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Vertical Greenery Systems: A Review of Factors Influencing Their Thermal Performance

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Abstract

Urbanization and rapidly growing population change cities' features and convert them to concrete jungles with more buildings and fewer green areas. This bad conversion cause number of aesthetic, economical, and environmental issues like air and water pollution, higher energy consumption, increasing air temperature which lead to discomfort in outdoor and indoor environments. Vertical greenery systems (VGSs) stand as one of the green infrastructure features used to indemnify the lack of horizontal greenery and enhance the building envelop interaction towards the internal and external environment.

Vertical greenery systems are living and dynamic component. Many studies have been conducted to recogise how vertical greenery systems work and what affect their thermal performance. This paper aims to provide a deep understanding of different factors that affect the impact of this vegetated wall. These factors fall into two main categories: building-related factors and greenery-related factors. Comprehensive review of the variables influencing VGS performance will lead to better design decisions for VGS elements and will improve utilization potentials.

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1. Introduction

The increasing energy problems weather it is about generating energy or dealing with climatic issues caused by the generated energy alongside with growing building densities have become a global problem. Such issues calling for climate adaptation strategies in building and urban scale. Thus, modifying the building envelop to reduce this impact is highly critical demand.

Integration of vertical greenery uses plants as a sustainable material has proven to be dual-benefit solution in term of internal temperature reductions and cooling energy as well as urban outdoor temperature modification. There are many ways to apply these plants on walls. Generally, vertical greenery system fall into two broad categories: “Green Facades” which can be termed as support systems and living walls as carrier systems [1].

Green facades are based on the utilization of climbing or hanging plants along the wall, which can be grown directly on the ground or in planters situated at different intervals along the façade height, where plants can grow upwards the wall or grow downwards and hang along the vertical surface. [2]. As climbing plants need support along the wall, therefore GF can be categorized depending on this support into two categories:

- Direct Green Façade: this system depends in self-clinging climber plants that use the envelope as supporter [3].
- Indirect Green Façade: plants guided on a structural support to control the growth of plant and to provide a gap between the façade and the green layer. Indirect systems are divided into two categories based on the type of support: modular indirect GF: uses modular trellises made steel, wood, plastic and aluminum mounted on the building [2]. And continuous indirect GF that uses ropes, cables, metal grid or mesh structure to guide plant growth.

A living wall is a system in which vegetation is fully integrated into the facade construction where plants and planting media are both placed on the vertical surface of exterior walls, so it depends on a carrier to hold growing media so living wall systems considered as “carrier “systems. All these types are connected to rigid backup support behind to hold the carriers and form a gap to insert the irrigation pipes. Living wall classified based on several types of carriers and growing methods as following:

- Vegetated mat/ continuous living wall: these system is based on installation of a base panel that supports layers of permeable, flexible and root proof screens [3]. Vegetated mats are hydroponic systems as plants pre-grown in nurseries are inserted into holes cut in the fabric layer that serves as a growing medium [4].
- Felt Pocket living wall: where plants are fitted into felt pockets of soil or growing medium and attached to a waterproofed backing. The felt is kept continually moist with water that contains plant nutrients[4] [3].
- Modular living wall: is named as soil-cell system according to (Riley, 2017) this system uses rigid containers filled with soil or growing media. Containers have can be shaped as framed boxes, precut holes boxes (horizontal or slanted holes), planter boxes (horizontal or slanted), wire cages and cassette [5].

As there are many types of plant application on facades, this paper aims to find how these vegetated wall work on building thermal performance and to achieve a deep understanding of various factors affecting the performance of these systems in order to evaluate the VGS effects on and optimize the application potentials.

Nomenclature	
VGS	Vertical Greenery System
LAI	Leaf Area Index

2. How do Vertical Greenery Systems work as a passive technique?

VGSs have strong thermal effects inside and outside the building through a combination of four fundamental mechanisms: shading by interception of solar radiation, thermal insulation provided by the vegetation and substrate, evaporative cooling that results from evapotranspiration and modification of the wind pattern in the building envelope. The successful combination of all these processes has demonstrated the potential VGS to be used as passive energy-savings systems [6].

2.1.1. Shading

The shading effect is one of the most apparent advantages of greenery systems for energy savings since plant layer leads to solar radiation interception. (Besir and Cuce,2018). A layer of plants placed on a buildings' exterior wall intercepts a fraction of total radiation incident on leaves, reflects some radiation, and transmits the rest to the exterior wall behind it as shown in **fig. 1.**

The shading effect of a vertical greening system depends strongly on the coverage ratio and the density of the foliage, which is mostly indicated by LAI, also it is affected by light source which differs according to climate zone and orientation.

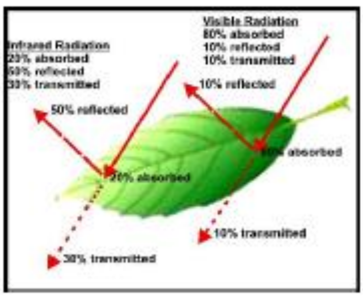


fig. 1. Shows radiation distribution on plant leaf [7].

2.1.2. Evapotranspiration

Evapotranspiration contributes effectively to the cooling potential of VGS. It combines the effects of transpiration and evaporation, as solar energy is absorbed by plants for growth purposes, transformed into latent heat, and released as water vapour. This procedure lowers the air's temperature while raising humidity.

Evapotranspiration occurs through stomata, microscopic pores on leaf surfaces that control the gas exchange between a plant and its environment, rate of evapotranspiration is determined by typical leaf stomatal conductance, one of the physiological characteristics of individual plant species which expresses the pore size and number per leaf surface area. Stomata are very sensitive to relative humidity, air temperature, water potential (a tendency of water to flow from one area of the plant to another), light level and carbon dioxide concentration inside and outside the leaves [4].

2.1.3. Thermal Insulation

The effect of insulation is strongly relevant to the properties of the layers used in the greenery systems such as foliage thickness and density identified as Leaf Area Index* (LAI), soil (thickness and composition) and the air cavity between the building and some systems like: indirect GF and LW systems [8]. This formulation acting as a thermal buffer or additional insulation material ,hence reducing the heat flux through the building envelope by regulating the ambient air temperature, wind speed and humidity [9].

2.1.4. Wind Barrier

A green wall system functions as a wind barrier, preventing the impacts of wind on a building's façades. even in airtight buildings, the wind reduces the effectiveness of regular insulation [10]. This effect is determined by a number of factors, including: the density and permeability of the vegetation, air gap distance, the orientation of the wall, the direction and velocity of the wind itself [6].

Each mechanism attribute to this holistic passive process to enhance the cooling potential of the green system, **Table 1**. is to summaries the features affecting each cooling mechanism according to [11].

Table 1. Cooling mechanisms and main variables influencing each mechanism[11].

