

Article

Impact of Green Wall and Roof Applications on Energy Consumption and Thermal Comfort for Climate Resilient Buildings

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Abstract: Nowadays, reducing energy consumption and obtaining thermal comfort are significant for making educational buildings more climate resilient, more sustainable, and more comfortable. To achieve these goals, a sustainable passive method is that of applying green walls and roofs that provide extra thermal insulation, evaporative cooling, a shadowing effect, and the blockage of wind on buildings. Therefore, the objective of this study is to evaluate the impact of green wall and roof applications on energy consumption and thermal comfort in an educational building. For this purpose, a university building in the Csb climate zone is selected and monitored during one year, as a case study. Then, the case building is modelled in a well-calibrated dynamic building energy simulation tool and twenty-one different plant species, which are mostly used for green walls and roofs, are applied to the envelope of the building in order to determine a reduction in energy consumption and an increase in thermal comfort. The *Hedera canariensis gomera* (an ivy species) plant is used for green walls due to its aesthetic appeal, versatility, and functional benefits while twenty-one different plants including *Ophiopogon japonicus* (Mando-Grass), *Phyllanthus bourgeoisii* (Waterfall Plant), and *Phoenix roebelenii* (Phoenix Palm) are simulated for the green roof applications. The results show that deploying *Hedera canariensis gomera* to the walls and *Phyllanthus bourgeoisii* to the roof could simultaneously reduce the energy consumption by 9.31% and increase thermal comfort by 23.55% in the case building. The authors acknowledge that this study is solely based on simulations due to the high cost of all scenarios, and there are inherent differences between simulated and real-world conditions. Therefore, the future work will be analysing scenarios in real life. Considering the limited studies on the effect of different plant species on energy performance and comfort, this study also contributes to sustainable building design strategies.



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Keywords: green systems; green roof; green wall; educational buildings; energy consumption; thermal comfort

1. Introduction

Reducing energy consumption in educational buildings is crucial, as these facilities account for a significant portion of total energy demand in the building sector due to their high occupancy rates, extended operational hours, and intensive heating, cooling, and lighting requirements [1]. On the other hand, the thermal comfort of the students in these educational buildings should be satisfied for a sustainable education [2]. Rodriguez et al. [3] proved that poor thermal comfort levels in educational buildings affect the productivity of students. Considering that the students spend most of their time in classrooms, having an adequate understanding of thermal comfort in educational buildings is crucial [3]. Furthermore, physical, physiological, and psychological parameters which could affect thermal comfort of the students also influence the energy consumption of the educational buildings [1–4]. To satisfy better thermal comfort and decrease energy consumption in the educational buildings, scholars used retrofitting strategies such as insulating the walls [5], changing lighting systems with more efficient ones [6], green wall and roof (wall/roof) applications [7] and installing Trombe Wall to take advantage of the sun [8].

Green wall and roof applications could be one of the solutions to achieve these goals (Figure 1). Green systems are defined as wall and roofs that consist of plants growing vertically/horizontally on a wall/roof, which aim to save energy and increase thermal comfort beyond their environmental impacts. The benefits of green walls and roofs include a decrease in the heating loads of the buildings while improving the thermal comfort of the occupants [9]. The European Union promotes nature-based solutions (NbSs) as an integrated approach to addressing environmental challenges in urban areas while simultaneously contributing to social well-being and climate resilience [10]. “To be human-friendly” is now being integrated with “to be nature-friendly”. On macro and urban aspects, green walls and roofs decrease urban temperatures and improve outdoor thermal comfort [11–13]. On the other hand, the micro-climate of indoor built environments can be arranged with green wall and roof applications [14–19]. For instance, Charoenkit and Yiemwattana [14] stated that green and living walls (dark-green and yellow-green walls) could decrease the cooling energy demand by 37.3% in a Mediterranean climate compared to a reference building without green and living wall and roofs. The green wall applications can also improve the thermal comfort of the occupants. For instance, Li et al. [15] used green wall to improve thermal comfort and the authors concluded that this modular system improved thermal comfort by 26.6% in Chenzhou City/China.

