have some days of drought.

The modules are identical in shape, size (2.50 m × 2.50 m × 3.00 m), and construction materials, the only difference being the incorporation of a vertical greenery system (VGS) on the western facade of one module. This strategic orientation ensures that each module faces all four cardinal directions, providing comprehensive exposure to varying sun angles and environmental conditions. These modules are designed as single-room structures without any air conditioning systems to simulate typical free-running indoor conditions. Figure 1a,b provides planimetric and 3D views of the modules, highlighting their placement and the distinct presence of the VGS. The envelope of these modules is constructed from self-supporting lightweight walls (W_LW), utilizing sandwich panels that include an insulated polystyrene core and external layers made of oriented strand board (OSB). This configuration is consistent across the walls, the roof, and the floor, ensuring uniform thermal properties throughout the structure. The construction details and material specifications were provided by the company responsible for fabricating these prefabricated modules: their thermal transmittance (U = 0.50 W/m^2K for walls and roofs) was rigorously assessed through heat flux measurements conducted by the "Thermozig" device according to the ISO 9869 standard [22]. The green facade element, installed on the western wall of one module, features an indirect VGS utilizing "*Trachelospermum Jasminoides*", an endemic and evergreen climbing plant species also known as "*False jasmine*" or "*Rhincosperma*". This choice is significant, as the Jasminoides species are suitable for the Mediterranean environment. Jasminoides are endemic plants, drought-tolerant, and suitable for high solar radiation exposure, making them particularly able to maintain themselves in the typical Mediterranean climate of Catania. Jasminoides exhibits a dynamic leaf area index (LAI), fluctuating between 2.0 and 4.0 m^2/m^2 over the year [15], thus potentially offering varying degrees of shading and cooling effects. The LAI values ensure a variable shading effect throughout the year, enhancing the thermal performance of the building during the hot summer months while allowing more sunlight to penetrate during cooler periods. The design and materials of the VGS support structure, along with further details on the selected plant species, are elaborated upon in the referenced literature [21].

Figure 1. Full-scale experimental mock-ups: (**a**) Plan view; (**b**) 3D view of the modules from north-west.

2.2. Features of the Thermal Model and Validation

The experimental setup described above was modeled using the TRNSYS software tool. The simulation was based on the heat balance for a multi-zone building designated as Type 56 in TRNSYS. This approach enabled a comprehensive analysis of the thermal interactions within and across the building spaces. Central to these simulations was the incorporation of the vertical greenery system (VGS), represented by the vertical foliage component (VFC), also known as Type 9644 [23]. This component, drawing on the theoretical framework established by Susorova [24], simulates the complex heat transfer processes within a control volume that encompasses both the vertical vegetation layer and the adjacent bare wall surface of the multi-zone building model [23].

The energy balance in the simulation accounted for several factors:

- Direct and diffuse shortwave solar radiation hitting vegetation and wall surfaces.
- Longwave radiant heat transfer from the wall to vegetation, ground, and sky.
- Heat transfer by convection and evapotranspiration from the foliage to the air.

Figure 2 shows the flowchart for coupling the multi-zone building model (Type 56) to the green facade component (Type 9644) in the TRNSYS simulation studio.

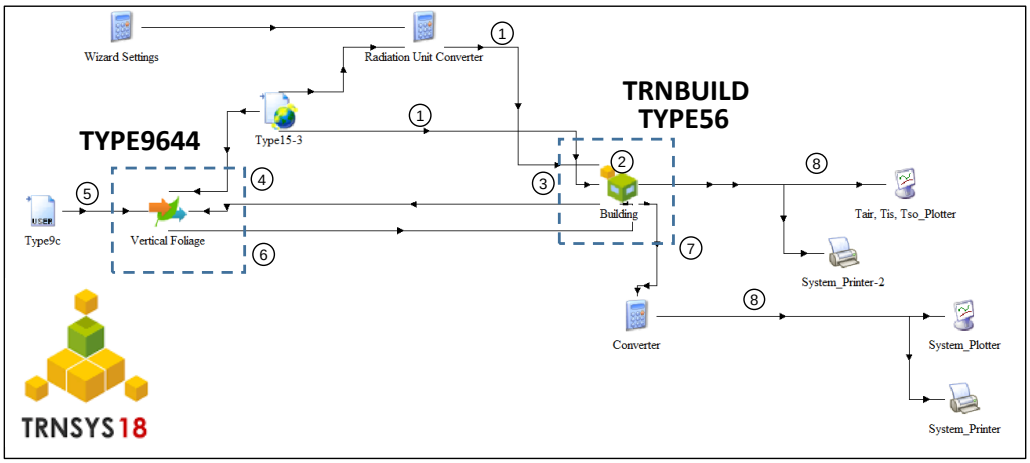


Figure 2. The coupling of the multi-zone building model to the vertical foliage component in the TRNSYS simulation studio, with the numbering of each modelling phase.