Mechanism	Method	Variables
Shading	Direct solar radiation interception provided by plants and support structures	- LAI (foliage density) -Facade orientation -Substrate thickness, composition and moisture
Evapotranspi ration	Evapotranspiration from the plants and substrates	- LAI (foliage density) -Plant species (stomatal conductance) -Humidity -Wind speed -Substrate composition and moisture

Insulation	Insulation capacity provided by materials and layers: plants, air gap, substrates and support system.	- LAI (foliage density) -Air gap distance -Substrate thickness, composition and moisture
Wind barrier	Capacity of plants and support structures to modify the direct wind effect and remove air from the VGS's internal layers.	- LAI (foliage density) -Facade orientation -Wind speed and direction

3. Variables affecting VGS thermal performance

3.1. Variables related to building features.

Various studies discussed many aspects related to buildings' features and location that affect the application of VGS. In the following a review discusses the effect of building location and different weather conditions affect the greenery effect on the building facades, also the placement and coverage percentages of plants on different facades changes the effects on these plants on the building.

3.1.1. Effect of Climate

There are several climate factors that need to be considered when applying a vertical greenery system. [12] conducted a sensitivity analysis on the most effective meteorological parameter and discovered that these characteristics include, in order of importance, solar radiation, wind speed, relative humidity, and outside air temperature.

- Different climate zones

Realizing that one of the main purposes of vegetation systems is to intercept solar radiation, different locations on Earth will always generate varied results, which has been the focus of many research., [13] exanimated three of the US Department of Energy (DOE) standard reference buildings (medium office, primary school and hospital) using EnergyPlus. Each building was examined in four representative local climates on the US (Phoenix is hot and dry, Miami is hot and humid, Chicago is cold and Los Angeles is warm and dry). Among the four climates studied, greenery systems have the offer the highest cooling savings in a hot and dry climate. See **fig. 2 .**

b

b

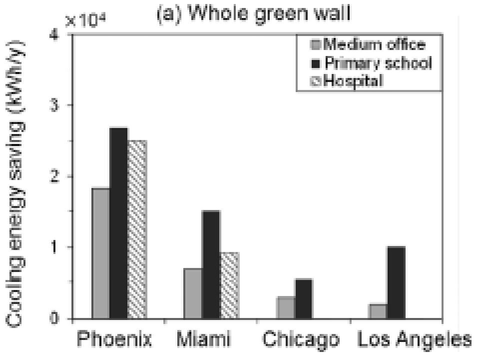


fig. 2 Annual cooling energy saving due to whole green wall in three different buildings in 4 cities/ climate zones in the U.S.[13].

Also [14] run a mathematical model to investigate potential greenery solutions in different urban geometry situations in 8 cities in distinct climate zones, each city is examined for its hottest month. Regarding surface temperature decrease of the south-oriented wall in **fig. 3**, it reaches from 18.7 ºC maximum and 14.3 ºC daytime average for Riyadh to 9.8 and 5.6 ºC for Moscow. It can be concluded that using vertical greenery systems provided greater temperature reduction effect in hotter and drier climates as well as humid climate.

b

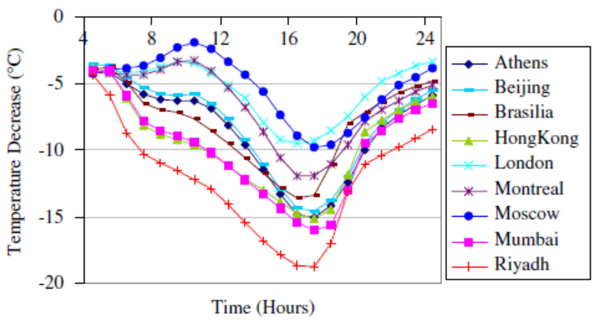


fig. 3. Surface temperature decrease of the south oriented wall covered with vegetation for different climate examined [15].

- <u>Weather condition (sunny or cloudy)</u>

Cooling of vegetation surface is more prominent on summer-sunny day mainly due to absorption of latent heat of vaporization in the process of transpiration (Jim, 2015). Many studies investigated this observation. [16] conducted an experiment in Hong Kong on 9 modular living wall using 8 unit each one has a different plant species and one unit is left without any plant as a control unit. The canopy air temperatures of the eight plant species in the VGSs were compared with the ambient air temperature, it is clearly noticed that temperature reduction in sunny days are higher than other summer conditions (cloudy and rainy days), in **fig. 3** it is noticed that the temperature reductions achieved on sunny days were 1.8–3.8 °C, while the equivalent ranges on cloudy and rainy days were 1.2–2.5°C and 1.2–

2.4 °C. Also [17] concluded the same results in their observational study of a building with indirect green façade in Hong Kong.

[18] Performed a field experiment in Spain. They found that efficiency of a LWS is extremely influenced by solar radiation intensity. On a sunny day with a maximum vertical radiation (MVR) of 692W/m2 K, the highest recorded temperature was 46.7 1C for the conventional façade, and 22.1 1C for the green façade. In a cloudy day with less solar radiation (MVR:140.8W/m2 K), the temperature differences between the two façades was only 3.1 degrees.

b

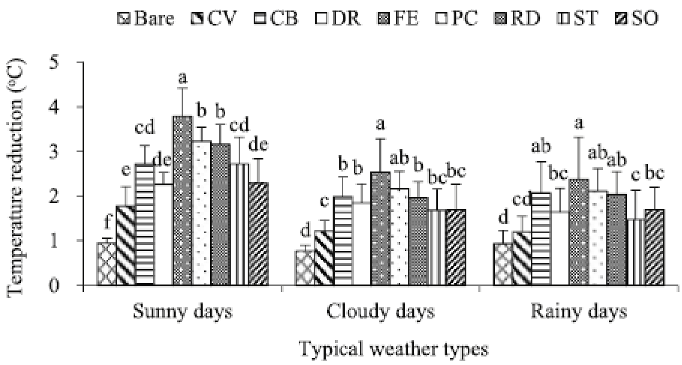


fig. 4 Canopy temperature reduction among different plant species in different weather conditions (sunny, cloudy, rainy) [16].

- Different seasons (summer and winter)

[13] Found that the cooling effect of the VGS is significantly better in summer than in winter since the latent heat flux from transpiration of the VGS was 3 - 4 times higher in summer than in winter. Also [19] found that in absence of solar radiation, GW may act as a thermal insulator for increasing the indoor air temperature. The negative values in cooling load reduction for the winter period mean that cooling load is increased. This increase in loading is used to compensate for the higher indoor temperature due to the insulating effect of GW.

3.1.2. Effect of Covering Ratio

Considering greenery as an insulating layer on building façade, It is therefore reasonable to assume that depending on the area covered by the system, the influence of the system on the building may vary both internally and externally. Several studies have addressed this issue in this regard. [20] run a mathematical model to investigate different covering ratios on a small, cubic and windowless room. They stated that the increase of plant foliage percentage from 0% to 100% causes an almost linear decrease of the indoor temperature, moreover the decrement intensity varies based on the orientation of the building and material configurations (different wall material configurations were also investigated), as illustrated in **fig. 5**.

