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The impact of vertical greenery system on building thermal performance in tropical climates

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ABSTRACT

The thermal benefits of Vertical Greenery System (VGS) in providing thermal comfort, reducing internal building temperature, and lowering operational energy consumption are not widely known. There is a lack of research and technical knowledge on the effects of vertical greenery systems related to thermal performance, especially in tropical climates, such as that of Malaysia. Therefore, this paper addresses this gap by investigating the effect of VGS on heat transfer and the thermal performance of hypothetical buildings. In this paper, a data prediction method is used to identify the overall thermal transfer value (OTTV) from several hypothetical case studies. A variety of combinations of variables have been used to identify the best design with the lowest OTTV reduction through VGS. From the calculation, Linear Greenery System achieved the highest OTTV reduction with an average of 6.87%, followed by Modular Green Wall (6.82%), Double-skin Green Facades (2.97%), and Direct Green Facades (1.32%). Therefore, this paper can conclude that Linear Green Wall is the best greenery system for reducing heat transfer for the tropical climate of Malaysia.

1. Introduction

The 21st century has seen the rise of environmental awareness and increased the integration of sustainability concepts and green design in the built environment industry [1]. The concept of sustainable development revolves around the three (3) main pillars of environmental, social, and economic sustainability [2]. Generally, sustainable development can be integrated into the built environment context by reducing waste and pollution, minimizing the usage of water and electricity, and organizing systematic public green spaces [1]. Creating green spaces within urban areas is one of the strategies to develop a sustainable city, as it provides environmental, social, and health benefits, as well as mitigating strategies to combat climate change and urban heat island (UHI) effects [1]. UHI is a phenomenon in which major temperature differences can be found within a city or between a city and its suburbs and/or its rural surroundings [3].

Urban UHI can be mitigated by creating more greenery systems in urban spaces integrated with buildings [4] as vegetation can provide shading, reduced urban temperatures, increase carbon sequestration potential, and provides oxygenated air and a healthier environment to urban dwellers (within proximity) [6]. These green spaces act as a shading layer to reduce heat transmission and the temperature of the surrounding environment [5]. According to Stec et al. [7], a tree shading system can reduce the cooling loads of the building by absorbing 60% of solar radiation and transforming it into latent heat from the evapotranspiration process [8]. These urban greenery systems can also be integrated into buildings as green façade or green roofs [4]. Besides, vertical greenery systems (VGS), commonly known as green facades, can reduce heat transfer into the internal spaces and act as a natural barrier that can prevent excessive solar radiation. Since façade design has such a strong influence on building performance, the reduced heat transfer will lower the energy demand for interior space cooling [9]. Therefore, VGS is part of a strategy that can reduce the urban heat island effect and operational energy in buildings.

However, most VGSs in Malaysia are implemented for aesthetic value [10]. Research by Bakar et al. [10] on VGS found that three out of five projects implemented the VGS due to its aesthetic value. Only two projects fully utilized VGS for both environmental and aesthetical

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benefits [10]. This implies there is a lack of awareness and technical knowledge in the effect of VGS on building's thermal performances and thermal comfort in the tropical climate of Malaysia [11]. Thus, this paper aspires to provide technical data on VGS and its thermal benefits for the tropical climate in Malaysia.

1.1. Vertical greenery system

VGS as a concept has been in existence for decades, while the idea of the green walls date back to ancient Babylon. One of the Seven Wonders of the Ancient World, the Hanging Gardens of Babylon, was the first recorded green wall [12]. King Nebuchadnezzar designed the gardens [13] to cheer up his homesick wife [12]. The green dividers included vaulted patios raised over one another, laying on columns looking like a solid shape, and soil to permit the planting of trees [12]. Based on the reports of ancient Greek historians, the Hanging Gardens of Babylon (see Fig. 1 [13]) was around 400 × 400 feet in length and 80 feet in height [14].

VGS can be defined as growing plants on vertical surfaces or the surfaces of a building or using vertical structures attached to the building wall [15]. [16]. Such structures can be man-made or natural and can be mounted in buildings such as interior walls, bio statues, or partitions [17]. For the exterior, the VGS can climb balconies, fences, or wall covers [17]. VGS is also a good complement to greenery roof systems, as it offers a higher wall-to-roof ratio with a larger surface area to grow plants [18].

1.2. Advantages of vertical greenery system

VGS offers environmental, economic, and social advantages to the built environment. Urban greenery is not only recognized for its aesthetic significance and improvement but also provides a space for social occasions and mental restoration [13]. [19] to preserve the wellbeing of the urban population [20]. Additionally, urban greenery helps to support the environment by introducing advantageous ecosystems in the urban landscape and acts as a water filtration system [13]. According to Timur et al. [13], vertical gardens can provide economic and ecological benefits which vary based on the building's typology, green wall innovations, plant variations, and choices of plant medium. Besides VGSs' benefits in reducing the UHI effect [4]. [21], they can also improve aesthetical value [26]. [27], improve air quality and occupants health [22]. [23]. [30]. [31], and reduce noise pollution [28]. [29]. VGSs can also improve energy efficiency [24]. [25] and reduce the indoor temperature of buildings [32]. [33]. Table 1 summarizes the advantages of VGS in both tropical and non-tropical countries.