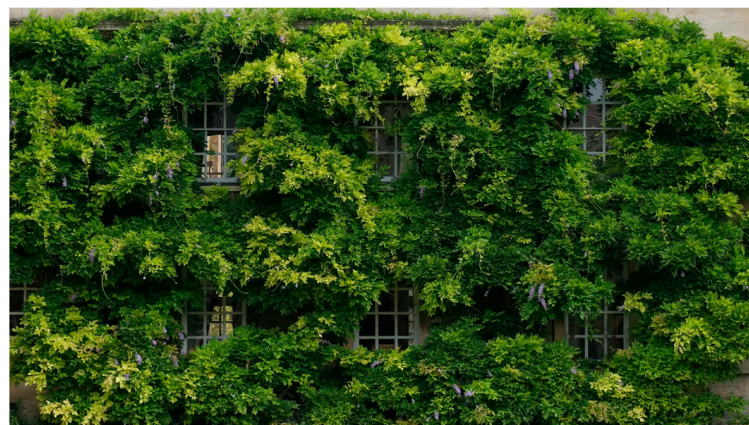


Figure 1. An example application of the green wall [16].

Considering the fact that one of the main objectives of the United Nations General Assembly’s is making cities and buildings more resilient and sustainable [17], a suitable retrofitting strategy is that of applying green walls and roofs to buildings. To this aim,

Assimakopoulos et al. [17] analysed a case study in Athens/Greece by applying green wall to the building. The authors used *Sedum*, *Lawn*, and *Grass* on the building envelope and concluded that cooling load of the building decreased by 3.1% with applying green wall. Similarly, Razzaghmanesh and Razzaghmanesh [18] showed that ambient air temperature in buildings could be decreased up to 1.8 °C via applying green walls. In another study by Olivieri et al. [19], the surface temperature of the walls in Madrid/Spain were decreased by 6.4 °C by adding an extra vegetal layer to the existing walls. Jamei et al. [20] stated that the design elements of green roofs significantly impact their potential for energy savings, with effectiveness being strongly influenced by prevailing climatic conditions in temperate climate zones. Jun et al. [21] conducted a study to investigate the effects of different green roof plants on cooling. However, this study included only four plant species.

Recent studies have extensively examined the impact of green walls and roofs on energy consumption and thermal comfort, highlighting their role in improving building sustainability. For instance, Pérez et al. [22] investigated how the leaf area index (LAI) of green facades influences energy performance, demonstrating that higher LAI values contribute to greater insulation effects. Raji et al. [23] conducted a review of green roof technologies and concluded that these systems can reduce cooling energy demands by up to 75% in certain climates. Similarly, Jamei et al. [20] emphasised the role of climate in determining the efficiency of green roofs, noting that temperate and hot climates show significant reductions in energy loads. Yang et al. [24] quantified the energy savings potential of green roofs in urban environments, reporting a reduction in annual energy consumption of 2–48%, depending on climate conditions and building characteristics. Coutts et al. [25] analysed the microclimatic benefits of green roofs in Melbourne and found that they significantly mitigate urban heat island effects. Additionally, research by Berardi et al. [26] reviewed the effectiveness of green walls and roofs in enhancing indoor comfort, particularly in reducing peak summer temperatures. Manso and Castro-Gomes [27] explored various types of green facade systems and their thermal insulation properties, concluding that modular systems provide superior cooling benefits. Furthermore, Santamouris [28] highlighted the economic and environmental advantages of large-scale green infrastructure in urban planning. Studies by Coma et al. [29] demonstrated that green walls can lower indoor temperatures by 3–5 °C, thereby reducing cooling energy demand. Lastly, Ascione et al. [30] examined the integration of green roofs with other passive design strategies, suggesting that their combination with high-performance glazing and shading elements maximises energy efficiency.

Most studies to date have been concerned with the influence of green walls and roofs on the surface temperature of the envelopes; therefore, the knowledge gap on the effect of these systems on thermal comfort and energy consumption of the buildings still exists. Nonetheless, some studies concluded that the cooling effect of these wall and roofs is certain, thermal comfort and energy saving potential of green wall and roof applications should be conducted in detail. Therefore, the main aim of this study is assessing the impact of various species on energy consumption and thermal comfort in green wall and roof applications in a case building located at Csb-type climate zone.

The remainder of this paper is structured as follows: Section 2 presents the materials and methods, including details on the case study building, data collection process, and simulation approach. Section 3 outlines the results and discussion, where the impacts of the green wall and roof applications on energy consumption and thermal comfort are analysed and compared with prior studies. Section 4 provides conclusions, highlighting key findings, practical implications, and recommendations for policymakers and practitioners.