The TRNSYS simulation workflow included the following phases (the numbers refer to Figure 2):

(1) Implementation of the local meteorological data inputs (outdoor air temperature, relative humidity, wind speed and its direction, global, direct, and diffuse solar radiation).

(2) Building modeling and settings in Type 56, e.g., the definition of the opaque and transparent building components, infiltration rate, and boundary conditions.

(3) Energy balance on the building model with the bare walls.

(4) Implementation of input data as feedback from the bare wall of Type 56 (TRNBuild output) in the VFC component.

(5) Implementation of input weather data in the VFC component.

(6) Calculation of the outputs from the energy balance on the VFC component.

(7) Energy balance on the building model (Type 56) coupled with VFC component.

(8) Calculation of requested outputs (Indoor air temperature, surface temperature, and exchanged heat fluxes).

Specific input parameters reflecting the vegetative characteristics and environmental conditions were required for the VFC. These included weather data and detailed vegetative data such as leaf area index (LAI), leaf solar absorptance (α_l), emissivity (ε_l), stomatal conductance (g_s), characteristic dimension (D), and the radiation attenuation coefficient (k). Additionally, the model required inputs for the ground temperature (T_g) and the external surface temperature (T_w) of the wall beneath the vegetation [23,24]. The chosen parameters for the VFC, fundamental for the accuracy of our simulation, are summarized in Table 1.

Table 1. Thermo-physical properties of the vertical vegetation layer.

Parameter	Name	Unit	Value
Leaf area index	LAI	m^2/m^2	4.0 [25]
Leaf absorptance	α_l	-	0.54 [25]
Leaf stomatal conductance	g_s	mol/m^2s	0.40 [24]
Leaf typical dimension	D	M	0.11 [26]
Leaf radiation attenuation coefficient	K	-	0.70 [27]
Leaf emissivity	ε_l	-	0.96 [25]

The primary outputs from the VFC component were the total radiant heat flux (QR) exchanged between the external surface of the wall and the foliage cover and the convective heat transfer coefficient (h) calculated for the same external wall surface. These outputs were fundamental for understanding the thermal effects of the green façade [24,28].

Given the study's focus on assessing indoor thermal conditions under varying wall configurations in free-running scenarios, certain simplifications were made in the modeling process:

- *Unoccupied Interior Space*: The interior space was treated as unoccupied, devoid of internal heat gains, and lacking any active heating or cooling systems.
- *Adiabatic Surfaces*: To isolate the thermal effects of the green facade, all the heat exchange surfaces were modeled as adiabatic except for the west-facing wall equipped with the VGS. This was achieved by setting the "boundary = identical" option for the external components in the TRNSYS model, ensuring equal air temperatures on both sides of the roof, floor, and walls and thus preventing them from contributing to thermal exchanges.
- *Air Infiltration Rate*: Fixed at a constant rate of 0.5 h^{-1}. This value was chosen based on international building standards commonly used for residential buildings in Mediterranean climates [29], as well as previous studies that adopt similar rates for thermal performance analysis [30,31]. The infiltration rate reflects typical conditions in free-running scenarios, and no mechanical ventilation systems were considered to evaluate a worst-case scenario in terms of heat gains/losses due to air leakage [32].

Simulations were conducted over a typical summer week, from the 8th to the 14th of July, using a one-hour timestep. The initial conditions for the simulation, including the temperature and relative humidity of the indoor air, were based on measurements recorded at 1:00 a.m. on the 8th of July during the experimental campaign.

Key performance indicators (KPIs) such as peak inner surface temperatures, heat flux fluctuations, and indoor air temperature variations were monitored and analyzed. Indeed, peak inner surface temperatures were measured to determine the maximum temperature

reached by the inner wall surfaces. Heat flux fluctuations were used to assess the variation in heat transfer through the walls, providing insights into the thermal buffering capacity of each configuration. Indoor air temperature variations were used to evaluate the overall impact of VGSs on indoor thermal comfort.