Also [19] found similar results in their simulation based study. They modeled case A is a model of single-storey experimental setup in the Hong Kong, while case B is 100 m height hypothetical high-rise buildings. Buildings where covered with LW with coverage ratio varies from 25%,50%,75% and 100% on opaque parts of each building façade in four orientations (E,W,S,N). For both cases, it was concluded that the cooling load decreases as the coverage ratio increases in a liner coloration differs as the green area and configuration changes in case A and B. This relation can be expressed in the following equations in **Table 2**, considering that the y_w stands for percentage annual cooling load reduction with LW (%) and A_w is for area of greenery(m²).

b

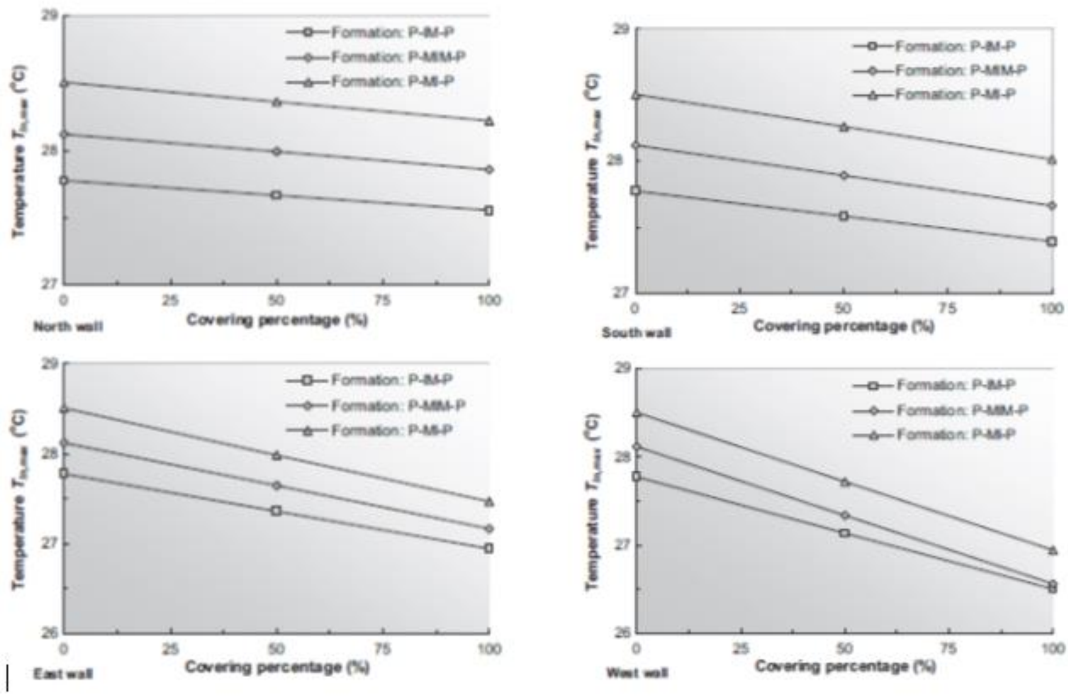
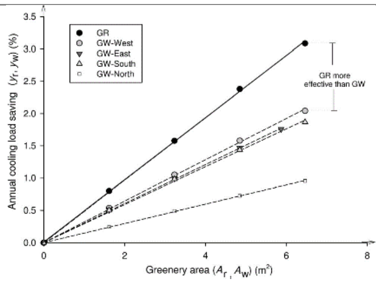
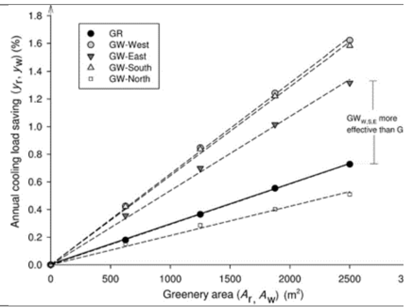


fig. 5 Variation of maximum reductions in indoor temperature(Tin,max) vs. leaf covering percentage, orientation and type of wall configuration [20].

Table 2 Equations and charts expresses the coloration between annual cooling load reduction and area of geometry [19].

	Building A	**Building B**
west-facing	$y_{w,W} = 0.3209A_{w,W}$	$y_{w,W} = 0.0007A_{w}$
east-facing	$y_{w,E} = 0.3021A_{w.E}$	$y_{w,E} = 0.0005A_{w}$
south-facing	$y_{w,S} = 0.294A_{w,S}$	$y_{w,S} = 0.0006A_{w,S}$
north-facing	$y_{w,N} = 0.1487A_{w,N}$	$y_{w,N} = 0.0002A_{w,N}$
		

[21] Analysed the eastern façade of high-rise residential building in China. Parts of the facade covered in indirect GF in different coverages, part A covered in greenery by 37.5% and part B covered by 54.4%. Different coverage ratios lead in different reduction in external surface temperature for part A and B by 4.4°C and 4.8°C, respectively. [22] built a miniature house to perform as thermal lab in Indonesia, two different coverage ratios of indirect GF were examined: 50% and 90%. The difference of exterior wall surface temperatures between bare wall and green facade are 6.8 °C and 7.8 °C for 50% and 90% plant cover respectively. While on the interior wall surface, the differences are 6.7 °C and 7.3 °C for 50% and 90% plant cover respectively. This indicates that areas with more leaf coverage experience larger cooling effects, especially on interior surfaces.

3.1.3. Effect of Orientation

Building orientation has been observed to play a considerable role in temperature decreases caused by vegetation, as the amount of solar energy received by vertical planes varies immensely. An experiment by [23] approve this finding obviously, the shadow factor of indirect green façade was measured for each façade of a cubicle experimental model in Spain, it is noticed that the shadow factor obtained for the green facade during daily peaks of solar radiation by orientation (at 10:00 h on the East, at14:00 h on the South, and at 18:00 h on the West orientation) as shown on **Table 3**, they also found that the highest exterior surface temperature reduction was recorded for east-facing, south-facing and north-facing orientations, respectively. Similar findings was obtained by [12], they confirmed that the east and west facades have the highest surface temperature reduction as they exposed to peak exposure to solar radiation during the early morning and late evening at low sun angles.

Table 3 Daily shadow factor evolution by orientation in the studied indirect GF [23].

Daily shadow factor evolution by orientation in the studied double-skin facade.

Orientation/height	East			South			West		
Daily time	10:00 h[a]	14:00 h	18:00 h	10:00 h	14:00 h[a]	18:00 h	10:00 h	14:00 h	18:00 h[a]
Upper level	0.19	0.08	0.03	0.12	0.57	0.13	0.08	0.35	0.55
Middle level	0.12	0.05	0.02	0.11	0.26	0.08	0.03	0.28	0.20
Lower level	0.06	0.02	0.01	0.04	0.15	0.05	0.02	0.14	0.06

Also [19] in their previously mentioned study found that the west-facing, east-facing, and north-facing orientations show higher cooling energy saving during Hong Kong's summer (11.7%,11%, 6.6% respectively) with peak saving in July. A simulation study by [20] showed that cooling reductions are 20.08%, 18.17%, 7.60% and 4.65%, respectively for west, east, south and north orientations in summer months in Greece. Also [24] compared to identical cubicle rooms, one is covered by LW in four orientations and one bare walls cubicle, they found that the highest external wall temperature reduction was 6.4 °C in the west wall, whereas reductions in eastern wall external surface was 4.1°C and 4.0°C in south.

It can be concluded that VGS performance affected directly by solar radiation intensity and distribution, which is regulated by two main variables: location (climate zone) and orientation to sun path. **Table 4** and **Table 5** show some researchers studied these factors simultaneously.

Table 4 Comparison in reduction in external wall surface among different orientation in different studies (researchers).

