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Evaluation of Vertical Greenery System Efficiency for Thermal Behavior of Conventional Residential Buildings in the Hot and Dry Climate, Isfahan Province, Iran*

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ABSTRACT

Optimization of energy efficiency is one of considerable topics these days. For this purpose, sustainable architecture techniques, especially greenery or greenery have become highly important. Informed use of plants in the design of buildings is one of the cost-effective strategies for the optimization process that is rising worldwide. Hence, the Vertical Greenery System (VGS) is one of the most effective concepts and foundations of sustainable development in architecture that plays a vital role in reducing energy consumption. Regarding the structural diversity of VGS, this study examines the impact of green façade with six climbing plant species on the thermal performance of conventional residential buildings in Isfahan City. To do this evaluation, some indicators such as the leaf area index of plants, the gap between plants and wall (0, 5, 10, 15, and 20 cm), thermal transmittance or U-value, and placement height of plant (ground, second and fourth floor) are measured. First selected climbing plants (six species) were tested, and the leaf area index (LAI) was measured with a camera and Photoshop software then U-value was measured and collected through an infrared thermometer and Light Meter Lux program. The data obtained from U-value were then used to do simulation through DesignBuilder Software to find the impact of green façade in summer and winter solstices on the thermal performance of the building. After the data were classified and analyzed, the Lonicera Japonica plant with LAI of 10, U-value of 0.21 w/m2.k, and air layer of 20cm on the ground floor was selected as the optimum case. Other findings included a direct relationship between LAI and the thermal performance of the building and a reverse relationship of air layer presence between the green façade and external wall. Also, the component of plant height in the floors relative to the ground floor would decrease the heat penetration into the interior environment.

Keywords: Green Façade, Energy Saving, Conventional Residential Building, Hot and Dry Climate.

* This paper is derived from the M.Sc thesis by the first author titled "Design of Residential Complex to Analyze and Determine the Impact of Vertical Greenery System on the Thermal Performance in Isfahan City" which is guided by the second author in Islamic Azad University, Najafabad Branch.

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1. INTRODUCTION

The human need for energy and consuming various fossil fuels have led to higher CO2 rates and many problems and threats to health (Ebtekar 2017, 20). In the current world, man's outlook of surrounding urban space is only made of an artificial and soulless environment that is expanding day by day. Creating greenness in residential spaces is based on achieving a sustainable architecture and green space by preventing solar radiation, which makes the space cool and reduces the cooling load in the building. This measure positively affects the weather of the city and region by decreasing urban heat islands and compensating for the green space shortage (Mahmoudi Zarandi, 2014). In this lieu, walls are the surfaces with the most potential for plantation. Vertical green façade serving as an inactive system in sustainable design is one of the optimal techniques for energy saving that provides environmental and aesthetical benefits for people. Various factors, including type of plant (Koyama et al. 2013), type of system (Coma et al. 2016), the materials used in the system (Kokogiannakis et al. 2019), height of plant and LAI (Perez et al. 2016), plant cover percentage (Morakinyo et al. 2019), and plant thickness (Cuimin, Jingshu, and Chunying 2019) would affect the efficiency of VGS. The positive effects of VGS can be divided into three environmental, social, and economic groups.

This study aims to find the effect of climbing plants that are suitable for the hot and dry climate of Isfahan existing in the VGS on the thermal performance of residential buildings. To do this, this system is affected by various structural characteristics, including plant species, LAI that expresses the plant's ability to use and absorb social energy, and thermal conductivity coefficient. The gap between the green system and the wall (presence of air between two layers) that is a kind of insulation and height of plant situation in heat penetration into interior space along with hot and dry climate features may maximize the energy optimization.

1.1. Research Questions

- How much energy can be saved in the design of a residential complex in a hot and dry climate (Isfahan) by using one of these indicators: plant species and LAI, thermal conductivity coefficient, gap between system and wall, and height of plant's placement.
- What would be the behavior of VGS performance in energy consumption during summer and winter when plant species and LAI, thermal conductivity coefficient, gap between system and wall, and height of plant's placement are changed?

1.2. Hypotheses

- Energy consumption is considerably reduced when suitable plants for climate and optimum LAI are selected, and the optimal gap is observed between the plant and the building's body at an appropriate height.
- When the thermal conductivity coefficient of a plant increases, this system performs as an insulation and decreases input heat caused by solar radiation, and subsequently prevents building warming through the day by creating the shadow. This case would lead to heat loss from the building's interior space during winter.

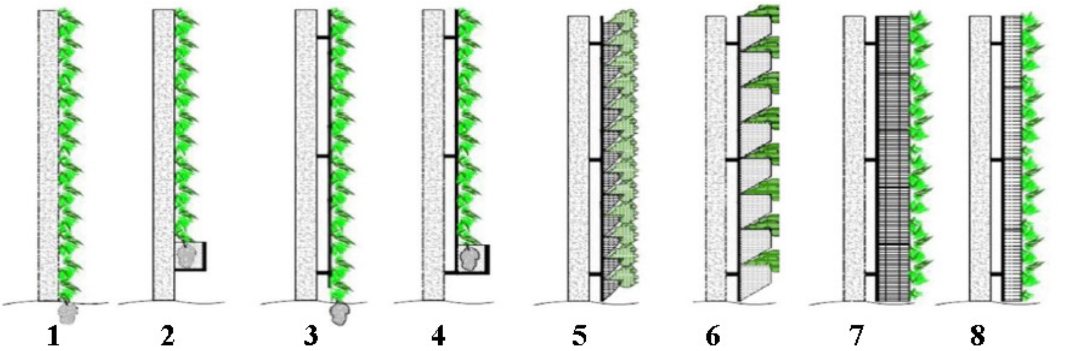
Because VGS is mainly studied in temperate and tropical climates with emphasis on the plant species and important indicators in this system and because these indicators have not been investigated in the climatic zoning of Iran, particularly in hot and dry climates, including Isfahan City, this topic must be studied more. On the other hand, the proper design of the building's façade and the use of sufficient sunlight energy regarding the greenness element in the structure of the green façade led to the replacement of new energies and increased quality of the environment.

2. BACKGROUND

VGS is a system that links plants to the structure or walls of the building to cover a part or whole of vegetation (Mir 2011). VGSs are generally divided into two groups of green façades and living walls (El Menshawy, Mohamed Abdelaziz, and Fathy 2022). A green façade is shaped based on the behavior of climbing or hanging plants so that plant growth is vertically placed in the façade surface and is classified into two main categories: 1. Straight: plants are directly stuck to the wall in this case. 2. non-straight: in this case, plants are reinforced with steel cables or scaffolds (Ottele 2011). Living walls in generally connected to more complicated infrastructures, including a support structure through various methods, and vegetation is rooted in a substrate connected to the wall. Living walls are classified into two types continuous and modular systems (El Menshawy, Mohamed Abdelaziz, and Fathy 2022). Table 1 and Fig. 1 indicate various states of this system and its application methods.

Table 1. Types of Vertical Greenery Systems

VGSs							
Green Façade				Green Wall			
Direct Connection		Indirect Connection		Continuous System	Modular System		
Plant's Root in the Soil	Plant's Root in the Pot	Plant's Root in the Soil	Plant's Root in the Pot	Felt System	Potted System	Panel System	
						Sponge System	Mineral Wool System



Left to right: 1. direct connection (plant's root in soil), 2. Direct connection (plant's root in the pot), 3. Indirect connection (plant's root in soil), 4, indirect connection (plant's root in the pot), 5. Felt system, 6. Potted system, 7. Sponge system, 8. Mineral wool system

Fig. 1. Types of VGS Structure

(Ottele 2011)

The VGS is an inactive system in sustainable design (Mohamed Farid et al. 2016, 180) that provides many benefits for humans (Kolyaei et al. 2020). The VGS provides social benefits such as positive mental and spiritual influences for humans (Safavi 2014). Environmental advantages include a reduction in CO2 and an increase in oxygen rate (Taghavi 2014), air pollution control (Azmoodeh 2021; Janzadeh 2016), sound control (Davis et al. 2017; Ashianegar et al. 2021; Bastanfard 2018), and preventing urban heat island that affects the micro-climate improvement by decreasing temperature of surrounding space (Morakinyo et al. 2019; Azmoodeh 2021; Mahmoudi Zarandi 2014). Also, VGS provides some economic benefits such as controlling direct sun radiation, saving the cooling and heating system of buildings, and environmental temperature.