To ensure the accuracy of the simulation results, the thermal model was calibrated against empirical data obtained from the physical experimental setup (W_LW) at the University Campus of Catania. This involved adjusting the model parameters until a satisfactory match between simulated and observed data was achieved. The validated model was then used to simulate the theoretical configurations with walls made of Poroton (W_POR) and lava stones (W_LST). A sensitivity analysis was conducted to evaluate the impact of various parameters on the thermal performance of the VGSs. This included varying the foliage density, leaf area index (LAI), and thickness of the greenery layer. The sensitivity analysis helped identify the most critical factors influencing the system's effectiveness and provided insights into optimizing the design of VGSs for maximum thermal benefit.

The validation of the thermal model was carried out based on hourly values of indoor air temperature and internal surface temperature on the west-oriented wall of the prefabricated module with and without VGSs, respectively. Figure 3 depicts the comparison between the simulated internal surface temperature profile and the corresponding internal surface temperature on the west-oriented wall measured by means of an experimental survey in the bare façade and green façade configurations during a typical hot summer week (8th–14th July). Figure 3 shows a good correlation between predicted data (dashed line) and measured data (solid line). Indeed, despite some differences in some hours, the analysis of the trends reveals a great coincidence of the profiles of internal surface temperature achieved by the simulations and experimental measurements during the daytime and in hours of the maximum solar radiation. The correlation coefficient (R2) between simulated and measured data for bare façade and green facade are 0.96 and 0.99, respectively. For further details about the validation process of the TRNSYS model, the reader can refer to [21].

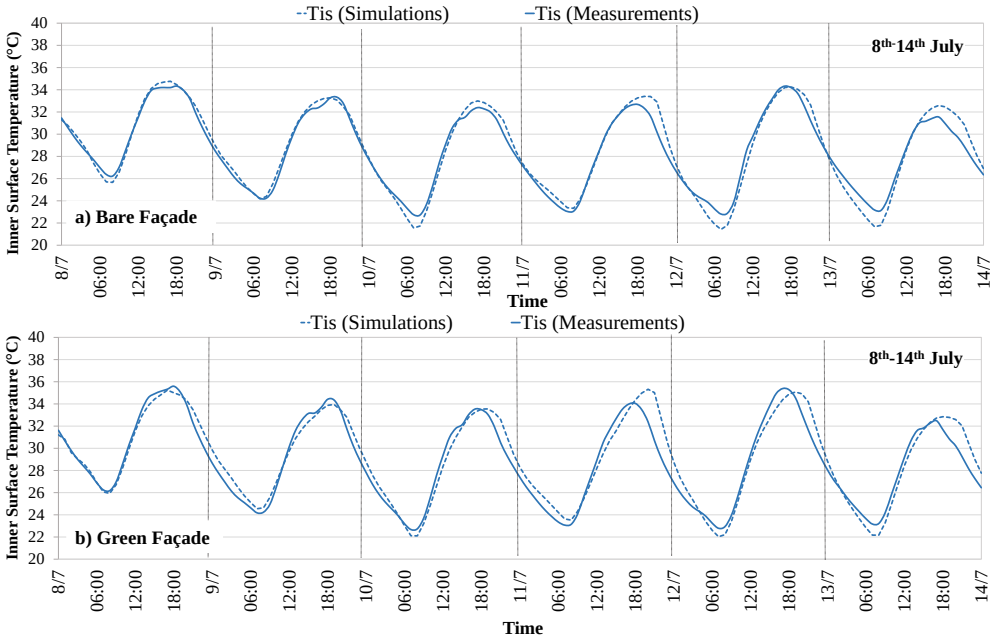


Figure 3. Comparison between simulated and actual internal surface temperature during a typical summer week 8–14 July 2022: (**a**) bare wall; (**b**) green façade [21].

2.3. Investigated Wall Configurations

The study investigates the thermal behavior of three distinct wall configurations:

- Walls made of insulated lightweight sandwich panels (*W_LW*), which represent the physical experimental mock-ups currently in place at the University Campus of Catania.
- Walls constructed with Poroton blocks (*W_POR*), which is the first theoretical scenario explored only through dynamic thermal simulations.
- Walls built from lava stone blocks (*W_LST*), which is the last theoretical scenario investigated through simulations.

The inclusion of W_POR and W_LST configurations, alongside the W_LW setup, broadens the study's scope and applicability, allowing for comparative analysis across different material properties and their interactions with VGSs. The thermal properties of the three distinct wall configurations evaluated in this study are detailed in Tables 2–4.

Table 2. Stratigraphy and thermal features of the lightweight wall (W_LW).

No.	Layer	s (mm)	λ (W/mK)	ρ (kg/m^3)	C_p (J/kgK)
1	OSB panel (outer layer)	9	0.12	650	1700
2	Polystyrene	65	0.04	15	1450
3	OSB panel (inner layer)	6	0.12	650	1700

Table 3. Stratigraphy and thermal features of the wall made of Poroton blocks (W_POR).