	Reduction in external wall surface (ºC)				
	Pérez et al. 2017	**Susorova et al., 2014**	**Pan et al., 2018**	**Coma et al., 2017**	
	LW	direct-GF	LW	indirect-GF	LW
E	15	1.2	4.1	13.8	17
W	16.4	0.7	6.4	10.7	21.5
S	16	0.1	4	13.9	20.1

Table 5 Comparison in cooling savings among different orientations and climates in different studies (researchers).

Cooling savings (%)

	Yuan et al. 2018		Dahanayake and Chow, 2018	Kontoleon and Eumorfopoulou, 2010
	hot desert climate	Tropical Monsoon	Humid Subtropical	Dry and hot summer
E	ng	ng	11%	20.08%
W	1.77%	0.78%	11.70%	18.17%
N	ng	ng	6.60%	4.65%
S	3.92%	1.15%	4.80%	7.60%

3.2. Variables related to greenery.

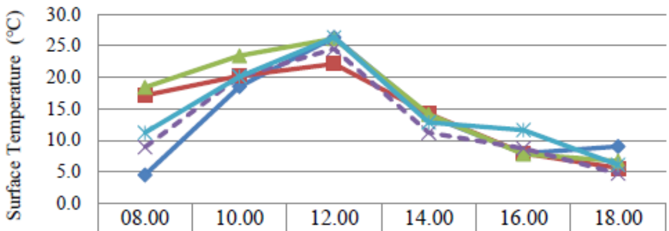
3.2.1. Effect of Plant Characteristics

- Leaf Area Index (LAI) vs Plant species

Determining plants to be used in a greenery system is not a random decision, because plants influence thermal performance of the system, as plants have wide features and characteristics like: leaf stomatal conductance, leaf size, leaf area index and thickness. Numerous studies have examined this issue considering that plants are the most intriguing and delicate component in these greenery systems.

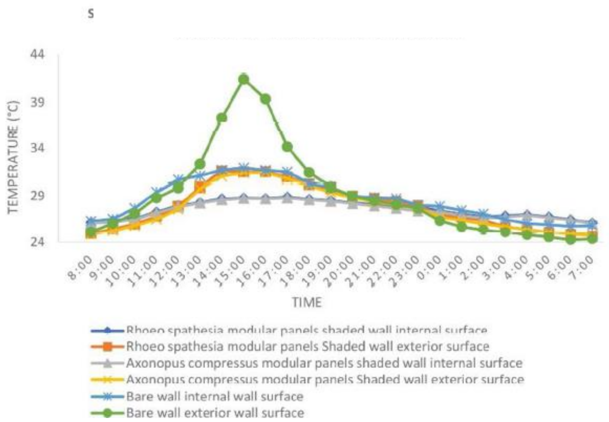
[5] conducted an experiment in Malang, Indonesia, temperature reduction measurements were carried out on several types of herbal plants. Results in **fig. 6** show a variation of average decrease in temperature can be noticed due to variant plant species up to 1.7 °C (amaranthus hybridusb plant (14.7°C) and orthosiphons picatus (13°C)). Also [25] tested four different plants each on freestanding walls oriented to the south, they claimed that the correlation coefficient for the averaged wall surface temperature reduction with the leaf transpiration rate and the leaf solar transmittance was 0.804 and 0.998, respectively.

In contrary [26] tested eight plant species on west-facing modular planters in Hong Kong. It was concluded that the canopy temperature reduction ability of these species increased with canopy cover and LAI. All other parameters measured including height, leaf area, leaf number and vertical LAI, were not significant with respect to canopy temperature as there was no significant variations between different species in terms of plant traits and canopy temperatures. [27] found matching results, they revealed that plant coverage and LAI strongly correlate with the ability of LWs to reduce temperatures with small to moderate strength, as evidenced by correlation coefficient values ranging from 0.145 to 0.464 after comparing 12 different species. Also, [28] found similar results when their study analysed four different plant species in term of evapotranspiration capacity, there was no substantially different thermal effect on tested wall between four species. [29] reported no significant differences between the different plant species grown on living wall panels. See **fig. 7**.



	08.00	10.00	12.00	14.00	16.00	18.00
brassica juncea	4.5	18.5	26.3	13.9	7.9	9.0
apium graveolens linn	17.1	20.2	22.1	14.2	7.9	5.6
gynura segetum	18.4	23.4	26.1	14.1	7.8	6.7
orthosiphon spicatus	8.9	20.1	24.5	11.2	8.7	4.7
amaranthus hybridus	11.2	20.1	26.3	12.8	11.6	6.1

fig. 6 surface temperature reduction (°C) on the living wall with the use of different types of the herbal plants [5].



MAXIMUM TEMPERATURE REDUCTION COMPARED TO BARE WALL CONTROL		
	Exterior Wall surface Temp.	Interior Wall surface Temp.
Axonopus compressus	10.08°C	3.15°C
Rhoeo spathacea	9.97°C	3.11°C

fig. 7 surface and internal temperature behavior on walls shaded by indirect GF covered in two different plants [29].

[12] Used validated self-developed model to examine sensitivity to plant parameters (leaf area index (LAI), radiation attenuation coefficient, leaf absorptivity, leaf typical dimension, and plant stomatal conductance). Only LAI and stomatal conductance were revealed to have a Only LAI and stomatal conductance were revealed to have a significant effect on plant thermal performance among the investigated parameters. On average, each unit increase in LAI resulted in an extra effective R-value of approximately 0.06 m2 K/W. effect on plant layer thermal performance among the investigated parameters. On average, each unit increase in LAI resulted in an additional effective R-value of approximately 0.06 m2 K/W on average and approximately 5% reduction in conductive heat transfer through the wall. This indicated that the different behaviours of the different species can be related to features like coverage ratio and LAI, instead of plant functional type and botanical characteristics, **fig. 8** shows that thermal resistance of plants differ significantly as LAI changes.

Confirming this result, [30] conducted a sensitivity analysis using DesignBuilder software to compare the effect of LAI and plant height on energy consumption in residential building in Qatar, the study stated that LAI had a significantly higher impact than the plant height, it is indicated an electricity savings of 2% when a green wall with LAI of 5 was installed, an increase in the building electricity consumption of 0.4% if the LAI was reduced by one unit to reach LAI =4, whereas reducing one unit (one cm) result in 0,2% increase in electricity consumption. Result shown in

Table 6 affirms these finding.