In general, some studies have been done on the benefits of VGS. These studies have been mainly done for temperate climates (Perini et al. 2017; Li et al. 2019; Wong and Baldwin 2016; Convertino, Vox, Ileana, and Evelia 2018; Ramirez Davis and Pérez 2016; He et al. 2020; Feng et al. 2018), while few of them have been conducted in tropical, continental, and dry climates (Othman and Sahidin 2016; Sudimac et al. 2019; Zolfaghari, Saadatinasab, and Noroozi Jajarm 2019). The VGS has optimal effects on the thermal performance air temperature inside and outside the environment, and moisture (Daemi et al. 2021). In more detailed assessments, this effect has been considered on some variables such as thermal comfort (Azmoodeh 2021), heat loss and performance (Daemi et al. 2021), heating and cooling rate (Coma et el. 2019; Tan et al. 2020), heat flux (Sklje et al. 2019) and in combination with ventilation device on its back (Davis, Ramirez, and Pérez 2016) that all of them have confirmed this effectiveness in decreasing energy consumption. Despite the difference between climates, plant species, and other variables, Pérez et al. (2017) concluded that LAI has a reverse relationship with plant height, and façade orientation has a considerable impact on energy storage. A cooling energy storage of 34% is required for the selected plant species in the temperate Mediterranean climate during summer. In the study conducted by Coma et al. (2017), there is a direct relationship between sun radiation and energy storage, and regarding the radiation in the temperate Mediterranean climate, green walls and green façade would reduce 23.4% and 19.4% energy consumption, respectively. Moreover, the use of this system in the Mediterranean climate led to a 25% decline in energy consumption for ventilation during summer and a 10% decrease in temperature within two states with simple façade and green façade (Perini et al. 2017). According to these studies and consideration of variables diversity and effective factors, a reduction of 1-10°C in temperature and about 65% decrease in energy consumption in the presence of VGS (Kolyaei et al. 2020). Ultimately, various case studies in the world have been analyzed, and the effect of this system has been considered in different climates. These studies indicate that the hotter and dryer the climate, the more the yield of green walls and the lower the temperature of buildings and city will be due to decreased heat absorption, evaporative cooling, and low thermal conductivity (Mahmoudi Zarandi et al. 2018).

In general, the difference between green façade and green walls has been examined (Coma et al. 2016). Other studies have explained and analyzed various types of green systems, including green façade with direct connection (Charoenkit, Yiemwattana, and Rachapradit 2020; Davis et al. 2017; Mohammad Shuhaimi et al. 2022; Li et al. 2019; Kokogiannakis et al. 2019) and indirect connection (Charoenkit, Yiemwattana, and Rachapradit 2020; Vasigh and Mohammadi 2020; Kokogiannakis et al. 2019; Mohammad Shuhaimi et al. 2022), continuous (felt) green wall (Charoenkit et al. 2017; Kokogiannakis et al. 2019) and modular green wall (Davis et al. 2017; Rachapradit 2020; Oquendo-Di Cosola et al. 2020; Mohammad Shuhaimi et al. 2022), which consists of potted (Oquendo-Di Cosola et al. 2020; Li et al. 2019; Vasigh and Mohammadi 2020; Kokogiannakis et al. 2019) and panel systems (Shafiee, Faizi, and Yazdanfar 2020; Nan et al. 2020). In addition to these factors, the effect of the selection of these systems, including a budget, type of plant and green system, and structural features are studied (Torabifar and Suzanchi 2021). Among plant characteristics in these systems, two variables of LAI and thermal conductivity coefficient are mentioned, and variables of air layer thickness between green façade and external wall and placement of green system in the buildings' floor height can be named as features of these systems concerning the building that are reported in Table 2. Finally, this study analyzes independent variables of LAI, the plant's thermal conductivity coefficient, the thickness of the air layer between the green façade and the external layer of wall, the floor height of the building, and the thermal performance rate of the building as dependent variables in the hot and dry climate of Isfahan based on the available studies.

Table 2. Background of Studies Conducted on the Effect of Variables and Indicators on the Performance of VGS in Different Climates

Variable	Climate-Country		Author
LAI	Temperate Mediterranean-Spain		(Perez el al. 2016)
	Subtropical Temperate	China	(Li et al. 2019)
		Tokyo, Japan	(Koyama et al. 2013)
Thickness of Plant Foliage	Subtropical temperate-China		(Li et al. 2019)
Walls' Orientation	Mediterranean Temperate	Hong Kong	(Morakinyo et al. 2019)
		Spain	(Coma et al. 2016)
Vegetation	Tropical-Indonesia		(Widiastuti, Zaini, and Caesarendra 2020)
	Subtropical Temperate-Tokyo, Japan		(Koyama et al. 2013)
Plant Species	Tropical	Tropical-Sri Lanka	(Rupasinghe and Halwatura 2020)
		Thailand	(Charoenkit et al. 2020)
	Temperate	Oceanic-UK	(Thomsit-Ireland et al. 2020)
		Subtropical-China	(Nan et al. 2020)
		Mediterranean-Italy	(Vox, Ileana, and Evelia 2018)
		Mediterranean	(Ileana et al. 2019)
		Subtropical-Tokyo, Japan	(Koyama et al. 2013)
Wall Materials on the Back of the Greenery System, such as Insulation and Type of Brick	Oceanic Temperate-Austria		(Tudiwer, Florian, and Azra 2019)
Construction and Structure of the Living Wall's Substrate	Mediterranean Temperate-Spain		(Pérez-Urrestarazu et al. 2019)
Evaporation and Transpiration of Plant Foliage	Subtropical Temperate- China		(Zhang et al. 2019)
			(He et al. 2020)
Photosynthesis	Subtropical Temperate- China		(Zhang et al. 2019)
Wave Transmission Rate, Reflectivity, Light Absorption	Subtropical Temperate- Hong Kong		(Lee and Jim 2019, 3)
Air Gap of Green System and Wall	Subtropical Temperate- South America		(Davis et al. 2017)

3. METHOD

The research method is simulation, and this is an applied study in terms of objective. In the first phase, climbing plants of the VGS that are matched with the hot and dry climate of Isfahan are found through interviews and library studies. The plantation substrate for testing and collecting the considered data of plants was chosen in Research Center 2 of the Parks and Green Space Organization of Isfahan Province in Mahmoud Abad Area. The plants were planted in an area with southern sunlight in a space of the same size and coverage. The type of structure used in the system is a green façade and indirect connection; the plant's root is in the pot with a polyethylene mesh net to keep the plant stem vertically. In the second phase, quantitative data collection was done through observation and experiments. Daily data were collected over the year from the middle of every month and at noon when sunlight is at a maximum rate between 11:30 and 13:30. The relevant tools are the infrared thermometer TES1326 Model and Lux Light Meter 2.1.1 to measure the thermal conductivity coefficient and LAI of plants in front and back of the plant, respectively. The third phase determined the LAI of plants by using a digital camera and converting them into pixel images through Photoshop software. In the fourth phase, the energy analysis software of Designbuilder, 7,0,0,096 Version with Energyplus, 9.4 Version engine was used to organize and simulate data. Fig. 2 depicts the research phases. Simulations were considered in seven modes (six plants with reference mode) in a space with residential use. The LAI, thermal conductivity coefficient or U-value of the plant, the thickness of the air layer gap between the green façade and the external layer of wall, floor height of the building, and thermal performance rate are simulation variables. Winter and summer solstices were selected for the thermal behavior of VGS through Designbuilder Software due to sun placement angle and its radiation rates within various modes to analyze light penetration indoors and heating at minimum and maximum conditions regarding the plants' density. Finally, statistical software and the Design Explorer website were used to analyze data and achieve the optimum case.