1.2.1. Improved energy efficiency

Greenery contributes enormously to energy efficiency in the cities by improving the thermal insulation capacity to regulate external temperatures [24]. [25]. The VGS can trap a layer of air within the plant mass and limits the movement of heat through thick vegetation mass to reduce heat penetration through the wall [23]. Increasing the amount of vegetation in an urban area is one of the strategies to reduce the air temperature, according to Canero et al. [34]. Pérez et al. [25] believe VGS can be an effective method for energy reduction in warm temperate and temperate climates during the cooling period, with 5%–50% reductions. The most common reductions range between 20% and 30% for a west facade orientation [25].

Estimated energy savings vary from 90% to 35% for different cities when all feasible facades were installed with vertical greenery systems, demonstrating the opportunity for major improvements in thermal comfort and decreasing cooling load demand [24]. VGS can minimize air-conditioning workload by shading walls and windows from solar radiation. A 5.5 °C reduction in temperature outside a building can decrease the energy required for air-conditioning by 50%–70% [35]. According to Bass & Baskaran [36], the shade impact of VGS helps to reduce the electricity consumption for ventilation by approximately 23% and around 20% reduction in electricity consumed by fans, resulting in an 8% decrease in total energy usage.

Di & Wang [37] investigated the cooling effect of a traditional green façade at Beijing Tsinghua University Library using theoretical calculations. This paper found that the total solar radiation obtained on the ivy-covered wall facing the west during daytime was 133 W/m2. The maximum transpiration heat flux was 42% from the overall solar radiation consumed by the plants, while 40% was lost by thermal convection, and 18% was lost by long-wave radiation to the ground [37]. When the radiation heat transfer decreases, it will subsequently reduce the indoor temperature and cooling load demand [37]. Galagoda et al. [22] revealed that the application of green walls reduced indoor air temperature by around 2.4 °C which resulted in potentially 10.97 MW energy saving and financial benefits.

1.2.2. Thermal performances of vertical greenery systems in tropical climate

Previous research related to the use of vertical greenery networks in a tropical climate emphasizes enhancing the thermal performance of a building by utilizing herb and flowering plants [32]. [38]. [39]. Few studies also investigated the use of edible plants in tropical climate environments instead of ornamental plants. Basher et al. [32] demonstrated that indoor thermal performance can be improved with the usage of edible vertical greenery system. This paper was conducted in Penang (Malaysia) using indirect VGS mounted with edible plants, resulting in reducing the wall surface temperature by a maximum of 11.0 °C [32]. This transformation can offer several advantages leading to a reduction in energy consumption and increase some food supply for the household [32].

Examining thermal effects, Sunakorn [33] performed a study in Thailand and was able to reduce the air temperature by up to 4.71 °C between the external ambient temperature and indoor temperature during summer using a living wall. Research by Laopanitchakul [40] in Bangkok showed that the surface temperature of walls attached with plants is lowered at an average of 7.03 °C compared to walls without

Fig. 1. The hanging gardens of babylon [13].

Table 1
Advantages of VGS.

Benefits of VGS	Descriptive Detail	Climate	Author	Year
Social Benefits				
Aesthetic improvement	Increase property values by improving the aesthetic, cultural, and social conditions of the community.	Non-Tropical	[26]	2008
	Produced a beautiful pattern on the vertical façade or wall.	Non-Tropical	[27]	2012
Health improvement	Plants on green facades can reduce direct contact with radiation that could have a bad effect on the eyes and skin.	Non-Tropical	[31]	2015
	Plants can have a profound impact on the mental well-being and serenity of communities in an office or home.	Tropical & Non-Tropical	[30]	2017
Economic Benefits				
Improved energy efficiency	Energy savings vary from 90% to 35% for different cities when all feasible facades are installed with VGS.	Non-Tropical	[24]	2008
	5%–50% energy reductions in warm temperate and temperate climates.	Non-Tropical	[25]	2014
Reduce indoor temperature	Reducing the air temperature by up to 4.71 °C.	Tropical	[33]	2008
	The edible plant has the potential to lower the wall surface temperature by a maximum of 11 °C.	Tropical	[32]	2016
Environmental Benefits				
Reduce Urban Heat Island (UHI) Effect	Significantly reduce the building's extreme temperatures by blocking the walls from the sunlight and reducing daily temperature fluctuations by 50%.	Non-Tropical	[4]	2008
	Reducing the impact of urban heat island effect.	Non-Tropical	[21]	2013
Improved air quality	Green façade can improve air quality by filtering the contaminated air via natural ventilation systems.	Tropical & Non-Tropical	[23]	2012
	The application of green walls can reduce 1.6%–1.81% and 0.63% of relative humidity and CO2 concentration at 0.1 m of the green wall compared to normal façade.	Tropical	[22]	2018
Noise reduction	Average decrease in sound mitigation in dB was from 2% to 3%.	Non-Tropical	[29]	2012
	Acoustic reduction index (Rw) produced by VGS which is 15 dB and the weighted acoustic absorption coefficient (α) which is 0.40.	Non-Tropical	[28]	2015