Table 6 Results in cooling energy savings due to change in plant height and LAI in VGS plants (energy consumption increase (+) or decrease (-) and %). [31]

Green roof/wall parameters						
	Plant height					
Reference parameter value	Parameter value increase [cm]	−1	−2	−3	−4	−5
7 cm	Impact on final result [%]	+0.2	+0.5	+0.7	+0.8	+0.8
	Leaf area index					
Reference parameter value	Parameter value increase [–]	−1	−2	−3	−4	−5
5 [–]	Impact on final result [%]	+0.4	+0.6	+1	+2	+3

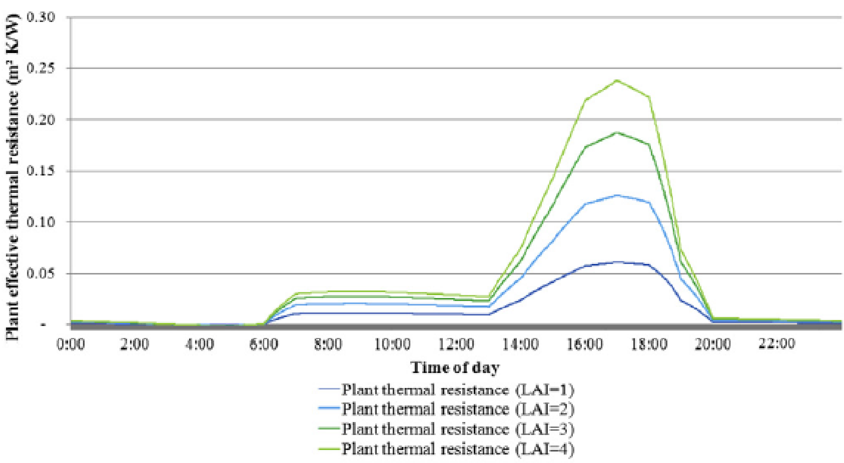


fig. 8 Plant effective thermal resistance (m² K/W) on different values of LAI [12].

- <u>Plant thickness</u>

[32] Carried out field measurement on a south-facing wall covered with direct- GF in Suzhou, China. Three points on the wall at the same height but different foliage thicknesses where measured as shown in **Table 7**, it can be noticed that higher foliage thickness means higher LAI does not always means stronger thermal performance. The results showed that foliage thickness of 19.8 cm achieved the best thermal performance because of stronger convective heat transfer between envelop surface and plant leaves. Also [33] performed another field experiment was conducted in three residential houses, building (A and C) are

covered in deciduous climbing plants on the southwestern side of the buildings, while building (B) have a bare southwestern façade. Building A is 100% covered by dense foliage with thickness of 20-30, and building C is 80% covered with 10-15 cm foliage and building b left as reference building. Due to high differences of foliage thickness between room A and C, major differences in indoor temperature and surface temperatures are noticed, see **fig. 9**. A maximum external surface temperature reduction is 10.5 ⁰C and 8 ⁰C for A and C, respectively. **Table 8** summarizes and compare results of previous two studies.

Table 7 Plant measured features [32].

Position	Average area (cm^2)	Average foliage thickness (cm)	LAI
P1	26.6	7.2	1.21
P3	68.2	19.8	3.32
P4	191.2	30.5	4.53

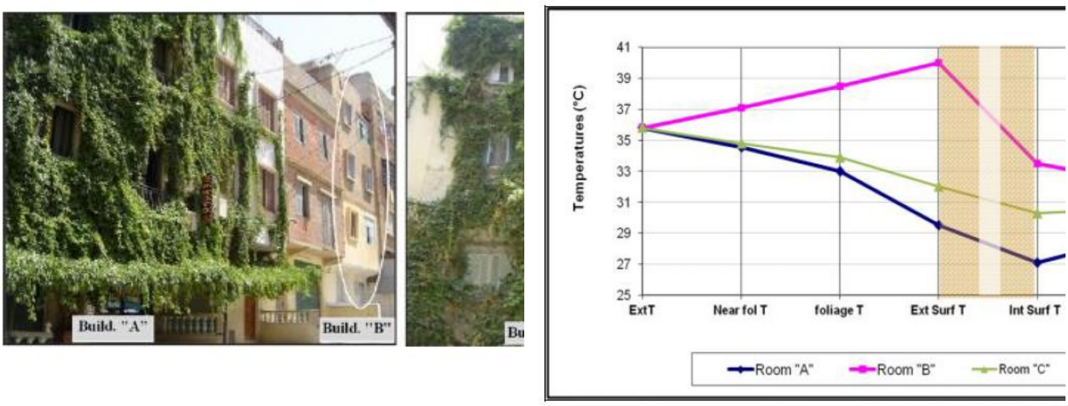


fig. 9 Temperatures evolution in the three rooms at maximum outdoor temperature [33].

Table 8 Comparison between reduction in external wall surface due to different plant thicknesses in two studies (researchers)

Reduction in external wall surface (⁰C)					
	Benhalilou et al., 2020		**Cuimin Li et al., 2019**		
Plant thickness (cm)	10-15	20-30	7.2	19.8	30.5
Max. external surface wall reductions (⁰C)	8	10	2.6	6.3	4

3.2.2.Effect of Growing Media

The physical and chemical properties of a soil or substrate are critical to plant performance, influencing parameters such as relative growth rate, growth habit, total leaf area and plant health. In the following a review on studies discussed this effect of growing media on plant growth rate in living wall systems specially. [34] tested three different substrates: perlite, expanded clay and pumice. To examine how far growing media affect the plant growth in felt pockets living wall system in Spain. Green cover grown in pumice and expanded clay reached 90% to 80% coverage ratio, while perlite reached 80% to 45% coverage ratio.

Also [35] grew 7 different plant species in 7 different growing media on east facing felt pocket living wall system in the UK. The plant media included: Horticultural grade mineral wool, vermiculite, charcoal, coconut fiber, sphagnum moss, pond grown algae and straw. It was found that:

• Mineral wool and vermiculite were by far the best performing media, with an average growth per plant of 14.7 and 13.7 cm respectively

• Coconut fibre and pond algae were the worst performing medium and growth in the plants of 5 and 6 cm, respectively.

Growing media has another effect than influencing plant growth and health. Substrate has a significant role in thermal insulation effect of living wall, [36] tested the insulation effect of different growing media used in planter box living wall system installed in a test room in Turkey. Growing media were prepared by mixing Municipal Solid Waste Compost* (MSWC), commercial peat, rice hull, and perlite in various proportions. **Table 9** Used growing media discerption and influence on interior temperature reductions **[36].**

Table 9 Used growing media discerption and influence on interior temperature reductions [36].

	Growing media name and composition	**interior temperature reductions**
highest interior temperature reductions	PPR3 (50% peat and 50% perlite)	6
	PRH3 (50% peat + 50% rice hull)	5.4
	PPR2(75% Peat + 25% Perlite)	5.2
	PPR1 (87,5% Peat + 12,5% Perlite)	4.5
lowest internal temperature reduction	CRH1(87,5% MSWC + 12,5% Rice Hull)	3.3
	CPR2(75% MSWC + 25% Perlite)	3.4
	CRH2(75% MSWC + 25% Rice Hull).	3.7

Therefore, it can be noticed that growing media including perlite and peat have high thermal insulation properties. Also, the contribution of perlite to thermal insulation is higher that than rice hull. [26] found that substrate moisture is often considered indicative of the insulating capacity of VGSs, but the correlations between substrate moisture, daily

* Municipal Solid Waste Compost* (MSWC): is an organic solid waste per day is composted after 8 weeks of aerobic fermentation. The organic matter content of the compost used is 34.28%.

evapotranspiration and canopy temperature reduction were non-significant in this study. although substrate moisture affected the thermal mass of the VGSs and the physiological processes of the vegetation. The substrate cooling impact (expressed as the temperature difference between substrate and ambient air) was strongly regulated by the substrate moisture. On sunny days, high substrate moisture was correlated with lower substrate temperature. The heating of substrate moisture by solar radiation reduced substrate temperature on sunny days. On rainy days, high substrate moisture played the opposite role, increasing substrate temperature by raising the thermal capacity.