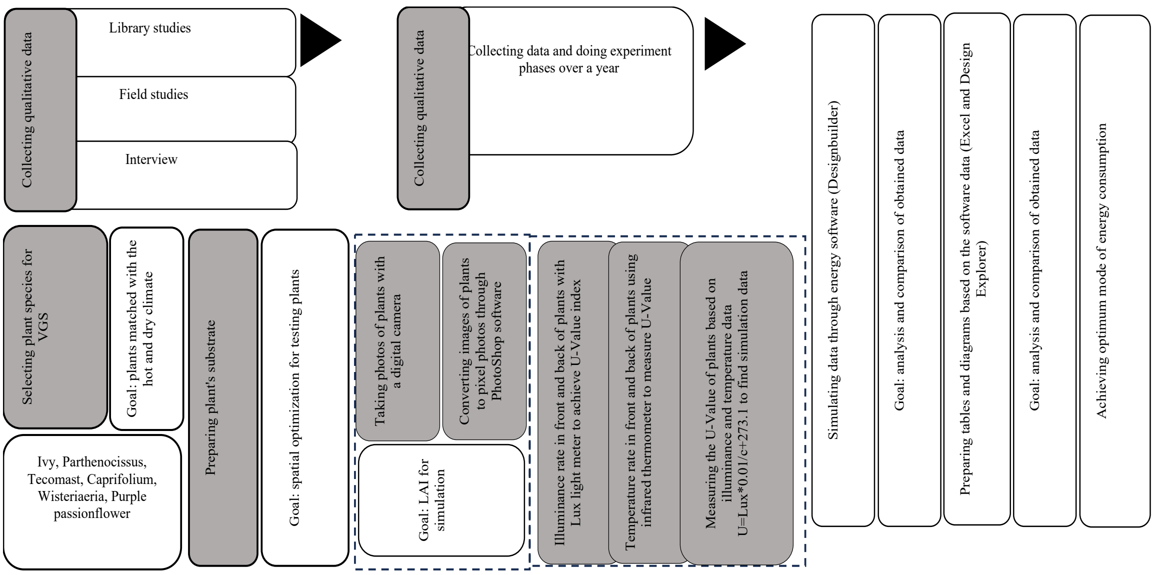


Fig. 2. Research Process

3.1. Climate of Isfahan City

Isfahan City having an eastern longitude of 51.67° and northern latitude of 32.65° is located 1574m above sea level. According to the Köppen climate classification, Isfahan is a hot and dry climate in the semi-arid zone (Bwk). In this climate, sun radiation is severe, and the sky is cloudless most of the time. Table 3 reports the climate conditions of Isfahan.

Table 3. Average Annual Temperature and Relative Humidity of Isfahan 1950-2010

Minimum Temperature (°C)	Maximum Temperature (°C)	Average Temperature (°C)	Minimum Relative Humidity (%)	Maximum Relative Humidity (%)	Average Relative Humidity (%)
-19.4	43	16.2	11	81	35.41

(Hasehzade Haseh, Khakzand, and Ojaghlou 2018)

3.2. Introduction to the Base Model

The model selected for simulating the green façade was considered based on general principles of the fourth topic of National Construction Regulations as shown in Fig. 3. Therefore, a 3*4 m room (minimum surface (m^2) for main accommodation space of residential unit) with 3.2 m height (minimum useful height of 2.6 m that equals 3.2 m considering the ceiling and floor of final height). The space has a south-facing window, and the ratio of translucent surface to floor equals 1:8 based on the light and air requirement considered in the fourth topic of National Construction Regulations. Table 4 reports the characteristics of the base mode for simulation. Dahanayake and Chow (2017) conducted a study to validate the accuracy of VGS through Energy Plus software, and compared the simulated indoor temperature and temperature of external and internal surfaces of the façade based on the results of two confirmed experiments, including an experimental thermal triangular sample and one residential building. A good match (R^2 approaches 1) was found between simulation results and experimental data, by using the correlation coefficient and its analysis, so this system provided a sufficient prediction for understanding thermal performance.

Table 4. Structural Characteristics of Room for Simulation through Designbuilder Software

Title	Characteristic
Location	Isfahan
Longitude and Latitude	51.67 & 32.65
Activity	Residential
Occupancy Density (People/m^2)	0.0188
Heating Temperature	21
Heating Set Back Temperature	12
Cooling Temperature	25
Cooling Setback Temperature	28
Window's Model	Double-Glazed Transparent Glass, without Awning
Type of Window	6-mm Transparent Glass - 6mm Air
Window Frame Structure	UPVC
Illuminance	LED
HVAC	Best Practice
Ventilation	Without Mechanical Ventilation

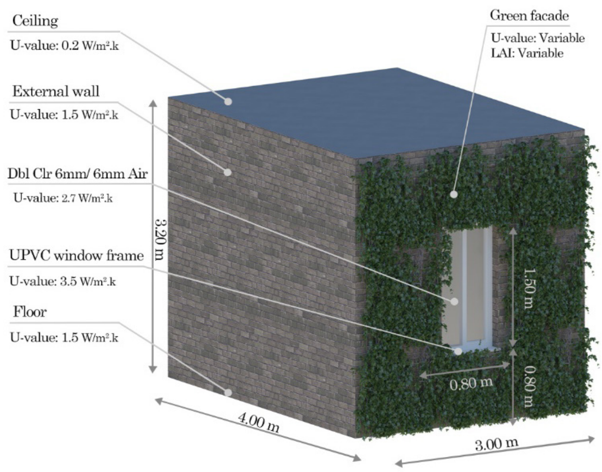


Fig. 3. Schematic of Simulated Room for Computations through Software

3.3. Variables

Variables of the study consist of LAI, U-Value of plant, the thickness of the air layer between the green façade and external layer of the wall (air gap), floor height of the building, and thermal performance rate that are reported in Table 5, and are explained herein.

Table 5. Research Variables

Variable	LAI	U-Value	Between the Green Façade and the External Layer of the Wall	Floor Height of the Building	Thermal Performance Rate
Measurement Unit	----	W/m^2.k	Cm	Floor (3.2 m)	KWh/m^2
Role of Variable	Independent				Dependent
Type of Variable	Quantitative				

4. FINDINGS

4.1. First Phase: Selecting Plants Matched with the Climate

The plants in this study were selected based on the structural diversity of VGS, which is limited to green façade, so the plant considered for this system is among climbing species. According to the classification of these climbing plants, they have about 27 species (Farahmand 2017, 34). More limited plant diversity resisting dry air and severe sun radiation was found in Isfahan due to the climatic features of this city, including hot and arid summers. Therefore, the data collection method in this phase was done by referring to the book "Ornamental Climbing Plants (Ornamental Vines) and Wall Covering Shrubs" (Farahmand 2017, 22) and doing interviews with engineers and experts in agriculture and horticulture disciplines. The result of this phase was the identification of Ivy, Parthenocissus, Wisteriaeria, Tecomast, Caprifolium, and Purple Passionflower, which are seen in Table 6 and Fig. 4.

Table 6. Sample Plants to do Experiments

Purple Passionflower	Parthenocissus	Ivy	Caprifolium	Tecomast	Wisteriaeria
Wisteria Sinensis	Campsis Radicans	Lonicera Japonica	Hedera Helix	Parthenocissus Tricuspidata	Passiflora Incarnata
Evergreen	Deciduous	Evergreen	Evergreen	Deciduous	Deciduous
					

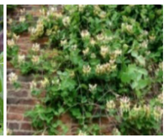
Fig. 4. Plans selected in the first Phase, Fall and Spring Seasons

4.2. Second Phase: Calculating the U-Value of Plants

The U-value of every plant is required for simulating green façade through Designbuilder software. Since the U-value was not available, some experiments were done and the data obtained from illumination and temperature can be used to measure this coefficient based on the Lux unit. The data of temperature and sunlight were measured using an infrared thermometer and Lux Light Meter program. The following formulas were then used, and the illuminance rate and temperature difference in the front and back of plants measured based on the Lux and °C, respectively were converted to w/m^2 and Kelvin (Table 7). These two values are divided by each other to obtain the U-value of each plant, which is defined as a simulated green façade through Designbuilder software.