No.	Layer	s (mm)	λ (W/mK)	ρ (kg/m^3)	C_p (J/kgK)
1	Lime and cement mortar (outer layer)	30	0.90	1800	1000
2	Hollow clay block—POROTON 850 [33]	300	0.18	850	1000
3	Lime and cement mortar (inner layer)	30	0.90	1800	1000

Table 4. Stratigraphy and thermal features of the wall made up of lava stone blocks (W_ST).

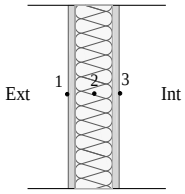
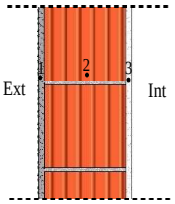
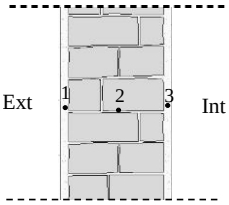
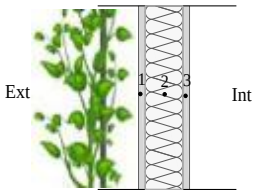
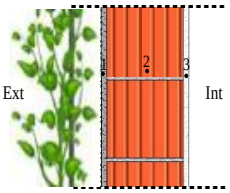
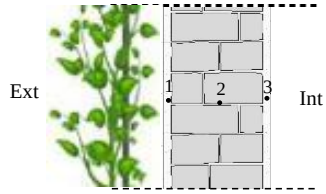
No.	Layer	s (mm)	λ (W/mK)	ρ (kg/m^3)	C_p (J/kgK)
1	Lime mortar (outer plaster)	30	0.90	1800	1000
2	Lava stone block and lime mortar [2]	300	1.70	2200	1000
3	Lime and gypsum mortar (inner layer)	30	0.70	1800	1000

The lightweight wall comprises an outer and inner layer of oriented strand board (OSB) panels sandwiching a core of polystyrene insulation. This configuration is designed for minimal thermal mass and high insulation efficiency, reflected in the properties of its constituent materials. On the other hand, the wall made from Poroton blocks (W_POR in Table 3) features a sandwich structure with lime and cement mortar encasing the Poroton block core. Notably, no additional insulation layer was introduced in the W_POR configuration to maintain a comparable U-value to the lightweight wall (W_LW), accepting the intrinsic insulating properties of Poroton blocks.

Finally, Table 4 describes the structure and thermal features of the wall constructed with lava stone blocks (W_ST). This configuration, representative of traditional building practices in Southern Italy, employs lime-based mortars with lava stone, offering high thermal mass but without the inclusion of modern insulation materials. This approach preserves the authenticity of historical construction methods while presenting a challenge in terms of thermal insulation.

The thermal transmittance (U) and surface mass (SM) values for each wall configuration, both with and without the incorporation of a green façade, are instead summarized in Table 5. These values highlight the comparative thermal performance of each wall type under different conditions, thus offering insights into the efficacy of green façades in enhancing thermal insulation.

Table 5. Thermal transmittance (U), surface mass (SM), and thickness values of the investigated wall configurations.

W_LW	W_POR	W_ST
		
W_LW_GF	**W_POR_GF**	**W_ST_GF**
		
U (W/m^2K)	0.52	0.52	1.85
SM (kg/m^2)	13	255	1100
s (mm)	80	360	560

3. Results and Discussion

3.1. Dynamic Simulations Results

This section presents the results of the dynamic thermal simulations performed for the three different wall configurations: lightweight wall (W_LW), wall with Poroton blocks (W_POR), and wall with lava stone blocks (W_ST). The performance of these walls was evaluated both with and without the inclusion of a vertical greenery system (VGS). The focus is on the daily variations in inner surface temperature (Tis) and the heat flux towards the interior (Qis) for the west-facing wall during a typical Mediterranean summer week. Figure 4a,b illustrates the daily variations in Tis for each wall configuration over the simulation period from 8th to 14th July, while Table 6 reports the average value of the peak, the minimum, and the amplitude of the fluctuations of the internal surface temperature of the investigated walls in the bare façade and green façade configuration during the selected period.