3.2.3.Effect of System Type/ Type of Support System

The wide variations of VGSs specially living walls, motivated many researcher to examine the impact of the difference of support system on the system's thermal performance. [27] Compared the thermal performance of felt pockets LW and planter box LW, they claimed that planter system had better performance in temperature reduction due to different moisture capacity in two systems, as planter LW has a water retaining system for backup water during the day, while a felt-pocket system can absorb water in a shorter time from the felt layer, which lead in high moisture in the felt and low moisture in substrate. A high level of moisture content of LWs increases thermal resistance and latent heat loss through an increasing rate of transpiration. On the other hand, dry substrate affects plant growth, it is noticed that felt-pocket system had less foliage density and percentage of plant coverage than a planter system.

[37] Investigated the impact of the different VGS types (direct GF, indirect GF, modular LW and continuous LW) on Overall Thermal Transfer Value* (OTTV) in different façade orientations in Malaysia. The study found noticeable variations in the effect of different VGSs types, as different components lead to different U-value and therefore different OTTV values, it is noticed that the higher the U-value of the greenery system, the lower the OTTV reduction percentages. Effect of support system can be noticed obviously in comparison between direct and indirect GF, OTTV reduction of 1.13-1.71% and 2.45-3.30% for direct GF and indirect GF, respectively. While no significant variation noticed between continuous and modular LW. **Table 10** illustrates the result of different VGS types on U-value and OTTV.

Also, [29] conducted observational investigation to assess the thermal benefit of existing different types of vertical greening (living wall, indirect GF and direct GF) covering different buildings in Colombo, Sri Lankan. a maximum temperature difference of 10.16 °C, 8.65 °C and 6.36 °C in external side of the walls compared with bare wall for living wall type, indirect green façade, and direct green façade accordingly. In comparison of indoor temperature reductions as of 2.21 °C, 1.82 °C and 0.66 °C compared to each bare wall control in building interiors of living wall type, indirect green façade and direct green façade accordingly, variant behaviour and thermal impact can be noticed among different studied types.

*Overall Thermal Transfer Value (OTTV) is described as a design parameter that indicates solar thermal load transmitted through the building envelope except for the roof. OTTV is a performance-based method, and its output is dependent on the thermal environment of the building.

Table 10 Specifications for the case study buildings and results on OTTV reductions [37].

Case Study	Type of VGS	Orientation	Shading coefficient (SC)	Total U-value (W/m²K)	VGS OTTV Reduction (%)
A (Baseline)	–	–	0.71	2.13	–
B1	Direct Green Facades	North	0.67	1.15	1.68
B2		East	0.69		1.32
B3		South	0.67		1.71
B4		West	0.69		1.13
C1	Double-skin Green Facades	North	0.62	0.93	3.24
C2		East	0.65		3.01
C3		South	0.62		3.30
C4		West	0.65		2.45
D1	Modular Green Wall	North	0.50	0.34	7.02
D2		East	0.55		7.26
D3		South	0.50		7.15
D4		West	0.55		5.78
E1	Linear Green Wall	North	0.50	0.21	7.09
E2		East	0.55		7.33
E3		South	0.50		7.22
E4		West	0.55		5.85

To achieve a brief comprehension on various studies discussed previously, the following **Table 11** Summary of the key findings and outcomes of the publications examined in this paper.

Table 11 Summary of the key findings and outcomes of the publications examined in this paper

Author	**Climate**	**Date**	**Study type**	**Study variables**	**VGS**	**Orientation**	**temperature reduction/ energy savings**	**Main findings**
Pan et al., 2020	Hong Kong	summer	experiemental	weather condition - plant features	LW	W	canopy air temperature reduction for the eight different species varies from 2.7-3.4 in sunny days, on cloudy and rainy days were 1.2–2.5°C and 1.2–2.4	*temperature reduction in sunny days are higher than other summer conditions (cloudy and rainy days). *no significant variations between herbs and shrubs in terms of plant traits and canopy temperatures. *The substrate cooling effect was strongly regulated by the substrate moisture. *no significant correlations between substrate moisture, daily evapotranspiration and canopy temperature reduction.
Pan et al., 2018	Hong Kong	one year/summer	experiemental	orientation - weather condition	LW	S-N - E-W	external wall surface reduction reaches6.4,4.1and 4.0 W, Eand S orientations, respectively.	*VGSs could reduce the optimal cooling plant size of the building envelopes in four orientations by 12–42%;

* Municipal Solid Waste Compost* (MSWC): is an organic solid waste per day is composted after 8 weeks of aerobic fermentation. The organic matter content of the compost used is

Lee and Jim, 2019	Hong Kong	summer	observational study	weather condition-airgap	Indirect GF	NW-NE	external wall surface reduction reaches 3.3, 2.9 and 1.1 °C average for sunny, cloudy and rainy conditions, respectively.(NW)	
Nori et al., 2013	Spain		experiement	weather condition	ng	W	reduction in external surface temp. in sunny day reaches 24.6, 3 degree in sunny day and cloudy day, respectively.	
Yuan and Rim, 2018	USA (4 climates)	summer (June to August)	simulation (EnergyPlus)	climate zone - building types - orientation	LW	S-N-E-W	for meduim office building, cooling savings can reach up to 6%, r hot-dry climate.	the greatest cooling potential in a hot and dry climate, then humid climates, because more energy is required to control moisture than dry climates.
Alexandri and Jones, 2008	8 climates	summer (each city is examined for its hottest	mathematical model	climate zone - canyon geometry - orientation	LW	S	external wall surface reduction reaches 9.8, 5.6 C daytime average for Riyadh and Moscow, respectively	the temperature decreases through greenery cover negatively correlates with the solar radiation a surface receives. using vertical greenery systems provided greater temperature reduction effect in hotter and drier climates as well as humid climate.
Kontoleon and Eumorfopoulou, 2010	Greece	summer	Self-developed thermal-network model	wall material configurations-orientation-coverage ratio	LW	S-N-E-W	Cooling load reductions are found as 20.08%, 18.17%, 7.60% and 4.65% for W, E, S and N orientations	plant foliage percentage from 0% to 100% causes an almost linear decrease of the indoor temperature
Dahanayake and Chow, 2018	Hong Kong	summer	simulation (EnergyPlus)	orientation-coverage ratio - seasons	LW	S-N-E-W	cooling load reduction 11.7%, 11%,11%, 4.8% and 6.6% for W, E, S and N orientations, respectively.	the cooling load decreases as the coverage ratio increases in a liner coleration. -west-facing, east-facing, and north-facing orientations show higher saving during summer months in Hong Kong.
H Lin et al., 2018	Guangzhou, China	6 days	observational	coverage ratio	Indirect GF		(GF A) covered with 37.5% greenery and (GF B)coverd with 54.4%, reduction in external surface temp by 4.4°C and 4.8°C respectively.	higher coverage ratioes leads to higher reductions in external surface temperature.
Widiastuti et. al, 2018	Semarang, Indonesia	10-16 december- hottest month is october	experiement	coverage ratio	indirect GF	E	for 50% and 90% greenery cover, reduction in exterior wall surface temperatures, 6.8 °C and 7.8 °C respectively. While reduction in interior wall surface temperatures,6.7 °C and 7.3 °C respectively.	It means higher leaves leavs has stronger cooling effect it is noticed specially in interior surface.