2. Materials and Methods

This study consists of in situ experiments by integrating measurements and simulation. An educational building in a university located in Ankara, Türkiye, was selected as a case study.

2.1. Case Study Building

Case study building is an educational building which was built in 2009 with a total area of the building of 13,572 m², which hosts 1389 active students (Figure 2).



Figure 2. Selected case educational building for green wall and roof applications (the north face is the main entrance of the building).

Ankara is in Csb-type climate zone of Köppen-Geiger Climate Classification [31]. The average annual air temperature is 12.6 °C, while the maximum and minimum air temperatures are 40.4 °C and −24.9 °C during the period 1927–2023 [32]. The building characteristics are given in Table 1. The U-values of the wall, floor, and ceiling are calculated as 0.41, 1.17, and 1.21 W/m²K, respectively. The U-values of door and window are determined as 2.66 and 1.60 W/m²K, respectively.

Table 1. Characteristics of the case building.

Layer	Thicknesses (mm)	U-Value (W/m ² K)
Wall		
Autoclaved fibre cement block	12	1.66
Concrete block	200	1.00
XPS	50	0.15
Plaster	20	3.30
Total		0.412
Windows		
Double-glaze (6 mm air gap)	7	2.66
Doors		
Glass door	8	1.60
Floor	600	1.17
Roof	500	1.21

Air-tightness of the building is taken as 0.7 ac/h. The building has a heating system with a natural gas-powered boiler, which pumps hot water to the radiators. Radiators have a constant set-point temperature with a value of 22 °C for 7/24 h. On the other hand, students open doors/windows manually for the summer period, since there are no mechanical cooling and ventilation systems in the building. A fluorescent type lighting system is used with a fix value of 9.8 W/m² for each. The flat roof includes 20 mm plaster, 200 mm air gap, 144.5 mm glass wool, 10 mm asphalt, and 150 mm external plaster.

2.2. Simulation Study

A dynamic Building Energy Simulation tool (BES), called DesignBuilder [33], was used to evaluate the energy consumption and thermal comfort of students. To this aim, the architectural drawing of the case building was obtained from a previous study of Turhan and Ghazi [34] and modelled in the BES tool for green wall and roof applications. The existing building model is called the baseline model in the study. However, the BES model should be calibrated with actual-measurements to obtain accurate results. For this reason, the case building is monitored during one year, including summer and winter periods. HOBO sensors, which measure indoor air temperature and relative humidity, are used for the measurement campaign in every classroom and the data are collected with ten minutes intervals. The accuracy and resolution of the sensors are ± 0.25 °C and 0.02 °C for the air temperature. On the other hand, air speed is also recorded with a ten minutes interval by the authors. During calibration, the average temperature and relative humidity of the zone's air in the model are compared to the real measurements throughout the entire year for each zone. Then, the mean bias error (MBE) and coefficient of variation of the root mean square error (CV) are computed for each zone. Finally, the average of all zones is conducted. Once the baseline model is validated with measured data, the modifications are processed over the BES model of the case building.

Figure 3 depicts the baseline model of the case building. It is worth noting that the weather data are obtained from the meteorological station of the university. Two outputs of the BES tool are used for the study: energy consumption and total discomfort hours.

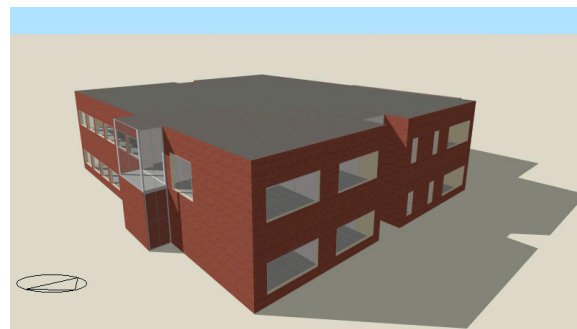


Figure 3. The BES model of the case building for simulations.

2.3. Green Wall and Roof Applications

In order to evaluate the impact of green wall and roof applications, an ivy species called *Hedera canariensis gomera* is used on the building in two scenarios: (1) applying plant to only walls; (2) applying plant to the walls and roof (Figure 4). Moreover, while *Hedera canariensis gomera* is applied to the walls in both scenarios, twenty-one different plant species are used on the roof for scenario 2. These plants are applied to whole opaque façades of the building.