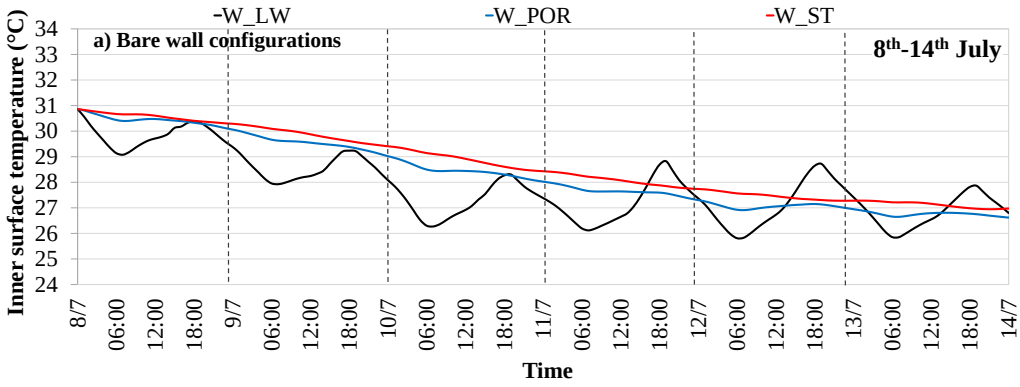


Figure 4. *Cont.*

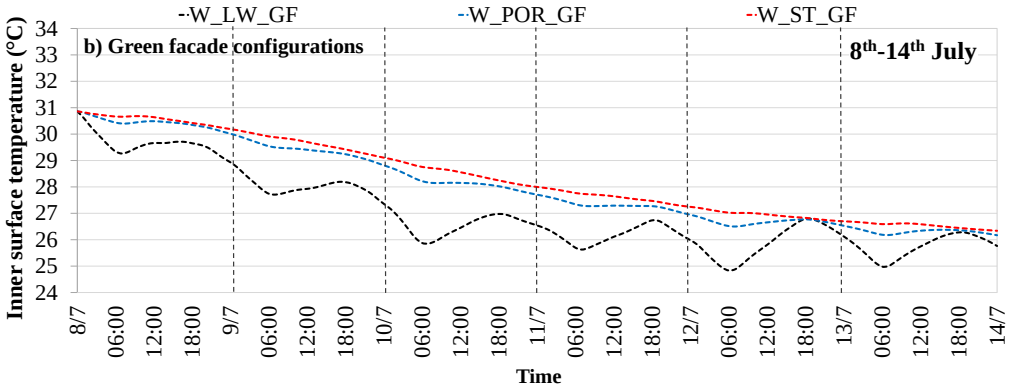


Figure 4. Simulated daily profile of indoor surface temperature (Tis) during the period 8th–14th July: (**a**) bare wall configurations; (**b**) green façade configurations.

Table 6. Main results regarding the internal surface temperature in the bare façade and green façade configuration from 11th to 14th July.

	Wall Configurations	$\overline{T}_{is,max}$ (°C)	$\overline{T}_{is,min}$ (°C)	$\overline{(\Delta T_{is,max})}$ (°C)
No VGS	W_LW	28.5	25.9	2.4
	W_POR	27.3	26.6	0.5
	W_ST	27.8	27.3	0.4
VGS	W_LW_GF	26.6	25.1	1.4
	W_POR_GF	26.4	26.1	0.3
	W_ST_GF	27.1	26.9	0.2

The analysis of Figure 4 and Table 6 reveals significant insights into the thermal performance of the investigated wall configurations under the influence of a green façade:

- *Lightweight Wall (W_LW)*: The lightweight wall exhibits the highest fluctuations in Tis, with temperatures peaking during the day and dropping at night. From July 11th to 14th, Tis oscillates between a minimum of 25.9 °C and a maximum of 28.9 °C. The addition of the VGS (W_LW_GF) results in a marked reduction in peak Tis, moderating it to a narrower range between 25.0 °C and 26.9 °C, thus effectively reducing the peak temperature by up to 1.9 °C. This indicates an enhanced buffering capacity against external temperature swings, showcasing the VGS's significant impact on improving thermal comfort.
- *Poroton Wall (W_POR)*: The Poroton wall shows moderate fluctuations in Tis, indicative of its higher thermal mass compared to the lightweight wall. The temperature fluctuations are significantly dampened, with Tis ranging between 26.0 °C and 27.5 °C. The incorporation of the VGS (W_POR_GF) further reduces the peak Tis by around 1.0 °C, highlighting the combined effect of the wall's inherent insulation and the green façade.
- *Lava Stone Wall (W_ST)*: The lava stone wall presents the most stable Tis profile, with peak values only marginally exceeding 27.0 °C from July 11th to 14th despite the intrinsically high thermal transmittance, thus reflecting the substantial thermal inertia of the material. The addition of a VGS (W_ST_GF) results in a slight reduction in peak Tis, demonstrating a modest improvement due to the already high thermal inertia of the lava stone.