plants during daytime. However, several aspects affected the outcome, such as the species chosen for analysis, coverage of the leaves area, layer of leaves, and the distance between the climbing plants and the building facades [40]. For tropical climates, Sunakorn [33] also recommended that the climbing plant be planted at 15 cm between the building wall to reduce the heat transmitted from the outside of the building wall towards the internal wall. Additionally, according to Wong et al. [41], the highest reduction in surface temperature of the wall was tracked at 11.58 °C with the usage of the support system or living wall. The temperature reduction can be caused by a combination of plant and soil substrates added to the wall surfaces [41].

Research by Safikhani et al. [42] examined the thermal performance of green walls between the wall surfaces and cavity of VGS frameworks and the internal temperatures in the tropical climate, such as Malaysia. The findings showed that living walls can reduce the temperature by up to 8.0 °C as compared to green facades that can only reduce 4.0 °C for the heat transfer from external to internal temperature [42]. There was a major difference in temperature reduction between the green façade and the living wall [42]. However, the experimental results may have been affected by the humidity produced by the cavity of the green facade that was data and slightly higher than the living wall [42].

Recently, Pan et al. [43] investigated the impacts of location and weather on the thermal performance of vertical greenery systems in Hong Kong. The experiment took place in experimental rooms with and without green walls. Based on the tests, the green wall could lower the building envelopes' cooling load and enhance the indoor thermal environment by 12%–42%, depending on their orientation [43]. The best attempt in reducing the ambient temperature occurred when the VGS was located on the north side [43]. Generally, using VGSs in the built environment could offer outstanding benefits for both outdoor and indoor environments [43].

1.3. *Impact of greenery system on the overall thermal transfer value (OTTV) and Envelope Thermal Transfer Value (ETTV)*

Research conducted by Ip et al. [44] identified the shading coefficient of a traditional green façade on the building in the UK's temperate temperature. The results indicated one layer of leaf allows 45% solar transmission, which can be reduced by 12% when it passes through another five layers of leaves [44]. In addition, other researchers studied the role of plants as a shading coefficient in improving the thermal performance of a building [44]. Wong et al. [41] studied the impact of VGS on the Envelope Thermal Transfer Value (ETTV) for a 20-storey hypothetical building with a glass facade. The findings showed that 50% of building facades covered with plants could reduce 40% of the building's ETTV [41]. When the shading coefficient increased from 0.5 to 0.98, the ETTV declined by 0.6% from 21%. It can be concluded that the larger the Leaf Area Index (LAI), the lesser the solar transmittance; thus, improving the thermal performance of a building [41].

Another indicator for a building envelope's thermal performance is the Overall Thermal Transfer Value (OTTV) [45]. Based on the Malaysian Standard 1525:2019: (Energy efficiency and use of renewable energy for non-residential buildings - Code of practice (Third revision), the OTTV of the building envelope for air-conditioned buildings should not exceed 50 W/m^2 [46]. A study conducted by Hasan et al. [45], regarding the application of green roofs and living walls towards the cooling energy performance of commercial buildings from OTTV of building wall in a sub-tropical climate, showed that an extensive green roof and external living wall could reduce cooling load by up to 10–15% [45].

2. Materials and method

The objective of this paper is to identify the overall OTTV and thermal performances of different types of VGS from hypothetical case studies. In this paper, quantitative research methods were used to collect the required datasets. Microsoft Excel is used to implement equations and formulas to predict the outcome according to different variables. The data prediction method is used to identify the OTTV from hypothetical case studies with the presence of greenery systems. By calculating the building OTTV, the building thermal performance with the presence of VGS can be identified. These predictions are based on Malaysia's tropical climate condition and geographical location, which experiences an average of 27 °C temperature throughout the year, with minimum and maximum temperatures of 23 °C and 32 °C, respectively [47,48], with the daily average sunlight of 6 h in Malaysia [48].