Pérez et al. 2017	Lleida, Spain	summer	experiement	LAI-orientation	Indirect GF	S-N-E-W	reduction in exterior wall surface temperatures, is 15°C, 16°C and 16.4°C on E, S and W facades respectively.	the shadow factor and highest reductions in wall exterior surface are obtained for the green facade during daily peaks of solar radiation by orientation (at 10:00 h on the East, at14:00 h on the South, and at 18:00 h on the West orientation)
Susorova et al., 2014	Chicago, USA	summer July 9 until July 18	observational study	orientation	direct GF	S-N-E-W	reduction in exterior wall surface temperatures, is 1.2°C, 0.1°C, 0.9°C and 0.7 on E, S W, N facades respectively.	The largest surface temperature reductions between the bare and ivy-covered exterior walls corresponded with the peak exposure to solar radiation for each facade.
Susorova et al.2013	Chicago, USA	ng	Self-developedmathematical model	plant features	direct GF	ng	reduction in exterior surface temperature by 0.7-13.1 C, reduce the heat flux through the exterior wall by 2-33 W/m2,	. Each unit increase in LAI resulted in : *an additional effective R-value of approximately 0.06 m2 K/W on average. *approx. 5% reduction in conductive heat transfer through the wall
Safikhani and Baharvand, 2017	Skudai, Malaysia.	14th April 2013 to 19th June 2013	simulation and experiement	gap distance	LW	W	in morning: 15 cm distance reduces indoor air temperature and external surface temperature 2◦C more than30 cm. -in afternoon: 30 cm distance reduces external surface temperature up to 1.5◦C more than15 cm.and reduces indoor air temperature 4◦C more than15 cm.	Duringthe morning, 15 cm distance has better thermal performance than30 cm distance.
M Nugroho, 2020	Malang, Indonesia	NG	experiement	gap distance-plant features	Direct GF			During the morning, 50 cm air gap distance has better thermal performance than 100 cm distance, and vice versa in the afternoon.
El-Zoklah and Refaat, 2021	New Cairo, Egypt		simulation	gap distance-orientations	Direct and in direct GF	S-E-W	energy savings for direct - indirect GF are (14.3-18.5%),(15.7-19.2%) and (16.1-24.1%) for S, E and W orientations, respectively.	*indirect GF has better thermal performance and can achieve higher energy savings. *direct and indirect GF achieve higher energy savings in W, E and S orientations, respectively.
Koyama et al., 2013	Nagoya, Japan	April and May 2008	experiement	plant features	Indirect GF	S		the correlation coefficient for the averaged WTRs (wall surface temperature reductions) with the leaf transpiration rate and the leaf solar transmittance was 0.804 and 0.998, respectively.

Charoenkit et al., 2020	Phitsanulok, Thailand	Aug-Sep 2018 and Oct-Nov 2018	experiement	VGS type, plant features	LW	W		*suggesting that plants with medium-sized leaves averagely reduced temperature better than plants with large and small leaves. *It is found that LW reduced 83.2% heat gain compared to BW.
Cuimin Li et al., 2019	Suzhou, China		observational study (field experiment)	plant thickness	Direct GF	S	reduction in exterior surface temperature by2.6, 6.3 and 4.0 for 7.2, 19.8 and 30.5 cm of foliage.	foliage thickness of 19.8 cm achieved the best thermal performance among other foliage with 7.2 cm and 30.5 cm thickness.
Benhalilou et al., 2020	Constantine, Algeria	summer	observational study (field experiment)	plant thickness - coverage ratio	Direct GF	S W	reduction in exterior surface temperature by 10°C and 8°C for building A and C, respectively.	denser foliage thickness resulted in more reductions in wall surface temperature and therefore lower indoor temperatures.
Urrestarazu et al., 2019	Seville, Spain	two tests: end of January to the end of	experiement	soil type	LW	ng	ng	Green cover grown in pumice reached 90% to 80% also expanded clay showed similar results, while perlite reached 80% to 45% coverage ratio
Khandaker and Kozten, 2018	the UK	summer	experiement	soil type	LW	E	ng	Among 7 different growing media, Mineral wool and vermiculite were by far the best performing media, Coconut fibre and pond algae were the worst performing media.
Dede et al., 2021	Sakarya, Turkey	August	experiement	soil type	LW	ng	highest reduction in interior space temperatures is 6°C, 5.4°C and 5.2°C for PPR3, PRH3 and PPR2 respectively.	growing media consisting of perlite and peat exhibit excellent thermal insulation characteristics. Also, the contribution of perlite to thermal insulation is higher that than rice hull.
Shuhaimi et al., 2022	Malaysia	ng	mathmatical model /steady-state formula	VGS type, orientation	Direct GF-indirect GF- LW	S-N - E-W	reduction in OTTV in diffferent orientation ranging (1.13to1.71%) for direct GF, (2.45to3.30%)indirect GF),(5.78to7.26%) for modular LW and (5.85to7.33%) for continuous LW.	
Rupasinghe and Halwatura, 2020	Colombo, Sri Lankan	ng	observational study and experiment.	VGS type, orientation- plant species	Direct GF-indirect GF- LW	S-E-W	reduction in exterior surface temperature by 10.16 °C, 8.65 °C and 6.36 °C for LW, indirect GF and direct GF. Reduction in interior space temperature of 2.21 °C, 1.82 °C and 0.66 °C for LW, indirect GF and direct GF.	*different types of vgs result in different thermal results. * no significant differences between different plant species in term of temperature reductions.

4. Conclusion

In this study, factors attribute VGS thermal performance were comprehensively analysed through presentation of the findings of various experimental and numerical works in literature. for an easier accumulative understanding of the factors regulating the impact of this greenery on the building facades.
The research is divided into subtopics for detailed investigation within the scope of this goal. First, an overview of the passive strategies used by VGS to influence building facades, including evapotranspiration, thermal insulation, shading, and wind blockage ability. Then, a review and analysis on the results of experimental and simulation investigations examining one or more variables of VGSs' variables and components. Studies were categorized into two main groups according to the discussed variable in the context, group one: factors related to buildings as it is main destination to measure the thermal effect and group two: greenery related variables as it is the game player in this passive system.

As plants are a living component that interacts with surrounding environment, it is clearly noticed that it is very sensitive to solar radiation which is differ in different climate zones and façade orientation. Also, it can be concluded that LAI and plant thickness significantly affect thermal performance of the system, the presence of growing media and its thickness affect plant growth and thermal insulation.

5. References

[1] B. Jaafar, I. Said, and M. H. Rasidi, “Evaluating the impact of vertical greenery system on cooling effect on high rise buildings and surroundings: a review,” *Procedia - Social and Behavioral Sciences*, vol. 9, no. 2, pp. 1-9, Dec. 2013, 2011.

[2] N. Dunnett, and N. Kingsbury, *Planting Green Roofs and Living Walls*: Timber Press, London, 2008.

[3] M. Manso, and J. Castro-Gomes, “Green wall systems: A review of their characteristics,” *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 863-871, Jan. 2015, 2015.

[4] I. Susorova, "Green facades and living walls: vertical vegetation as a construction material to reduce building cooling loads," *Eco-Efficient Materials for Mitigating Building Cooling Needs*, pp. 127-153: Elsevier, 2015.