The incoming heat flux (Qis) is another critical element to measure thermal performance, indicating the amount of heat entering the building through the walls. Figure 5a,b present the daily variations in Qis for each wall configuration, both with and without the VGS. Table 7 summarizes the average values of the peak of the heat flux entering the building through the west-oriented wall for each investigated wall configuration under bare façade and green façade configuration from 11th to 14th July. In Table 7, the percentage

reduction in the peak of the heat flux achievable with green façade configurations with respect to the bare facade scenarios is reported.

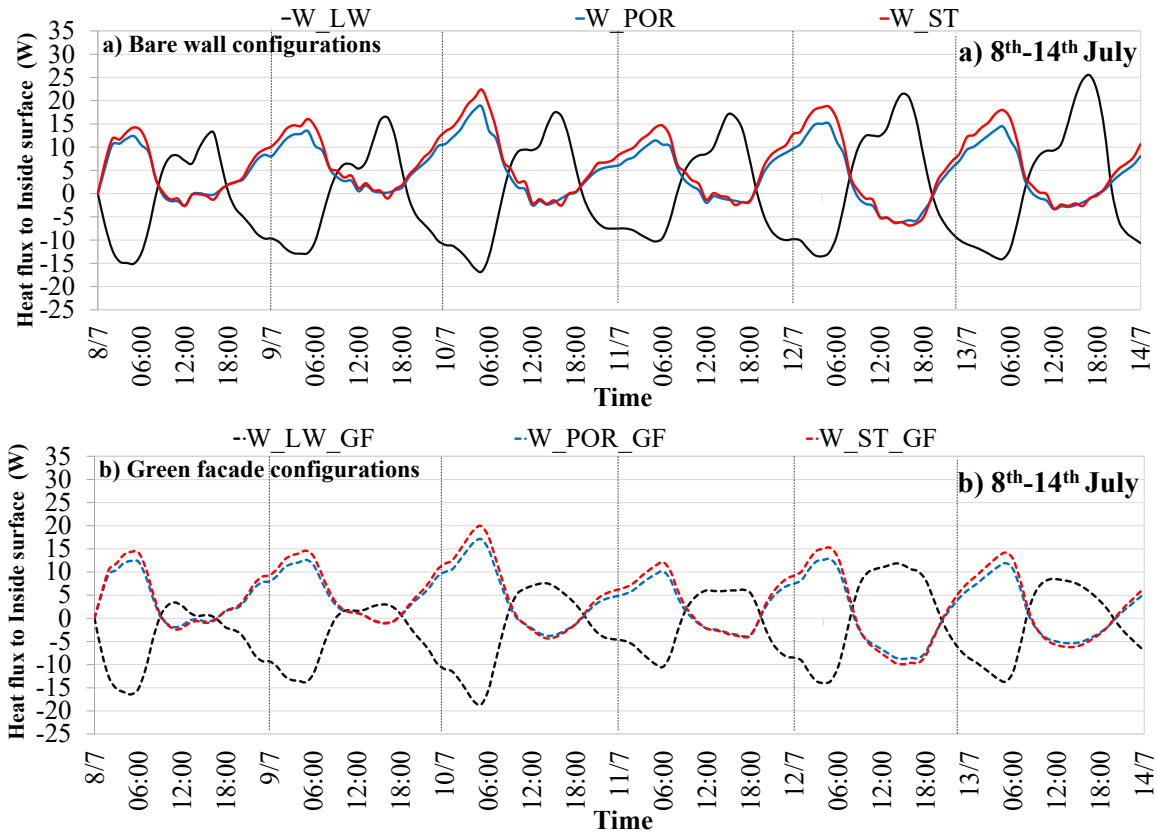


Figure 5. Simulated daily profile of heat flux through the west-oriented wall (Qis) during the period 8th–14th July: (**a**) bare wall configurations; (**b**) green façade configurations.

Table 7. Main results regarding the heat flux entering the building with and without VGSs.