Converting Illuminance Rate from Lux to w/m2	Lux*0.01 = w/m^2
U-Value obtained from Illuminance Rate divided by Temperature	$(w/m^2)/\ °k = (w/m^2)*(1/°k) = U$
Converting Temperature Unit from °C to Kelvin	c+273.15=°k°
General Formula	U=(Lux*0.01)/(°c+273.15)

Table 7. The U-Value of Plants in the First and Second Half of the Year from w/m^2 to Kelvin

	Purple Passionflower	Parthenocissus	Ivy	Caprifolium	Tecomast	Wisteriaeria
						
April 7, 2021	0.175	0.078	0.225	0.118	-	0.414
May 19, 2021	0.095	0.086	-	0.260	-	0.216
June 14, 2021	0.428	0.160	-	0.341	0.076	0.368
July 24, 2021	0.484	0.092	-	0.366	0.212	0.367
August 7, 2021	0.437	0.237	-	0.116	0.236	0.299
August 21, 2021	0.422	0.195	-	0.251	0.227	0.214
Average	0.324	0.131	0.225	0.215	0.175	0.333
November 9, 2020	0.154	0.099	0.127	0.110	0.110	0.223
November 25, 2020	0.043	0.165	0.124	0.182	0.041	0.339
December 12, 2020	0.083	0.185	0.168	0.137	-	0.094
December 26, 2020	0.073	-	0.246	0.203	-	-
January 25, 2021	0.155	-	0.045	0.128	-	-
Average	0.102	0.149	0.142	0.152	0.075	0.219

4.3. Third Phase: Measuring LAI

To measure the LAI of each plant over a year, photos of plants were taken from a 2 m distance using a digital camera a day in the middle of each month. According to Fig. 5, the images were converted to the same squares, and then images were simplified to checkered shapes through Photoshop 2018. The extra parts of the image that are leafless were removed and images were converted to black and white shapes. Regarding the pixel form, final images of all plants during different months are expressed in percentage values to measure the LAI of each image to achieve a range of 0-10 for each plant. Figure 6 and Table 8 indicate this simplification for LAI in green façade as a percentage value during different months.

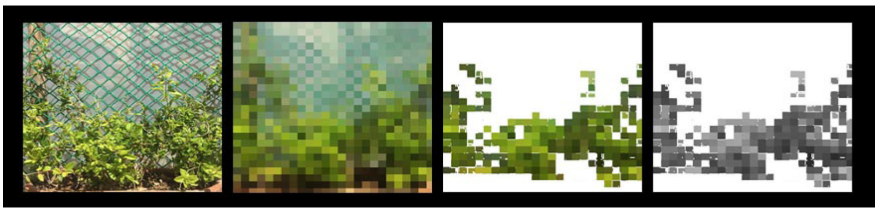
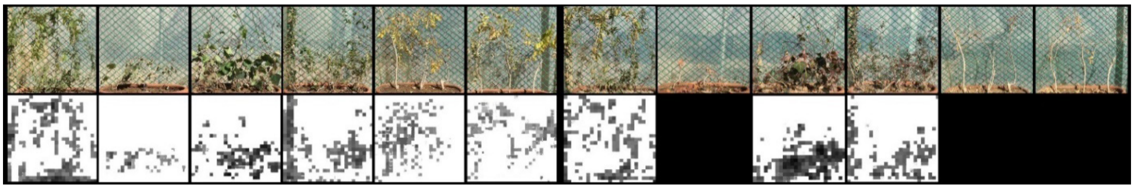
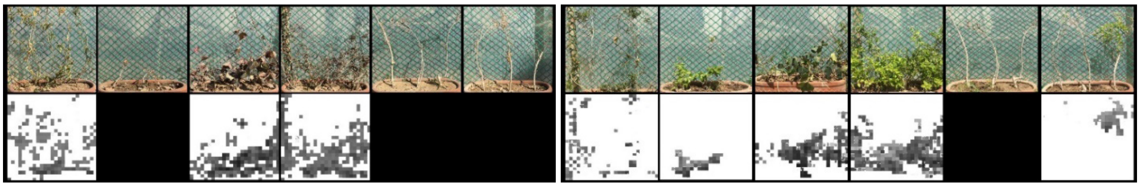


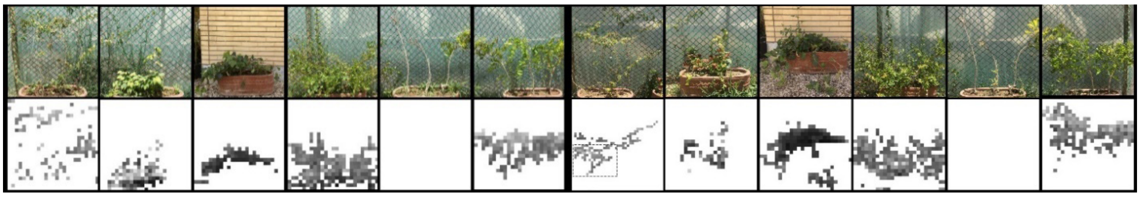
Fig. 5. Simplifying Images of Plants for LAI



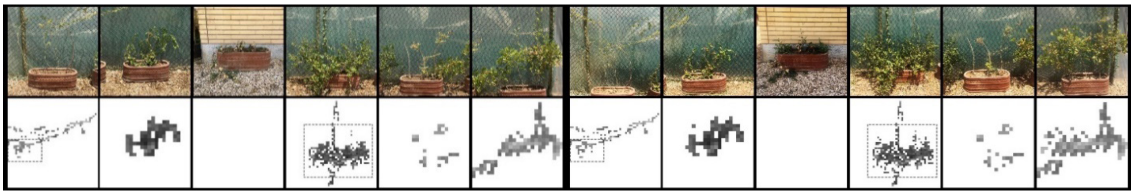
November 6-December 11



January 25-April 6



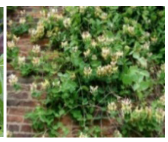
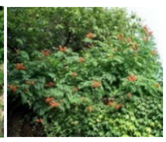
May 18-June 14



July 16-August 6

Fig. 6. Simplifying Images of Plants over the Year

Table 8. LAI of Plants without Units Varying between 0 and 10

	Purple Passionflower	Parthenocissus	Ivy	Caprifolium	Tecomast	Wisteriaeria
						
November 6, 2020	5.4	1.5	3.1	4.9	3.6	3.6
December 12, 2020	4.9	-	4.9	3.6	-	-
January 25, 2021	4.4	-	4.9	6.1	-	-
April 7, 2021	2.3	2.0	3.9	6.1	-	1.1
May 19, 2021	4.2	5.4	2.7	8.1	-	6.1
June 15, 2021	4.9	3.0	5.7	8.5	-	6.4
July 17, 2021	5.6	5.9	-	10.0	1.5	6.7
August 7, 2021	5.7	5.6	-	9.9	2.0	6.9
August 21, 2021	5.9	6.1	-	10	2.5	7.2

4.4. Fourth Phase: Simulation through DesignBuilder Software

This software is one of the most advanced simulation software in the energy field. Energy Plus is its simulation engine. DesignBuilder Software and obtained data of U-Value and LAI of green façade with various selected plants were used to simulate and analyze the models.

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4.4.1. Impact of Green Façade and U-Value

According to the impact of the U-value of plants in the green façade based on Fig. 7 and keeping LAI fixed in the modeled chamber in summer and winter solstices, a difference greater than 400 and 600wh/m² is seen compared to the base model, which implies the impact of green façade.