2.1. Data prediction method

A variety of combinations, in terms of material and orientation, was used to calculate the best design and temperature reduction produced by different types of VGS. Two (2) theoretical case study buildings of common brick wall and concrete wall were used as a baseline to calculate the OTTV and thermal performance of VGS. The OTTV formula used in this paper is a steady-state formula that is based on Malaysian Standard 1525, which was derived from the ASEAN-USAID Buildings Energy Conservation Project report written by Deringer and Busch in 1992 [59]. [60]. The formula was first proposed by ASHRAE Standard 90-75 in 1975, which was later amended as ASHRAE Standard 90A-1980 [61]. [62]. The calculations used in this paper were done using Microsoft Excel software and did not involve any simulation software to allow computations to be conducted at a basic research level, which can be easily replicated by other researchers.

2.1.1. Theoretical case study building

A hypothetical five-storey commercial building of 15 m in length by 15 m in width and with 4 m in height for each storey is used as a case study. This hypothetical building is modelled using Autodesk Revit software for illustration purposes only (as shown in Fig. 2). Also, the hypothetical five-storey building represents an average storey height for a commercial building in Malaysia [63]. The correlation co-efficient between the number of building storey (gross exterior wall area) [64] and the OTTV value is zero (Formula 1), therefore there is no difference between the height/storey of a building and its OTTV value. Two types of wall material were used in this calculation, which are the brick wall and concrete wall, as these are the most commonly used material in Malaysia [49]. The type of materials used for the brick wall was clay brick and plaster, while concrete walls include concrete blocks, surface resistance, and plaster. For the calculations, buildings A and F were used as the Baseline controller [41].

Example for building B1:

X-value (OTTV value)	100.17	100.17	100.17	100.17	100.17
Y-value (Gross exterior wall area) (m^2)	45	90	135	180	225

Correlation Coefficient Formula [64]:

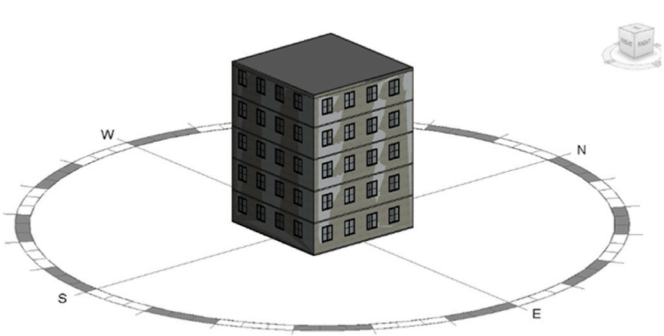

Fig. 2. Hypothetical five-storey commercial building.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{\left[n - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum x\right)^2\right]}}$$
$$= \frac{5(67614.75) - (500.85)(675)}{\sqrt{\left[5(50170 - (500.85)^2\right]\left[5(111375) - (675)^2\right]}} \qquad \text{Formula (1)}$$
$$= \frac{0}{\sqrt{(-0.72)(10125.00)}}$$
$$= 0$$

The type of window used in the model was a generic and common double casement window of 1400 mm width x 1800 mm height. There were 60 windows in total. The type of glass used for the window was double tinted glazed with a shading coefficient of 0.71. The U-values of the two types of building facades using concrete and brick walls were calculated in Table 2. The concept of thermal transmittance (U-values) has become a key parameter in assessing the thermal quality of the building façade to demonstrate the steady-state thermal transfer performance. The R-values for the building materials were based on Sukri et al. [54]. Table 3 and Table 4 shows the specifications used for the VGS and the total U-value for a façade with VGS. In this paper, Direct Green Facade, Double-skin Green Facades, Modular Green Wall, and Linear Green Wall were used. The Direct and Double-skin Green Facades were categorized as green façade systems, while the Modular and Linear Green Walls were categorized as living green wall systems. The U-value used for this paper is based on previous research [50]. Each of the case study buildings used for the calculation is described in Table 5.

Example of U-value calculation for a brick wall [55]:

$$U - value = 1/Total\ R - value$$
$$U - value\ for\ brick\ wall = 1/\left(\begin{array}{l} External\ surface\ resis\tan ce + clay\ brick + \\ Internal\ plaster + External\ plaster + \\ Internal\ surface\ resis\tan ce \end{array}\right)$$
$$= 1(0.04 + 0.14 + 0.08 + 0.08 + 0.13)$$
$$= 1/0.47$$
$$= 2.13\ W/m^2.K$$

Formula (2)

2.1.2. OTTV calculation

OTTV is one of the parameters that evaluate the thermal performance of a building envelope. OTTV is the value that represents the average rate of heat transfer to a building via building facades and it can be adopted to compare the thermal performance of different building envelop designs [61] for a hypothetical case study building. The average heat transfer rate of a building is calculated using three envelope components: opaque walls, roofs, and window glasses. According to

Table 2
Specifications of façade materials used for the calculation.