	Wall Configurations	$\overline{Q}_{is,max}$ (W)	$(\overline{Q}_{is,max,j} - \overline{Q}_{is,max,j,GF})/\overline{Q}_{is,max,j}$(%)
No VGS	W_LW	18	-
	W_POR	14	-
	W_ST	17	-
VGS	W_LW_GF	7	61%
	W_POR_GF	12	10%
	W_ST_GF	15	13%

The analysis regarding the heat flux highlights the following:

- *Lightweight Wall (W_LW)*: The lightweight wall configuration shows significant daily variations in Qis, with the peak heat flux aligning with periods of maximum solar irradiation. This suggests a quick response to external temperature changes due to the wall's low thermal mass. The VGS (W_LW_GF) significantly reduces the peak value and amplitude of Qis fluctuations, lowering the incoming peak heat flux by approximately 15 W. The addition of VGS thus reduced the incoming heat flux by 60% at peak hours compared to the bare façade configuration (W_LW). This demonstrates the VGS's efficacy in shielding solar radiation and enhancing thermal stability.
- *Poroton Wall (W_POR)*: The Poroton wall exhibits a reduced amplitude in heat flux fluctuations compared to the lightweight wall, indicating a more gradual response to thermal inputs from the outdoors. The peak heat flux occurs about 10 h later than

in the lightweight wall, illustrating the delayed response associated with its higher thermal mass. The addition of the VGS (W_POR_GF) further dampens the heat flux, reducing the peak values by around 3 W. The presence of the VGS has determined a reduction in the peak heat flux of about 10% with respect to the corresponding bare wall configuration (W_POR).

- *Lava Stone Wall (W_ST)*: The lava stone wall exhibits a delay in Qis of about 10 h with respect to the lightweight wall. Although the trend of heat flux is similar to that of the Poroton wall, the lava stone wall shows that the heat flux entering the building is higher if compared to the Poroton wall. This is because the lava stone has a thermal conductivity higher than Poroton blocks, which encourages heat exchange through the wall.

3.2. Advancements in the Field and Limitations of This Study

Most studies currently available in the literature focused on the assessment of the shading effect of a vertical greenery layer on the thermal performance of the buildings. To this aim, the studies were basically developed using measured external surface temperatures of the wall behind the vegetation layer, compared to a reference bare wall. Such studies were typically carried out in summer in the warm areas of the Mediterranean climate [6,10–13], in humid tropical regions, and in very hot dry zones [34–36]. Most of these experimental studies investigated the thermal performance of indirect green facades with medium-weight walls made of alveolar or perforated bricks [10–12,35,36] and double brick walls [13]. On the other hand, there is a shortage of studies based on numerical and/or experimental approaches that investigate the thermal performance of lightweight and massive walls equipped with indirect green façades. Therefore, the present study helps fill the current gap through the analysis of an indirect green façade installed on both lightweight and massive walls by means of dynamic thermal simulations. In particular, wall configurations with well-insulated and lightweight sandwich panels, Poroton blocks characterized by moderate density and thermal conductivity lower than common bricks, and heavy walls with lava stone characterized by high density and high thermal conductivity have never been investigated in the literature.

Amongst the papers available in the literature, the assessment of free-running internal thermal conditions of buildings with indirect VGS is only dealt with through experimental measurements by Coma [10], Zhang [34], and Nguyen [36]. Coma investigated the indirect green façade made by a wire mesh light support structure on the south side of one of two experimental house prototypes with walls realized in alveolar bricks (U = 0.78 W/m^2K) in Puigverd de Lleida, Spain. By experimental measurements, a reduction in the peak value of the internal surface temperature of 1.8 °C and a decrease in the indoor air temperature of around 1.0 °C compared to the bare wall were found [10]. Nguyen et al. assessed the effect of an indirect green façade installed on the exterior lightweight masonry wall composed of bricks of a building located in Vietnam. In the presence of a VGS, experimental measurements have shown a reduction in indoor air temperature of 1.0 °C [36].

In this research, the results indicate that the integration of vertical greenery systems significantly enhances the thermal performance of different wall configurations, albeit to varying degrees. The lightweight wall (W_LW) is composed of insulated sandwich panels characterized by a high insulation layer and very low density: since their thermal mass is negligible, the peak values of inner surface temperature and incoming heat flux through the west-oriented wall are attained at 4.00 p.m., and they are in phase with the peak of the incident solar radiation. The VGS on the west-oriented wall has the maximum shading effect in the same hours; therefore, the lightweight configuration (W_LW) benefits the most from the VGS due to its low thermal mass and high insulation properties, which are further amplified by the shading and cooling effects of the VGS. The reduction in peak Tis and Qis highlights the substantial impact of the green façade on thermal comfort.