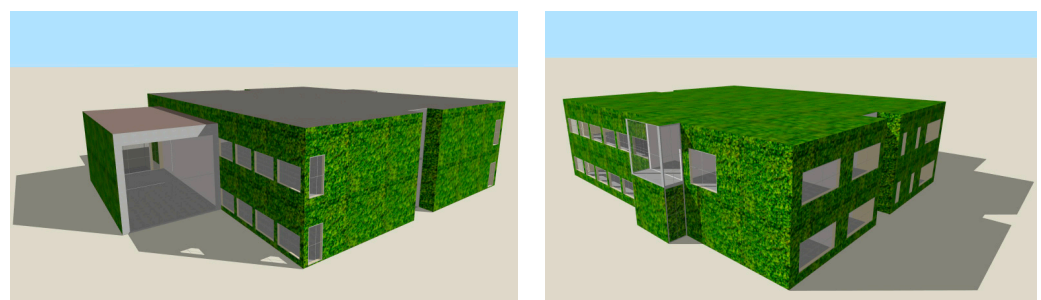


Figure 4. Scenario 1—green wall (left), Scenario 2—green wall + roof (right).

Table 2 presents the features of *Hedera canariensis gomera*, which are used as input data for the wall used in the BES tool. The reason for selecting this species is being one of the climbing and evergreen plant which exists in Türkiye. The plants easily grow and expand to the walls and roofs. Moreover, this ivy can resist environmental conditions of Csb-type climatic zones, where the zone has dry summers. It is worth indicating that the U-value of the wall decreased from 0.41 W/m²K to 0.22 W/m²K when the green wall applied to the existing wall.

Table 2. Green wall plant parameters (adapted from the DesignBuilder).

<i>Hedera canariensis gomera</i>			
Conductivity	W/mK		0.4
Specific heat	J/kgK		1100
Density	kg/m ³		641
Height	m		0.1
Leaf Area Index (LAI)	LAI		2.7
Leaf reflectivity			0.22
Leaf emissivity			0.95
Min. Stom. Res.	s/m		180
Max. Vol. Moisture Cont. Sat.			0.5
Min Residual Vol. Moist. Content			0.01
Initial vol. Moist. Content			0.15

Figure 5 depicts the added layers for the applications of green walls and roofs to the baseline model. It is worth noting that a 200 mm vegetation layer is added after applying soil. From the inside to the outside, an 89 mm air gap, a 10 mm PVC, a 50 mm wool fibre soil, 200 mm of cultivated peat soil, and 200 mm of vegetation are applied over the existed wall and roof layers.

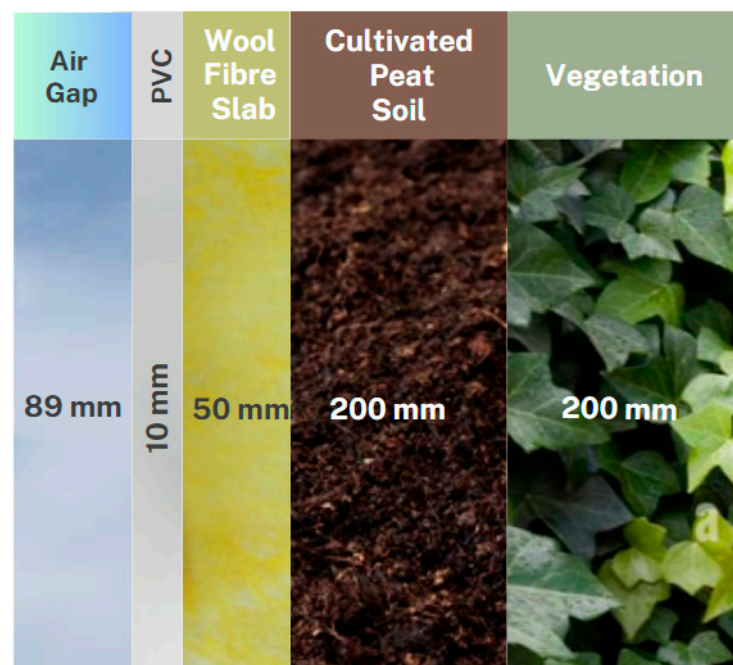


Figure 5. Layers of green wall and roof for both scenarios (developed by the authors).