Façade material	Type of material	R-value (m^2K/W)	U-value ($W/m^2.K$)
Brick wall	External surface resistance	0.04	–
	Clay brick	0.14	–
	Internal plaster	0.08	–
	External plaster	0.08	–
	Internal surface resistance	0.13	–
Total		0.47	2.13
Concrete wall	External surface resistance	0.04	–
	Concrete blocks	0.55	–
	Internal plaster	0.08	–
	External plaster	0.08	–
	Internal surface resistance	0.13	–
Total		0.88	1.14

Table 3
Specifications of VGS types used.

Type of VGS	Average thickness (mm)				R-value (m^2K/W)	U-value (W/m^2K)	*Citation*
	Metal frame/Planter	Substrate	Plants	Total			
Direct Green Facades	–	–	50	50	0.40	2.50	[50]. [51]
Double-skin Green Facades	50	–	50	100	0.60	1.66	[50]. [51]
Modular Green Wall	40	150	100	290	2.50	0.40	[50]. [52]
Linear Green Wall	40	250	200	490	4.20	0.24	[50]. [53]

Table 4
Total R-value and U-value of façade with VGS.

Case Study	Façade material	Type of VGS	R-value (m^2K/W)	Total U-value (W/m^2K)
A (Baseline)	Common brick wall	Not installed	0.47	2.13
B1, B2, B3, B4		Direct Green Facades	0.87	1.15
C1, C2, C3, C4		Double-skin Green Facades	1.07	0.93
D1, D2, D3, D4		Modular Green Wall	2.97	0.34
E1, E2, E3, E4		Linear Green Wall	4.67	0.21
F (Baseline)	Concrete wall	Not installed	0.88	1.14
G		Direct Green Facades	1.28	0.78
H		Double-skin Green Facades	1.48	0.68
I		Modular Green Wall	3.38	0.30
J		Linear Green Wall	5.08	0.12

Malaysian Standards MS1525:2019, the 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. According to the Malaysian Standards MS1525:2019, the general Overall Thermal Transfer Value (OTTV) equation can be expressed as:

$$OTTV_1 = 15\alpha(1\text{-}WWR)\ U_W + 6(WWR)U_f + (194 \times OF \ x\ WWR\ x\ SC) \qquad \text{Formula (3)}$$

Where:

WWR = The window-to-gross exterior wall area ratio for a specific orientation
U_W = U-values of wall (W/m2 K)
U_f = U-values of fenestration (W/m2 K)
$\propto$ = Solar absorptivity of wall
SC = Shading Coefficient of the glazing
OF = Orientation Factor
SHGC = Solar heat gain coefficient where SHGC = SC x 0.87

For this paper, the method of calculating OTTV is based on Malaysian Standard 1525:2019 stated below:

$$OTTV = (A_1\ x\ OTTV_1) + (A_2\ x\ OTTV_2) + \ldots + (A_n\ x\ OTTV_n) / A_1 + A_2 + \ldots + A_n \qquad \text{Formula (4)}$$

Where:

A_1, A_2 = Gross exterior wall area for orientation 1 and 2
$OTTV_2$ = OTTV value for orientation 1 from formula (3)

2.1.3. *Solar orientation factors and shading coefficient*

The solar orientation factors used by the building are stated in Table 6. The shading coefficient is the amount of thermal performance of

Table 6
Solar orientation factor stated by Malaysian Standard 1525:2019.

Orientation	Solar Orientation Factor
North	0.90
East	1.23
South	0.92
West	0.94

Table 5
Specifications for the case study buildings.

Case study	Type of VGS	Orientation	Shading coefficient (SC)	Total U-value (W/m^2K)	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
F (Baseline)					
G					
H					
I					
J					

a glass component (panel or window) in a building. This is also known as the ratio of solar gain due to direct sunlight that penetrates the glass panel. The type of shading devices created by the VGS can be considered a combined shading device or egg crate. The value of SC1 is the shading coefficient for windows, while SC2 is the shading coefficient for VGS. In this paper, the SC1 is 0.71 for all cases. The value of SC2 is estimated based on egg crate shading coefficients stated in Malaysian Standard, while if there are no shading devices, SC2 = 1 (MS 1525:2019) (Fig. 3). The value for SC2 is based on assumptions from Wong et al. [41]. Table 7 shows the shading coefficient used for the calculations.

The calculation for shading coefficient is stated as below:

$SC = SC1 \ x \ SC2$ Formula (5)

Where:

SC = Effective shading coefficient of the fenestration system.
SC1 = Shading coefficient of sub-system 1 (e.g., glass); and
SC2 = Shading coefficient of sub-system 2 (e.g., external shading devices)

3. Results and findings

This paper included an investigation of 22 theoretical case studies in total. Seventeen (17) buildings A, B1, B2, B3, B4, C1, C2, C3, C4, D1, D2, D3, D4 and E1, E2, E3, E4 were modelled using a brick wall façade, while five (5) buildings F, G, H, I, J were modelled using concrete wall facade. The type of window used is a double casement window with 1400 mm width x 1800 mm height. The type of glass used in the window is double tinted glazed with a shading coefficient of 0.71. Brick wall and concrete wall were selected for modelling as it is the most commonly used building construction in tropical climates, such as Malaysia. Therefore, the OTTV differences made to buildings by applying VGS on the building façade are investigated through the calculation of OTTV values. Buildings A and F were used as baselines for different building facades. Buildings B, C, D, and E were modelled in four (4) different orientations which are North, East, South, and West. Table 2 shows the facade material used for the calculation. Tables 3 and 4 show the specifications for VGS types used and the total U-value of building façade with greenery systems.