The Poroton wall (W_POR) shows notable improvements with the VGS, leveraging on its inherent insulation property and the added benefits of the green façade to moderate

temperature fluctuations and reduce the incoming heat flux. The lava stone wall (W_ST), despite its high thermal mass and already stable thermal behavior, gains additional benefits from the VGS. Despite the VGS improvement in the thermal performance of the Poroton wall (W_POR) and lava stone wall (W_ST), the contribution of VGS in the reduction in peak values of internal surface temperature and the incoming heat flux is less than that on the lightweight wall configuration (W_LW). This is because the peak values of incoming heat flux through the west-oriented wall in W_POR and W_ST configurations occur when the VGS does not have the maximum effectiveness. Therefore, the green façade enhances the wall's ability to buffer against external thermal variations, though the overall impact is less pronounced compared to the other configurations.

The simulation results are also influenced by some assumptions and limitations regarding the vegetation parameters of the vertical foliage component (VFC). In the VFC (Type 9644), it is assumed that the leaves have the same distribution and orientation. This assumption can affect the shading effect of the foliage layer with a consequent influence on the energy balance of the green facade. In addition, the assumption that the radiation attenuation coefficient is constant during all the analyzed periods also influences the shading effect of the vegetation layer and the heat flux entering the building.

According to the above considerations, measurements of the seasonal variation in the thermo-physical properties of VGSs for a longer period should be performed to refine the thermal simulation model. In addition, the extension of the measurement period of indoor and outdoor surface temperature and heat flux for seasonal analysis could provide a more comprehensive understanding of how VGSs interact with different wall materials over time. Therefore, the need to extend the analysis to a longer period to better capture the annual performance of VGSs is a potential direction for future research.

Despite the need for further investigations, the findings underscore the potential of VGSs as a sustainable architectural solution for improving indoor thermal comfort in Mediterranean climates. By reducing peak inner surface temperatures and heat flux towards the interior, a VGS not only enhances the building's thermal performance but also contributes to energy savings by lowering the demand for mechanical cooling systems. This study primarily evaluates the thermal effects of vertical greenery systems (VGSs), specifically focusing on surface temperatures and heat flux through walls, without considering their impact on occupants' thermal comfort. This approach justifies certain modeling assumptions, such as the use of adiabatic surfaces for components without VGSs, the exclusion of internal heat gains, and the absence of ventilation. While recent studies [32] emphasize the importance of incorporating metrics like operative temperature, PMV (Predicted Mean Vote), and mean radiant temperature for a comprehensive assessment of indoor comfort, these aspects were not the focus of the current work. Instead, this study centers on the thermal performance of this specific technology. However, future research will address these comfort metrics to provide a more complete understanding of the indoor environment in buildings with VGSs.

In conclusion, the study highlights several important implications for sustainable building design:

- Combining VGSs with modern insulating materials like lightweight panels or Poroton blocks yields significant thermal comfort benefits, suggesting a synergistic approach to sustainable building design.
- The application of VGSs on traditional heavy masonry walls, such as those made from lava stone, can provide measurable thermal improvements, making it a viable retrofitting strategy for enhancing the energy efficiency of historic buildings.

The effectiveness of VGSs in reducing the incoming heat flow and stabilizing indoor air temperatures makes it particularly suitable for Mediterranean climates, where high solar radiation and temperature fluctuations are common.

4. Conclusions

This study demonstrated the significant impact that both wall material properties and indirect green façades have on the thermal performance of buildings, specifically in terms of surface temperature and heat flux, without addressing the indoor thermal comfort of occupants. Indeed, the addition of a vertical greenery system (VGS) consistently moderates the incoming heat flux across different wall types, with the most significant effect observed in the lightweight wall configuration (W_LW). This configuration, coupled with a green façade (W_LW_GF), demonstrated a remarkable decrease in the peak internal surface temperature by approximately 2 °C and by about 15 W in the incoming peak heat flux, underscoring the VGS's effectiveness in enhancing thermal comfort. On the other hand, the Poroton block wall (W_POR_GF) and the lava stone wall (W_ST_GF)—both examples of new and historical buildings' assemblies in the Mediterranean context—reported less pronounced reductions in indoor temperature fluctuations (up to 1.0 °C) and incoming heat flux (about 3 W). These results highlight the complementary nature of green façades and building materials with high thermal mass, pointing to a synergistic approach to passive thermal regulation. Despite the limitations of this study and the assumptions made in the modeling phase, the effect of VGS is in line with the overall aim of green façades to offer a natural solution for energy-efficient building design. While the effects of a VGS on heavyweight walls are slightly less evident than on lightweight walls, VGSs can still be considered viable passive cooling technology that leads to improved comfort conditions. Future research should focus on the long-term performance of VGSs under varying climatic conditions and seasonal variations in VGSs' effectiveness due to the adoption of various plant species while also estimating the indoor thermal comfort of the occupants, as well as potential energy savings for space cooling.

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