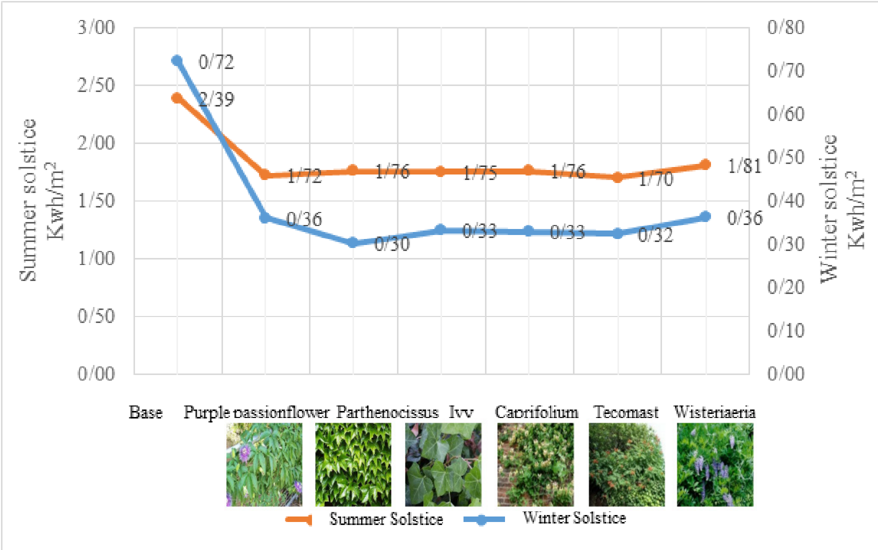
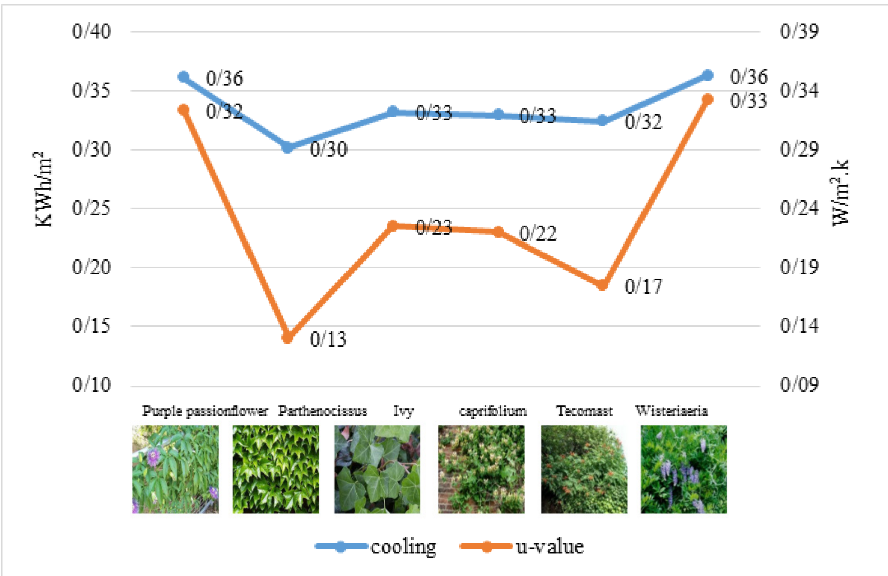


Fig. 7. Impact of Green Façade on Energy Consumption Reducing during Summer and Winter Solstices

According to the comparison between the U-values of six plants during summer solstices, as shown in Fig. 8, the U-value has a direct relationship with energy consumed for cooling the indoor space. Regarding winter solstice, also, increase in the U-value of plants leads to more energy consumption for heating in the simulated model.



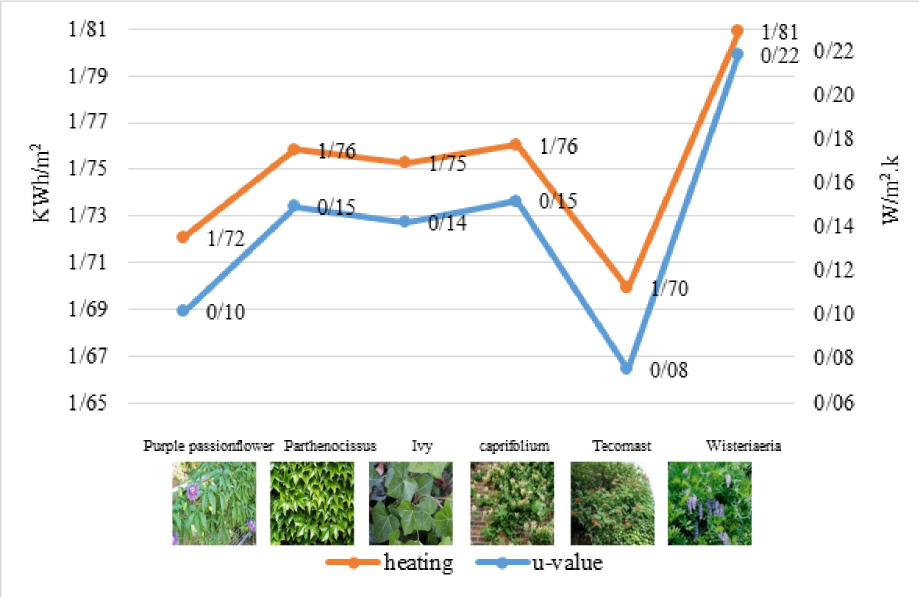
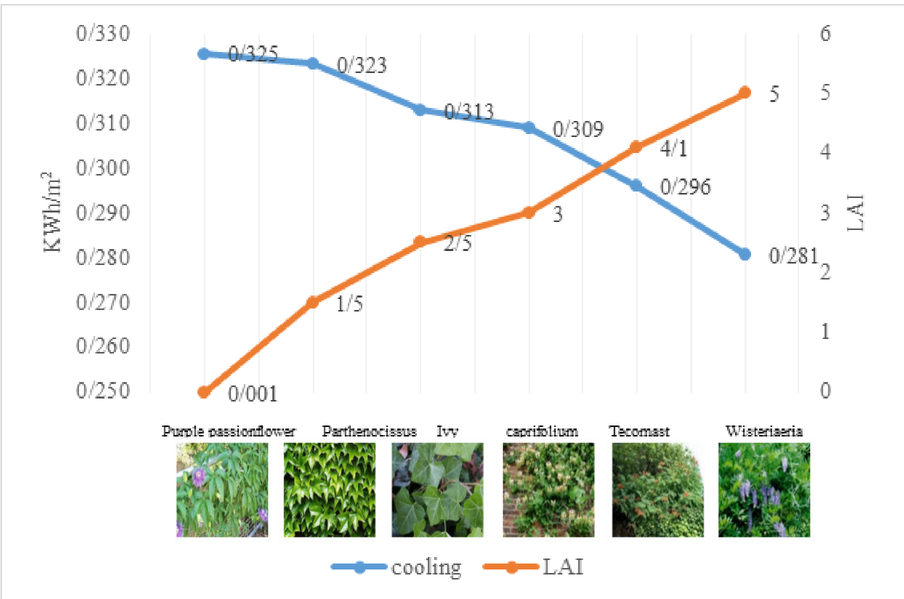


Fig. 8. Impact of U-Value during Summer and Winter Solstices

4.4.2. Impact of Green Façade and LAI

Fig. 9 indicates the effectiveness of plants' LASI in summer and winter solstice by analyzing the behavior of a plant while the U-value remains fixed. The Caprifolium plant is not a suitable choice for the winter season because it is not deciduous. An increase in the LAI of plants during summer solstice leads to an increase in the shade rate. A reduction was seen in the cooling load. Also, the data obtained during winter solstice indicate that an increase in LAI and shade rate leads to a higher heating load.