3.1. Overall building OTTV

The case study building with a brick wall has a higher OTTV value compared to the ones with concrete walls, as they have different U-values. Table 8 and Fig. 4 demonstrate the overall building OTTV for the theoretical case study building. Baseline buildings A and F have the highest OTTV value with 101.88 and 99.6 W/m^2 for the brick and concrete walls respectively. There is no VGS on the baseline building facades (Fig. 4). Building B has the second highest OTTV value, with an average 100.40 W/m^2 follow, fed by buildings G, C, H, D, and E with averages of 98.88, 98.82, 96.80, 94.95, and 94.88 W/m^2, respectively.

Ratios		Orientation				
R1	R2	North/ South	East	West	North-East/ South-East	North-West/ South-West
0.20	0.20	0.71	0.77	0.77	0.73	0.75
	0.40 - 0.60	0.62	0.69	0.69	0.63	0.66
	0.60 - 1.80	0.56	0.62	0.61	0.55	0.58
0.40	0.20 - 0.40	0.59	0.63	0.64	0.60	0.63
	0.60 - 1.20	0.49	0.54	0.54	0.48	0.52
	1.40 - 1.80	0.46	0.50	0.51	0.44	0.48
0.60	0.20 - 0.60	0.52	0.54	0.56	0.51	0.55
	0.80 - 1.80	0.43	0.44	0.46	0.39	0.44
0.80	0.20 - 0.60	0.50	0.49	0.52	0.47	0.52
	0.80 - 1.80	0.40	0.39	0.42	0.36	0.41
1.00	0.20 - 0.40	0.51	0.48	0.52	0.48	0.52
	0.60 - 1.20	0.41	0.39	0.42	0.36	0.42
	1.40 - 1.80	0.38	0.35	0.38	0.32	0.38
1.20 -1.80	0.20 - 1.80	0.38	0.33	0.38	0.32	0.38

Fig. 3. Egg crate shading coefficients stated in Malaysian Standard 1525:2019.

The lowest OTTV was calculated for Building I (92.81 W/m^2), which is the case study with Modular Green Wall and concrete wall for the facade. The orientation of the building also can affect the overall building OTTV. The second lowest OTTV value is building J at 92.83 W/m^2. The calculations for OTTV reduction and the percentage of reduction are shown in the formulas below.

OTTV Reduction = Baseline case study (A/F) - Hypothetical case study building with VGS (B1-J) Formula (6)

Percentage of Reduction = [Baseline case study building (A/F)] – [Hypothetical case study building with VGS (B1-J)] / [Baseline case study (A/F)] x 100% Formula (7)

Sample of calculation for B1:

$OTTV_1 = 15\alpha(1\text{-}WWR)\ U_W + 6(WWR)\ U_f + (194 \times OF \ x \ WWR \ x \ SC)$

$OTTV_N = 15\alpha(1\text{-}WWR)\ U_W + 6(WWR)U_f + (194 \times OF \ x \ WWR \ x \ SC)$

$= 15(0.45)\ (1\text{-}0.67)\ 1.15 + 6(0.67)\ 1.2 + (194 \times 0.90 \ x \ 0.67 \times 0.67)$

$= 2.55 + 4.84 + 78.61$

$= 86.00$ W/m^2

$OTTV_E = 15\alpha(1\text{-}WWR)\ U_W + 6(WWR)U_f + (194 \times OF \ x \ WWR \ x \ SC)$

$= 15(0.45)\ (1\text{-}0.67)\ 2.13 + 6(0.67)\ 1.2 + (194 \times 1.23 \ x \ 0.67 \times 0.71)$

$= 4.72 + 4.84 + 113.85$

$= 123.40$ W/m^2

$OTTV_S = 15\alpha(1\text{-}WWR)\ U_W + 6(WWR)U_f + (194 \times OF \ x \ WWR \ x \ SC)$

$= 15(0.45)\ (1\text{-}0.67)\ 2.13 + 6(0.67)\ 1.2 + (194 \times 0.92 \ x \ 0.67 \times 0.71)$

$= 4.72 + 4.84 + 85.16$

$= 94.71$ W/m^2

$OTTV_W = 15\alpha(1\text{-}WWR)\ U_W + 6(WWR)U_f + (194 \times OF \ x \ WWR \ x \ SC)$