A total of twenty-one plants is used for the green roof applications. Table 3 depicts the name and features of the used plants.

Table 3. Features of plants for the green roof applications [22,35].

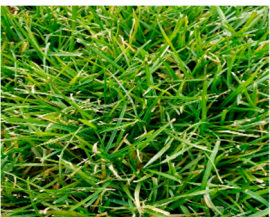
Roof Number	Image	Latin Name	Name	LAI *
1		<i>Hedera canariensis gomera</i>	Canary Island Ivy	2.70
2		<i>Crinum asiaticum</i>	Mangrove Lily	3.31
3		<i>Tabernaemontana divaricata</i>	Crape-jasmine	3.07
4		<i>Bougainvillea spectabilis</i>	Great Bougainvillea	4.95
5		<i>Ficus microcarpa</i>	Chinese Banyan	3.75
6		<i>Ophiopogon japonicus</i>	Mondo-grass (Dark Green)	6.66
7		<i>Ixora coccinea</i>	Orange Flower	5.82
8		<i>Caesalpinia pulcherrima</i>	Pride of Barbados	2.44

Table 3. Cont.

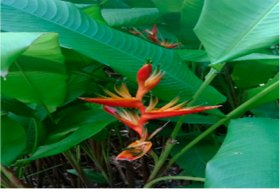
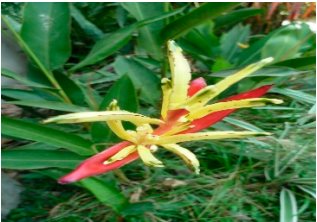
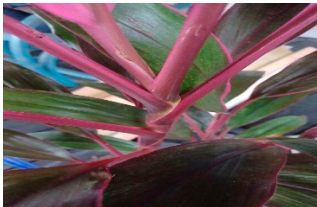
Roof Number	Image	Latin Name	Name	LAI *
9		<i>Phyllanthus bourgeoisii</i>	Waterfall Plant	6.59
10		<i>Chamaerops humilis</i>	Mediterranean Fan-Fern	4.41
11		<i>Turnera subulata</i>	White Alder	3.21
12		<i>Duranta erecta</i>	Golden Dewdrops	4.08
13		<i>Heliconia psittacorum</i>	Parakeet Flower (Long Leaves)	5.28
14		<i>Lagerstroemia indica</i>	Crape Myrtle	2.15
15		<i>Jasminum sambac</i>	Arabian Jasmine	3.32

Table 3. Cont.

Roof Number	Image	Latin Name	Name	LAI *
16		<i>Ophiopogon japonicus</i>	Mondo-grass (Light Green)	5.83
17		<i>Heliconia psittacorum</i>	Parakeet Flower (Small Leaves)	3.04
18		<i>Cordyline fruticosa</i>	Broadleaf Palm Lily	2.33
19		<i>Festuca glauca</i>	Blue Fescue	0.01
20		<i>Ziziphus jujuba</i>	Chinese Jujube	1.69
21		<i>Phoenix roebelenii</i>	Roebelin Palm	2.37

* LAI: leaf area index.

3. Results and Discussion

The BES model is validated with actual measurements. Table 4 represents the calibration results of the baseline model according to ASHRAE 14 Guidelines [36]. According to Table 4, the baseline model is satisfactorily validated; hence, the further modifications can be applied over the baseline model. The MBE and CV are calculated as 3.74 and 7.11 for the model. It is worth reminding that the ASHRAE 14 limits are 10 and 30, respectively.

Table 4. Validation results of the baseline model.