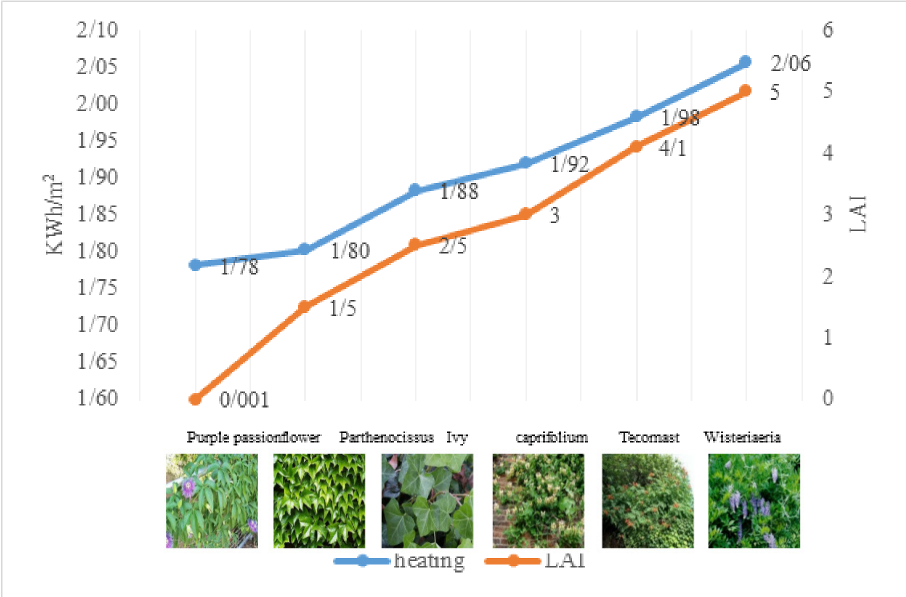


Fig. 9. Impact of LAI during Summer and Winter Solstices

4.4.3. Impact of Green Façade and Energy Consumption

All six plants with U-Value and LAI features were examined during summer and winter solstices to analyze these two features simultaneously because they are inseparable elements of plants. Fig. 10 indicates that the simultaneous impact of these two features in the green façade compared to the base model during summer solstice leads to a 370 wh/m^2 reduction in energy consumption for cooling the building. The highest effect of energy consumption reduction was provided by the Caprifolium plant followed by Parthenocissus, Ivy, Tecomast, Wisteriaeria, and Purple Passionflower in the last rank.

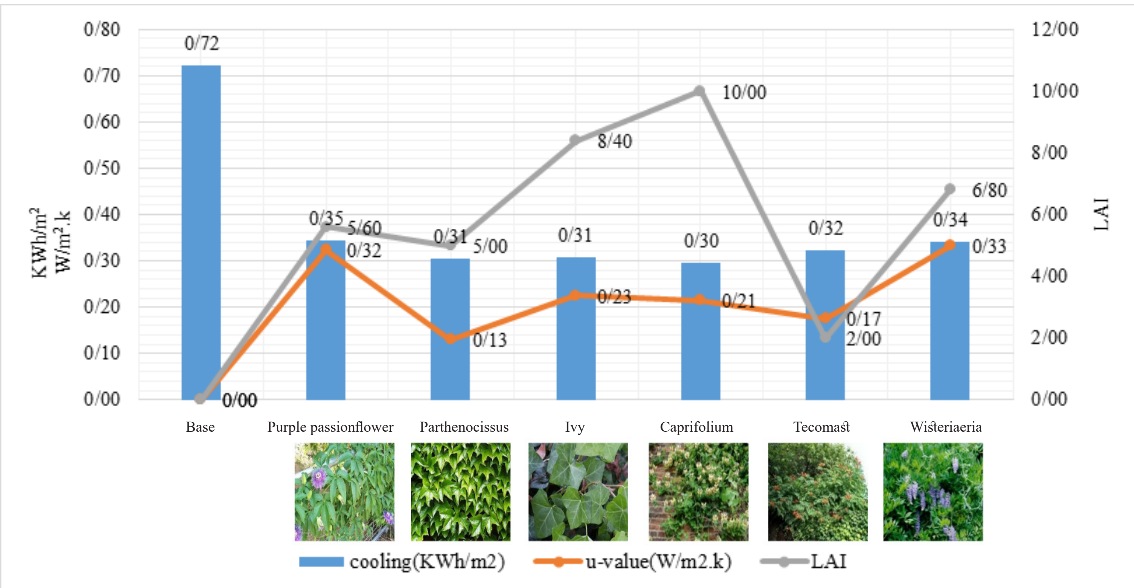


Fig. 10. Comparison between Thermal Performance Impacts of Six Plants during Summer Solstice

This diagram indicates a reverse relationship between LAI and cooling rate during summer, but a plant provides the impact of LAI and U-value simultaneously. According to values extracted in Table 9, variations in LAI and U-Value are matched in some modes, which results in changing energy consumption. In other cases, however, the final impact on energy consumption is caused by an increased percentage of one of these components. In total, two mentioned cases are expected to occur, but in 15 modes of pairwise comparisons, two cases (15 plants and 5-6 plants) indicated the effect of U-Value on the energy consumption rate despite the domination of LAI.

Table 9. Comparison of Effect Rate of LAI and U-Value

	LAI Variation (%)	U-Value Variation (%)	Cooling Energy Consumption Variation (%)	Dominant Variations	Dominant Effectiveness
1-2	-11	-59	-11	Uvalue	U-Value
1-3	50	-28	-11	LAI	Aligned Variations
1-4	79	-34	-14	LAI	Aligned Variations
1-5	-64	-47	-9	LAI	U-Value
1-6	21	3	-3	LAI	LAI
2-3	68	77	0	uvalue	Aligned Variations
2-4	100	62	-3	LAI	LAI
2-5	-60	31	3	LAI	Aligned Variations
2-6	36	154	10	uvalue	U-value
3-4	19	-9	-3	LAI	Aligned Variations
3-5	-76	-26	3	LAI	LAI
3-6	-19	44	10	uvalue	Aligned Variations
4-5	-80	-19	7	LAI	LAI
4-6	-32	57	13	uvalue	Aligned Variations
5-6	240	94	6	LAI	U-Value

According to Fig. 11, the deciduous plants of Parthenocissus, Tecomast, and Wisteriaeria were removed from the experiment, and the remained ones that are evergreen plants were compared. In this case, variations in energy consumption equals 500 to more than 600 wh/m^2. Purple Passionflower is in the first rank followed by Ivy and Caprifolium, which provided the most reduction in heating energy consumption. The U-value of plants is very similar due to seasonal changes during winter, so they can be considered the same, and the main impact is left by LAI and shading on the wall that its increase in winter leads to higher energy consumption.

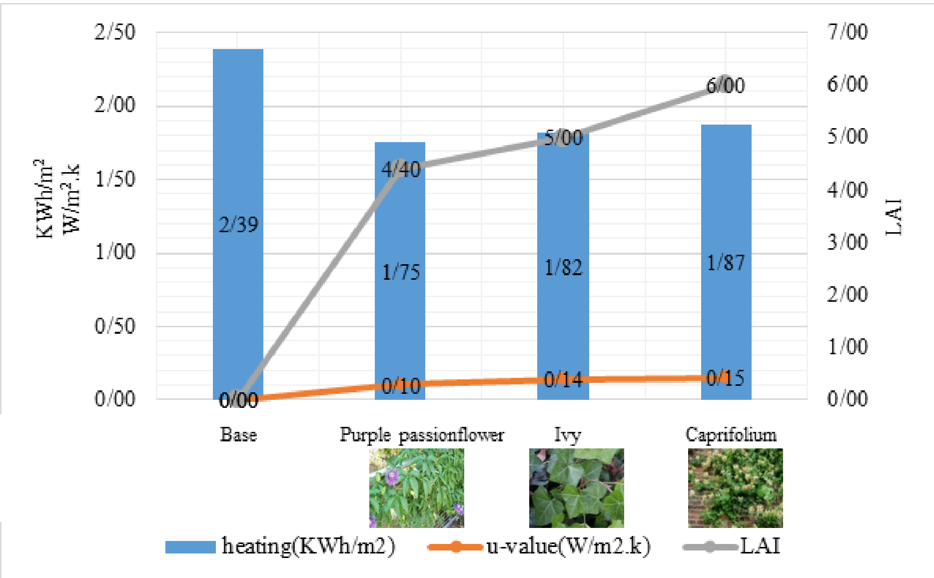
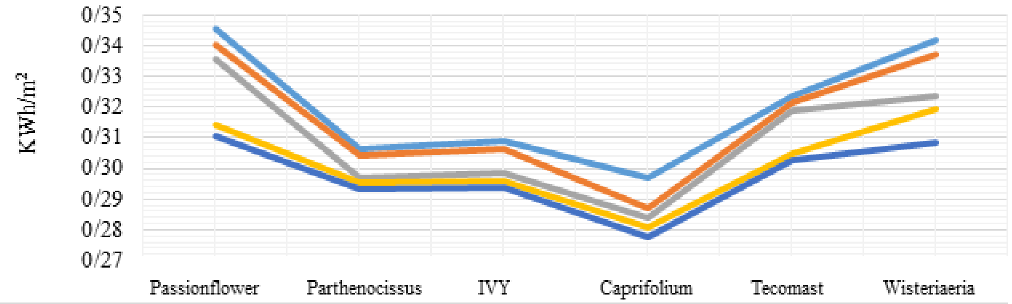