$= 15(0.45)\ (1\text{-}0.67)\ 2.13 + 6(0.67)\ 1.2 + (194 \times 0.94 \ x \ 0.67 \times 0.71)$

$= 4.72 + 4.84 + 87.01$

$= 96.56$ W/m^2

Therefore,

$OTTV = (A_1 \ x \ OTTV_1) + (A_2 \ x \ OTTV_2) + \ldots + (A_n \ x \ OTTV_n) / A_1 + A_2 + \ldots + A_n$

$OTTV = (A_S \ x \ OTTV_S) + (A_E \ x \ OTTV_E) + (A_N \ x \ OTTV_N) + (A_W \ x \ OTTV_W) / A_S + A_E + A_N + A_W$

$= (225 \times 86.00) + (225 \times 123.40) + (225 \times 94.71) + (225 \times 96.56) / 225 + 225 + 225 + 225$

$= 100.17$ W/m^2

OTTV Reduction (B1) = Baseline case study building (A) – Hypothetical case study building with VGS (B1)

$= 101.88 – 100.17$

$= 1.71$ W/m^2

Finally,

Percentage of Reduction = [(Baseline case study building (A)-(Hypothetical case study building with VGS (B1) / Baseline case study (A)] x 100%

$= [(101.88–100.17) / 101.88] \ x \ 100\%$

$= 1.68\%$

Table 7
Shading coefficient used for the calculation.

Case Study	Orientation	R1 ($\frac{\textit{Horizontal projection}}{\textit{window height}}$)	R2 ($\frac{\textit{Vertical projection}}{\textit{window width}}$)	SC1	SC2	SC
A	–	–	.	0.71	1	0.71
B1	North	0.03	0.02		0.94	0.67
B2	East				0.97	0.69
B3	South				0.94	0.67
B4	West				0.97	0.69
C1	North	0.07	0.05		0.87	0.62
C2	East				0.91	0.65
C3	South				0.87	0.62
C4	West				0.91	0.65
D1	North	0.20	0.16		0.71	0.50
D2	East				0.77	0.55
D3	South				0.71	0.50
D4	West				0.77	0.55
E1	North	0.35	0.27		0.71	0.50
E2	East				0.77	0.55
E3	South				0.71	0.50
E4	West				0.77	0.55
F	–	–	–		1	0.71
G	West	0.03	0.02		0.97	0.69
H	South	0.07	0.05		0.87	0.62
I	East	0.20	0.16		0.77	0.55
J	North	0.35	0.27		0.71	0.50

R1 = Projection/Window Height.
R2 = Projection/Window Width.
SC = Effective shading coefficient of the fenestration system.
SC1 = Shading coefficient of sub-system 1 (e.g., glass); and.
SC2 = Shading coefficient of sub-system 2 (e.g., external shading device.

3.2. OTTV reduction for type of building façade and VGS

Different types of VGS can affect the overall building OTTV. Four different types of VGS were applied to this study - Direct Green Facades, Double-skin Green Facades, Modular Green Wall, and Linear Green Wall. Table 9 shows the case studies according to orientation and type of building facade, which are B4, C3, D2, and E1 for buildings with brick walls and G, H, I, and J for buildings with concrete walls. Buildings B4 and G were compared together, as both have the same type of VGS and building orientation, namely the Direct Green Facades located on the West orientation. This is also applied to buildings C3, H, D2, I, E1, and J.

Based on Fig. 5, the reduction percentages for Direct Green Facades that are located at brick wall's building façade are slightly higher compared to concrete wall. The other type of VGS also showed similar results, most notably the VGS located at the brick wall is slightly higher compared to the concrete wall. This result might be due to the unique U-values for each building facade. The highest reduction with the brick wall belongs to building D2, whereas for the concrete wall is building I which has Modular Green Facades and is located at the Eastern orientation (see Fig. 5). The lowest reduction calculated were buildings with Direct Green Facades and are located on a West orientation, which is buildings B4 and G with brick wall and concrete wall respectively (see Fig. 5).

The thickness and the U-value of the greenery system can influence the building's OTTV and thermal performances (see Table 9). The higher the U-value of the greenery system, the lower the reduction percentages. For example, building D2 with the U-value of 0.40 W/m^{2}K, could reduce 7.40 W/m^2 for its OTTV value. For building G with Direct Green Facades and 2.50 W/m^{2}K of U-value, it only reduced 0.80 W/m^2 for its OTTV value. Thus, it can be concluded that the U-value of the greenery system can substantially affect a building's overall OTTV value.