Scenario Number	Total Source Energy	Energy Consumption (kWh/m ²)	Change (%)	Thermal Discomfort Hours (h)	Change (%)
	Baseline Model	284.50	-	3147	-
Scenario 1	Green Wall	280.93	−1.25	3012	−4.29
Scenario 2	Green Wall + Roof 1	273.73	−3.79	2874	−8.67
	Green Wall + Roof 2	271.25	−4.66	2786	−11.64
	Green Wall + Roof 3	272.07	−4.37	2805	−10.86
	Green Wall + Roof 4	267.98	−5.81	2595	−17.51
	Green Wall + Roof 5	270.11	−5.06	2702	−14.12
	Green Wall + Roof 6	258.58	−9.11	2405	−23.55
	Green Wall + Roof 7	261.25	−8.17	2507	−20.58
	Green Wall + Roof 8	274.85	−3.39	2876	−8.62
	* Green Wall + Roof 9	258.30	−9.21	2423	−23.24
	Green Wall + Roof 10	266.92	−6.19	2655	−15.61
	Green Wall + Roof 11	271.73	−4.49	2790	−11.35
Scenario 3	Green Wall + Roof 12	268.79	−5.52	2697	−14.33
	Green Wall + Roof 13	264.03	−7.19	2423	−22.98
	Green Wall + Roof 14	276.05	−2.97	2907	−7.61
	Green Wall + Roof 15	273.23	−3.96	2774	−11.84
	Green Wall + Roof 16	262.28	−7.81	2498	−20.63
	Green Wall + Roof 17	272.42	−4.23	2808	−10.77
	Green Wall + Roof 18	275.56	−3.14	2889	−8.19
	Green Wall + Roof 19	280.88	−1.27	3009	−4.37
	Green Wall + Roof 20	277.75	−2.37	2959	−5.98
	Green Wall + Roof 21	274.94	−3.36	2906	−7.65

* Bold row shows the best result.

Table 4 exhibits the comparison of the effect of the green wall and roof applications on energy consumption and thermal comfort. Based on the simulation of the baseline model, the energy consumption of the case building is calculated as 284.5 kWh/m². On the other hand, thermal discomfort hours of the students are obtained as 3147 h during a year. By applying only the green wall to the case building, the energy consumption of the baseline building is decreased by 1.25%, while this retrofitting strategy decreases the thermal discomfort hours of the students by 4.29%. Applying green walls and roofs decreases the energy consumption from 284.5 kWh/m² to 273.73 kWh/m² if the *Hedera canariensis gomera* is used for the wall and roof. This retrofitting strategy decreases total energy consumption by 3.79% compared to the baseline model. On the other hand, the thermal discomfort hours of the students are decreased by 8.67%. The best energy saving is obtained with the combination of the *Hedera canariensis gomera* for the wall and *Phyllanthus bourgeoisii* for the roof of case building. This retrofitting decreases energy consumption by 9.21%, while increasing the thermal comfort of the students by 23.21%.

Some discussions can be drawn in this section. Green wall and roof applications provide a cooling effect, decrease energy consumption, discomfort, and direct solar radiation to the surfaces, and create an insulation layer [37]. Similarly to our study, a 4% reduction in the need for cooling energy need was obtained in Athens, Greece, which is also in a temperate climate zone [17]. The authors concluded that the green walls and roofs cause an increase in heating loads in winter; however, a decrease was encountered in the cooling load in summer period. Similar results on the thermal comfort were also obtained compared with our study. In order to evaluate the seasonal differences, the best result was investigated as an example. Table 5 depicts the simulation results of the green wall and roof applications compared to the baseline model with respect to the seasons. A small increase (1.19%) in the hours of thermal discomfort occurs when green walls and roofs are applied to the case building for the winter season. Buildings with green walls and roofs experience

lower indoor temperatures during hot summer days, reducing the need for air conditioning and improving occupant thermal comfort. This can lead to significant energy savings and enhanced well-being for building occupants, particularly in densely populated urban areas where the urban heat island effect exacerbates heat stress. In contrast, the impact of green walls and roofs on the thermal comfort during winter months is more nuanced. While the insulating properties of the green walls and roofs help to retain heat within buildings, reducing heat loss through the roof and walls, the vegetation layer may also act as a barrier to solar gain, particularly if the plants are dormant and deciduous. In regions with cold winters, this can result in slightly cooler indoor temperatures compared to buildings with conventional roofs, especially on sunny days when the solar heat gain could contribute to passive heating. On the other hand, it is found that green walls and roofs have positive impact during the summer season.

Table 5. Comparison of the green scenario 2 with the baseline model based on seasons.