Fig. 11. Comparison of Thermal Performance of Four Plants Out of Six Plants during Winter Solstice

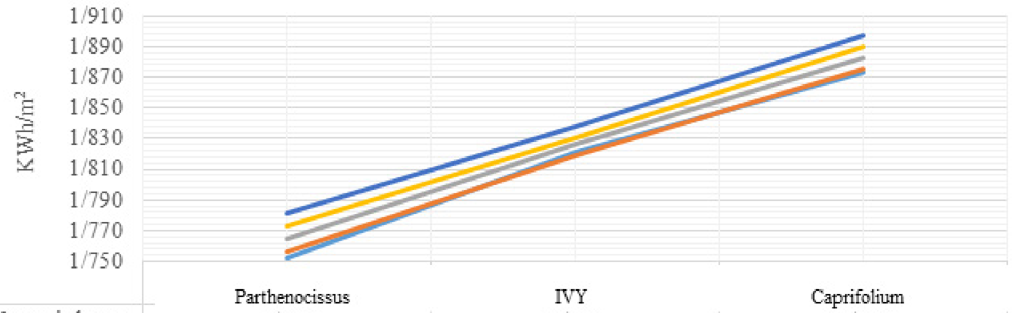
4.4.4. Impact of Green Façade and Air Layer Thickness

The thickness of air layers between the green façade and the external layer of the wall was simulated and analyzed within 0, 5, 10, 15, and 20cm thicknesses, respectively. As seen in Fig. 12, when the air layer thickness increases during the summer solstice, the energy consumption is reduced, and the most effective air layer is the one with 20cm thickness. The lowest energy consumption is provided by Caprifolium with 20 air layer, which is followed by Caprifolium with 15, 10, and 5cm air layers, Parthenocissus with 15, 20, and 10cm air layer, Caprifolium without air layer, the with 20cm air layer, and Caprifolium with 5cm air layer that provides the lowest energy consumption. Unlike the summer solstice, placing an air layer between the green façade and the external layer of the wall would increase energy consumption for heating in the winter solstice. Hence, the highest reduction in energy consumption during winter solstice belongs to Purple Passionflower without air layer, which is followed by Purple Passionflower with 5, 10, 15, 20cm air layer, Ivy with 20, 15, 10, 5cm, and finally Ivy without air layer. The mentioned 10 cases provided the lowest energy consumption compared to all simulations.



	Passionflower	Parthenocissus	IVY	Caprifolium	Tecomast	Wisteriaeria
0cm air layer	0/35	0/31	0/31	0/30	0/32	0/34
5cm air layer	0/34	0/30	0/31	0/29	0/32	0/34
10cm air layer	0/34	0/30	0/30	0/28	0/32	0/32
15cm air layer	0/31	0/30	0/30	0/28	0/30	0/32
20cm air layer	0/31	0/29	0/29	0/28	0/30	0/31

0cm air layer 5cm air layer 10cm air layer 15cm air layer 20cm air layer



	Parthenocissus	IVY	Caprifolium
0cm air layer	1/753	1/821	1/873
5cm air layer	1/757	1/819	1/876
10cm air layer	1/764	1/826	1/882
15cm air layer	1/773	1/831	1/890
20cm air layer	1/781	1/838	1/898

0cm air layer 5cm air layer 10cm air layer 15cm air layer 20cm air layer

Fig. 12. Comparison of the Impact of Different Air Layers of Plants on Thermal Performance during Summer and Winter Solstice

4.4.5. Impact of Green Façade in Floor Height of Building with Air Layer

The green façade decorated with the mentioned plants was simulated to examine their impacts on various heights. Selecting from the simulation done in the previous step, 10 modes that indicated optimal behavior in summer and winter solstices were selected. In this phase, the simulated height has been done based on the regular height of construction in Isfahan, which includes three cases of ground floor, second, and fourth floors. According to Fig. 13, the height difference in the floors does not indicate any specific effect during the summer solstice. When the green façade was placed on the second and fourth floors, a reduction was seen in heat penetration into the building compared to the green façade placed on the ground floor, while no significant difference was seen between higher floors. Parthenocissus provided better conditions for reducing energy consumption compared to the other two plants. The optimal mode that leads to penetration of less air into the building is the green façade with the Parthenocissus plant with a 20 cm air layer on the second and fourth floors. In winter solstice, Purple Passionflower indicated better behavior in reducing energy consumption compared to Ivy, implying it is more resistant to loss of indoor heat in buildings. The optimal case of energy consumption in the winter solstice is Purple Passionflower with a 20 cm air layer on all floors.