[5] A. Nugroho, "The Impact of Living Wall on Building Passive Cooling: A Systematic Review and Initial Test." p. 012120.

[6] G. Perez, L. Rincon, A. Vila *et al.*, “Green vertical systems for buildings as passive systems for energy savings,” *Applied energy*, vol. 88, no. 12, pp. 4854-4859, 2011.

[7] R. D. Brown, and Gillespie, *Microclimate Landscape Design : Creating Thermal Comfort and Energy Efficiency*: John Wiley & Sons, New York, 1995.
[8] A. B. Besir, and E. Cuce, “Green roofs and facades: A comprehensive review,” *Renewable Sustainable Energy Reviews,* vol. 82, no. 1, pp. 915-939, Feb. 2018, 2018.
[9] B. Raji, M. J. Tenpierik, and A. Van Den Dobbelsteen, “The impact of greening systems on building energy performance: A literature review,” *Renewable and Sustainable Energy Reviews,* vol. 45, pp. 610-623, Feb. 2015, 2015.
[10] S. M. Sheweka, and N. M. Mohamed, “Green facades as a new sustainable approach towards climate change,” *Energy Procedia,* vol. 18, pp. 507-520, 2012.
[11] G. Perez, J. Coma, M. Chafer *et al.*, “Seasonal influence of leaf area index (LAI) on the energy performance of a green facade,” *Building and Environment,* vol. 207, pp. 108497, Jan. 2022, 2022.
[12] I. Susorova, P. Azimi, and B. Stephens, “The effects of climbing vegetation on the local microclimate, thermal performance, and air infiltration of four building facade orientations,” *Building and Environment*

vol. 76, pp. 113-124, 2014.
[13] J. Yan, L. Zhao, Y. Zhang *et al.*, “Effects of microclimatic factors on stomatal conductance of plants in vertical greenery systems in humid subtropical areas,” *Sustainable Cities and Society,* vol. 85, pp. 104056, Oct. 2022, 2022.
[14] E. Alexandri, and P. Jones, “Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates,” *Building and Environment,* vol. 43, no. 4, pp. 480-493, 2008/04/01/, 2008.
[15] E. Alexandri, and P. Jones, “Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates,” vol. 43, no. 4, pp. 480-493, 2008.
[16] L. Pan, S. Wei, P. Y. Lai *et al.*, “Effect of plant traits and substrate moisture on the thermal performance of different plant species in vertical greenery systems,” *Building and Environment,* vol. 175, pp. 106815, 2020.
[17] L. S. Lee, and C. Y. Jim, “Multidimensional analysis of temporal and layered microclimatic behavior of subtropical climber green walls in summer,” *Urban Ecosystems,* vol. 23, no. 2, pp. 389-402, Dec. 2019, 2020.
[18] C. Nori, F. Olivieri, R. Grifoni *et al.*, “Testing the performance of a green wall system on an experimental building in the summer,” in sustainable architecture for a renewable future29th conference, Munich, Germany, 2013.

[19] K. C. Dahanayake, and C. L. Chow, "Comparing reduction of building cooling load through green roofs and green walls by EnergyPlus simulations." pp. 421-434.
[20] K. J. Kontoleon, and E. A. Eumorfopoulou, “The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone,” *Building and Environment*, vol. 45, no. 5, pp. 1287-1303, 2010/05/01/, 2010.
[21] H. Lin, Y. Xiao, and F. Musso, "Shading Effect and Heat Reflection Performance of Green Façade in Hot Humid Climate Area: Measurements of a Residential Project in Guangzhou, China." p. 012006.
[22] R. Widiastuti, W. Caesarendra, E. Prianto *et al.*, “Study on the leaves densities as parameter for effectiveness of energy transfer on the green facade,” *Buildings*, vol. 8, no. 10, pp. 138, Oct. 2018, 2018.
[23] G. Pérez, J. Coma, S. Sol *et al.*, “Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect,” *Applied Energy*, vol. 187, pp. 424-437, Feb. 2017, 2017.
[24] L. Pan, S. Wei, L. J. E. Chu *et al.*, “Orientation effect on thermal and energy performance of vertical greenery systems,” vol. 175, pp. 102-112, 2018.
[25] T. Koyama, M. Yoshinaga, H. Hayashi *et al.*, “Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls,” *Building and Environment*, vol. 66, pp. 96-103, April 2013, 2013.
[26] L. Pan, S. Wei, P. Y. Lai *et al.*, “Effect of plant traits and substrate moisture on the thermal performance of different plant species in vertical greenery systems,” *Building and Environment*, vol. 175, pp. 106815, 2020/05/15/, 2020.
[27] S. Charoenkit, S. Yiemwattana, and N. Rachapradit, “Plant characteristics and the potential for living walls to reduce temperatures and sequester carbon,” *Energy and Buildings*, vol. 225, pp. 110286, Oct. 2020, 2020.
[28] K. Perini, A. Magliocco, and S. Giulini, “Vertical greening systems evaporation measurements: does plant species influence cooling performances?,” *International Journal of Ventilation*, vol. 16, no. 2, pp. 152-160, Sep. 2016, 2017.
[29] H. T. Rupasinghe, and R. U. Halwatura, “Benefits of implementing vertical greening in tropical climates,” *Urban Forestry & Urban Greening*, vol. 53, pp. 126708, 2020/08/01/, 2020.
[30] I. Andric, A. Kamal, and S. G. Al-Ghamdi, “Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: Case study of Qatar,” *Energy Reports*, vol. 6, pp. 2476-2489, Nov. 2020, 2020.
[31] I. Andric, A. Kamal, and S. G. J. E. R. Al-Ghamdi, “Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: Case study of Qatar,” vol. 6, pp. 2476-2489, 2020.

[32] C. Li, J. Wei, and C. Li, “Influence of foliage thickness on thermal performance of green façades in hot and humid climate,” *Energy and Buildings*

vol. 199, pp. 72-87, June 2019, 2019.

[33] K. Benhalilou, S. Abdou, and R. Djedjig, “Experimental Investigation of Hygrothermal Behavior of Direct Green Facaades under Semi-Arid Climate,” *Journal of Fundamental Applied Sciences*, vol. 12, no. 1, pp. 213-229, Dec. 2019, 2019.

[34] L. Pérez-Urrestarazu, R. Fernández-Cañero, P. Campos-Navarro *et al.*, “Assessment of perlite, expanded clay and pumice as substrates for living walls,” *Scientia Horticulturae*, vol. 254, pp. 48-54, 2019.

[35] M. Khandaker, and B. Kotzen, “The potential for combining living wall and vertical farming systems with aquaponics with special emphasis on substrates,” *Aquaculture research*, vol. 49, no. 4, pp. 1454-1468, 2018.

[36] O. H. Dede, N. Mercan, H. Ozer *et al.*, “Thermal insulation characteristics of green wall systems using different growing media,” *Energy and Buildings*, vol. 240, pp. 110872, June 2021, 2021.

[37] N. D. A. M. Shuhaimi, S. M. Zaid, M. Esfandiari *et al.*, “The impact of vertical greenery system on building thermal performance in tropical climates,” *Journal of Building Engineering*, vol. 45, pp. 103429, 2022.