Seasons	Winter	Summer	Total
Energy Consumption (%)	−1.19	−8.43	−9.31
Thermal Discomfort Hours (%)	+2.88	−25.66	−23.55

Another important discussion is to consider the specific climatic conditions and micro-climatic factors when evaluating the seasonal differences in thermal comfort gained from green roofs. Factors such as roof orientation, building orientation, vegetation type, and maintenance practices can affect the performance of green roofs across different seasons. In conclusion, green roofs offer distinct benefits for thermal comfort throughout the year, with significant improvements in summer through reduced heat gain and enhanced cooling effects, and more subtle but still valuable contributions in winter through improved insulation and energy efficiency. By understanding and optimising these seasonal variations, designers and building owners can harness the full potential of green roofs to create comfortable, sustainable, and resilient built environments.

This study has some limitations. Outdoor temperature variations and environmental aspects such as biodiversity and thermo-hygrometric comfort are not included in the simulations. The authors prefer to use *Hedera canariensis gomera* as a vegetation layer over the existing layers. However, leaf reflectivity, LAI, and the moisture content of the plant species highly affect the results. Therefore, other plant species such as *Sedum* species, *Boston ivy* species and *Thymus* (i.e., as in [17]), which have LAI value greater than 4, could be applied to achieve higher energy savings and improved thermal comfort. Lastly, the results in this study should be different for other climate zones such as tropical (A-type climate zones) and continental (D-type climate zones) zones.

In simulations, the Leaf Area Index (LAI) values used were based on mature plants to provide a standardised comparison of their potential impact on energy consumption and thermal comfort. However, in practice, plant development varies over time and is influenced by factors such as soil depth, irrigation, and maintenance practices. To address this, future studies are needed for further experimental validation and additional simulations incorporating different growth stages and irrigation scenarios.

The strength of this study is that, while previous research has explored the benefits of green infrastructure, our study stands out by incorporating a comprehensive assessment of 21 different plant species, each with distinct thermal and physical properties, to determine their effectiveness in reducing energy loads and improving indoor comfort. Unlike many prior studies that solely focus on the thermal performance of green systems in general, this research integrates a well-calibrated Building Energy Simulation (BES) model, validated with real-world data collected over a one-year monitoring period. By providing a detailed

comparison of plant species based on their Leaf Area Index (LAI), thermal conductivity, and moisture retention properties, this study offers a valuable reference for optimising plant selection in future green wall and roof applications. Furthermore, the findings contribute to closing the knowledge gap on species-specific thermal benefits, offering practical insights for architects, urban planners, and policymakers seeking to enhance building sustainability through nature-based solutions [38].

Green walls and roofs have gained significant attention in recent years as a sustainable urban development strategy. From an economic standpoint, the implementation of green walls and roofs involve both initial and maintenance costs, which make it a complex topic for discussion. One of the primary economic considerations of the green walls and roofs is the initial investment required for installation. The cost typically includes materials, labour, engineering, and possibly modifications to the building wall and roof to support the added weight of the green walls and roofs. These upfront expenses can be substantial and may vary depending on factors such as roof and wall size, type of vegetation, and accessibility.

Finally, specific recommendations should be provided for policymakers and practitioners. Incentive programs supporting the integration of green walls and roofs in urban renovation projects, particularly in energy-intensive educational buildings, should be considered. Policymakers should promote adaptive green systems that incorporate moisture retention strategies to optimise thermal insulation benefits throughout the year.

4. Conclusions

This study evaluated the impact of green walls and roof applications on energy consumption and thermal comfort in an educational building located in a Csb climate zone. Using a validated Building Energy Simulation (BES) model, the study assessed the effects of 21 different plant species to determine their potential for reducing energy demand and improving indoor thermal conditions. The findings indicate that green walls and roofs can significantly enhance building performance, with energy consumption reductions of up to 9.21% and thermal discomfort hours decreasing by 23.24%, depending on the plant selection.

One of the key contributions of this research is the detailed analysis of plant species, considering Leaf Area Index (LAI), moisture retention, and thermal conductivity, which are often overlooked in previous studies. The results suggest that plant selection plays a crucial role in optimising energy efficiency and thermal comfort, particularly in temperate climates. Moreover, the study highlights the seasonal performance variations of green systems, showing that, while they are highly effective in summer for cooling, their insulating effects in winter require further investigation to avoid potential increases in heating loads. As a suggestion for future studies, different green wall applications using various types of greenery with different LAI values could be compared for existing buildings. Scaling these applications for different building types is significant by emphasising their suitability for high-occupancy structures where energy consumption is a major concern.

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