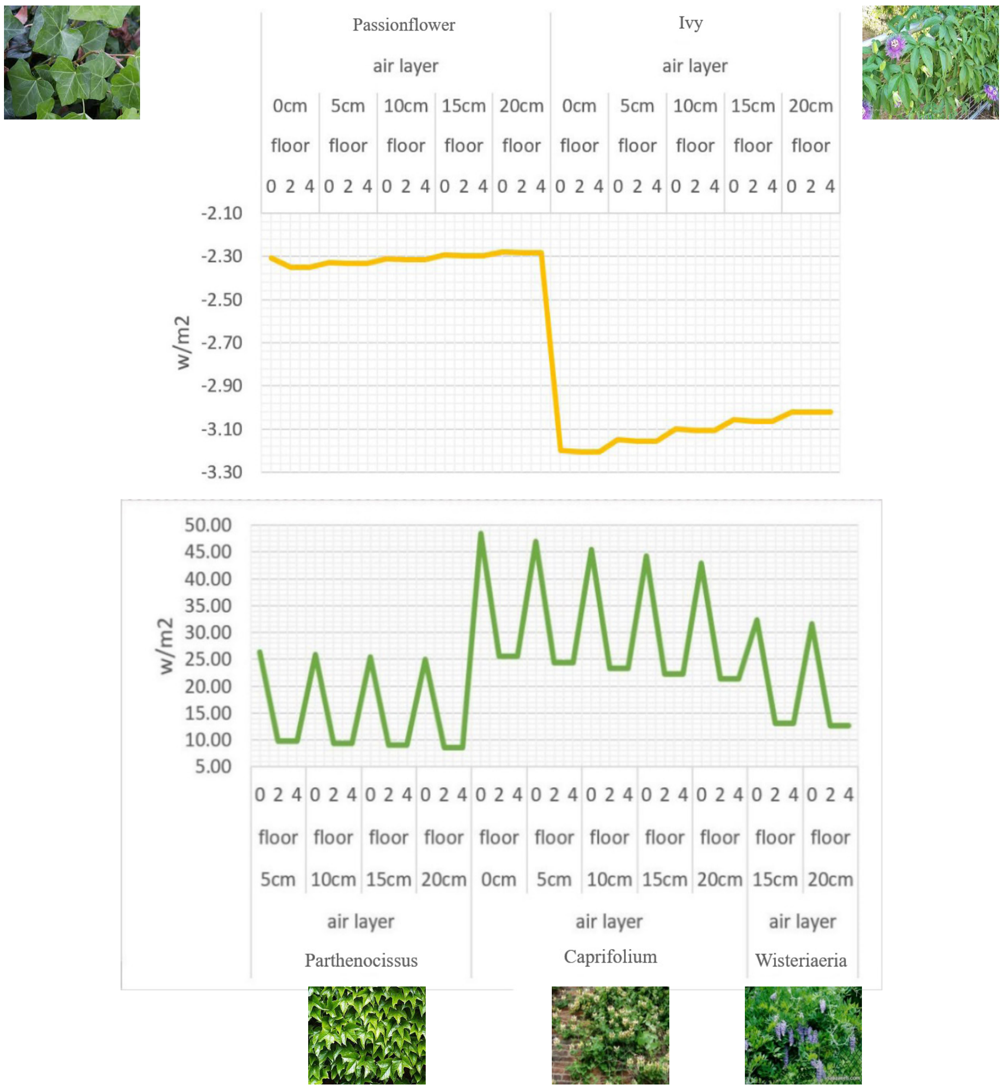


Fig. 13. Comparison of Heat Perpetration into the Building during a Summer Day (Right Hand) and Comparing the Heat Lost on a Winter Day (Left Hand) on Different Floors

4.5. General Findings

Design Explorer is used for better classification of simulation results, and its linear diagram is shown in Fig. 14.

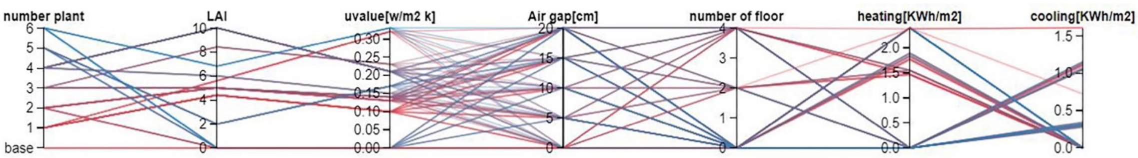


Fig. 14. Specifications of all Simulated Modules

According to examinations depicted in Fig. 15, the Caprifolium plant with LAI=10 and U-Value= 0.21 w.m^2.k in the presence of a 20cm air layer or air gap between the green façade and external layer of the building on the ground floor provided the best mode for reducing the cooling energy consumption during the summer solstice. This case led to a 61% decline in energy consumption per m^2 compared to the base mode. In the winter solstice, moreover, Purple Passionflower with LAI=4.4 and U-Value= 0.1 w.m^2.k and 20cm air layer in high floors (floors 2 and 4) provided the lowest heating energy consumption that provided a 38% decline in energy consumption per m^2 compared to base mode.

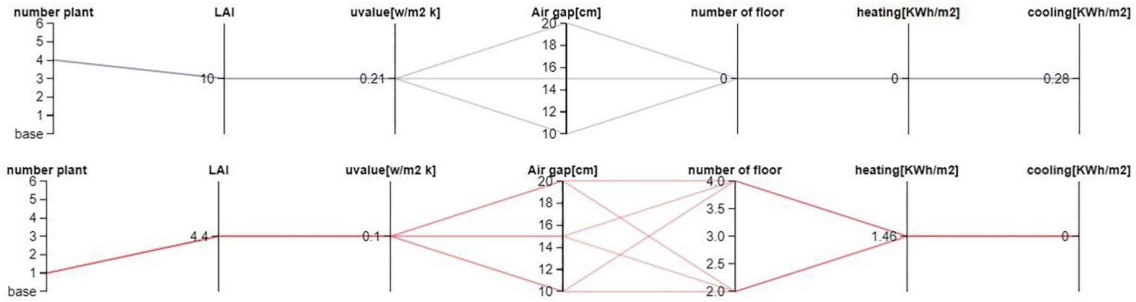


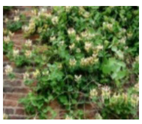
Fig. 15. Presentation of Optimal Mode Specifications in Summer and Winter Solstices

Table 10 reports the energy consumption reduction (percent) provided by these two plants during summer and winter solstices separately. According to the standard energy label in Iran, the energy consumption criterion of the building is based on primary energy. All energy carriers must be considered as energy consumption equivalent in the origin to measure the primary energy of residential buildings. The coefficients of converting gas and electricity fuels to primary energy equal 1.1 and 3.7, respectively. In total, research findings indicate that Purple Passionflower provides the highest reduction in energy consumption; however, when primary energy is considered and measured, Caprifolium is finally effective by reducing more energy consumption in summer and winter solstices. Table 11 indicates this case.

Table 10. Rate of Reduction in Energy Consumption by Optimal Cases during Summer and Winter Solstices

Variable	Caprifolium	Purple Passionflower
		
Reduction in Energy Consumption for Cooling (per m^2)	61%	57%
Reduction in Energy Consumption for Heating (per m^2)	21%	38%
Sum	41%	47.5%

Table 11. Measuring Value Coefficients of Gas and Electricity in the Rate of Energy Consumption Reduction provided by Optimal Cases during Summer and Winter Solstices

Variable	Caprifolium	Purple Passionflower
		
Cooling by Electricity (per m^2)	1.04	1.15
Heating by Gas (per m^2)	2.09	1.6
Sum	3.13	2.75
Reduction in Energy Consumption for Cooling and Heating during Summer and Winter Solstices (per m^2)	63%	48%

5. CONCLUSION

Green façade is one of the patterns applicable in architecture, which not only improves the visual appearance of the living environment but also provides many environmental and social benefits, including reducing pollution and increasing urban greenery. The humidity resulting from the green façade would reduce air dryness, especially in arid climates like Isfahan. In addition to the mentioned benefits, a green façade is effective in reducing energy consumption. According to the mentioned points, the results of this study indicate that two factors of LAI and U-Value are inherent features of plants that affect the thermal performance of the building. This effectiveness- particularly in cooling energy consumption- has broken the structure of U-Value in some cases and dominated LAI. An increase in the component of the air gap between the green façade and the building's wall in summer leads to a decline in energy consumption, which leads to its increase during winter. The variable of placement on higher floors rather than the ground floor leads to less heat penetration into the building. Among the simulated cases, the optimal ones include Caprifolium with LAI=10 and U-Value= 0.21 $w.m^2.k$ and 20 cm air layer in ground floor that provided 61% reduction in energy consumption during summer solstice, and the Purple Passionflower with LAI=4.4, U-Value=0.1 $w.m^2.k$ and 20 cm air layer in higher floors (floors 2 and 4) that provided 38% decline in energy consumption during winter solstice. If these two plants are used, the sum of the reduction in energy consumption over a year would equal 41 percent and 47.5%, respectively. Also, the sum of energy consumption reduction for cooling and heating equals 63% and 48% provided by these two plants, respectively after measuring the indoor value coefficients of gas and electricity. The mentioned values indicate that the green façade decorated with the Caprifolium plant outperforms another plant.

This study examines the thermal behaviors by evaluating the indicators of VGS in the residential building located in the hot and dry climate of Isfahan. Ultimately, the impact of each characteristic of the green façade on energy consumption was determined, and the best case was chosen by consideration of all components simultaneously. Further studies can investigate other components, including vegetation, the structure of the green façade and the wall on its back, and other orientations of the building in different climates. Since daylight is a highly important factor for the quality of indoor space, comfort, and livability conditions, daylight indicators, and their effects can also be studied.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

MORAL APPROVAL

The authors commit to observe all the ethical principles of the publication of the scientific work based on the ethical principles of COPE. In case of any violation of the ethical principles, even after the publication of the article, they give the journal the right to delete the article and follow up on the matter.

PARTICIPATION PERCENTAGE

The authors state that they have directly participated in the stages of conducting research and writing the article.

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