3.3. Building orientation and shading coefficient

Building orientation also influences VGS OTTV reduction, where different orientations have different maximum allowable shading coefficients. Fig. 6 shows the VGS OTTV reduction based on building orientation. Building B3 and C3 that have Direct Green Facades and Double-skin Green Facades located at South orientation have the highest VGS OTTV reduction compared to other orientations. Buildings D2 and E2 that have Modular Green Wall and Linear Green Wall located at East orientation have higher VGS OTTV reductions which are 7.26% and 7.33% respectively (see Table 10). Buildings D2 and E2 might have higher VGS OTTV reduction values due to the value of shading coefficient being lower than 0.60, as compared to buildings B3 and C3 which have shading coefficient value more than 0.60 (see Table 10). Therefore, it can be concluded that buildings with a shading coefficient of more than 0.6 have a better VGS OTTV reduction when located at South, whereas buildings with a shading coefficient less than 0.6 have a better VGS OTTV reduction when located at Eastern orientation.

4. Discussion

The heat transfer reduction was predicted using theoretical case study buildings with different types of VGS and building orientations with different U-values. The average VGS OTTV reduction was based on the different types of VGS. From the prediction, Direct Green Facades had the highest U-value at 2.50 W/m^{2}K, while the Linear Green Wall had the lowest U-value at 0.24 W/m^{2}K (see Table 11). For the average VGS OTTV reduction, Direct Green Facades achieved the lowest reduction at 1.32%, while the highest reduction was for Linear Green Wall at 6.87% (see Table 11).

From the findings, it can be concluded that the Modular Green Wall and Linear Green Wall with brick wall construction are the best vertical greenery systems to reduce the heat transfer (OTTV) in a tropical climate region, throughout all four orientations. The highest OTTV reduction was achieved with Linear Green Wall (living wall) on the East orientation with a 7.33% reduction, while the lowest is the Direct Green

Table 8
OTTV reduction for the theoretical case study building.

Case study	Type of building facade	Type of VGS used	Orientation	Total U-value (W/m^{2}K)	Shading Coefficient (SC)	OTTV (W/m^2)	OTTV Reduction (W/m^2)	Percentage of Reduction (%)
A (Baseline)	Brick wall	–	–	2.13	0.71	101.88	–	–
B1		Direct Green Facades	North	1.15	0.67	100.17	1.71	1.68
B2			East		0.69	100.54	1.34	1.32
B3			South		0.67	100.14	1.74	1.71
B4			West		0.69	100.73	1.15	1.13
C1		Double-skin Green Facades	North	0.93	0.62	98.58	3.3	3.24
C2			East		0.65	98.81	3.07	3.01
C3			South		0.62	98.52	3.36	3.30
C4			West		0.65	99.38	2.5	2.45
D1		Modular Green Wall	North	0.34	0.5	94.73	7.15	7.02
D2			East		0.55	94.48	7.4	7.26
D3			South		0.5	94.60	7.28	7.15
D4			West		0.55	95.99	5.89	5.78
E1		Linear Green Wall	North	0.21	0.5	94.66	7.22	7.09
E2			East		0.55	94.41	7.47	7.33
E3			South		0.5	94.52	7.36	7.22
E4			West		0.55	95.92	5.96	5.85
F (Baseline)	Concrete wall	–	–	1.14	0.71	99.68	–	–
G		Direct Green Facades	West	0.78	0.67	98.88	0.80	0.80
H		Double-skin Green Facades	South	0.68	0.62	96.8	2.88	2.89
I		Modular Green Wall	East	0.30	0.55	92.81	6.87	6.89
J		Linear Green Wall	North	0.12	0.5	92.83	6.85	6.87

Facades (green facade) on the West orientation with only 1.13% (see Table 8). Similarly, research conducted by Safikani et al. [42] found that living walls can provide better thermal performance than green facades, as living walls are constructed with growing media that serves as an extra insulating thermal layer for the building façade. Additionally, research by Jaafar et al. [56] found that green walls with a modular system can reduce surface temperatures more than a green wall with a cable system, due to the sun exposure and penetration towards the wall.

Based on the OTTV reduction results, the building's thermal performance can be improved by applying any type of VGS, which can be further enhanced when paired with the shading coefficient of the glass panel or windows of the building. Table 12 shows the VGS OTTV reduction based on the shading coefficient that was found to produce the highest OTTV reduction based on orientation. The highest VGS OTTV reduction was calculated by building E2 with a 7.33% reduction as the Linear Green Wall on the East orientation with a shading coefficient of 0.55.

The type of VGS used can influence the interior of a building's thermal performance, as well as the shading coefficient of the VGS (see Table 7), where the lower the shading coefficient, the higher the reduction of OTTV value (see Tables 10 and 11). Consequently, the orientation of the VGS also can influence the thermal performance of the indoor environment in optimizing the OTTV reduction, as the orientation affects the shading coefficient values. Calculations from Table 10 show that if the VGS shading coefficient value is higher than 0.6, the best orientation for a tropical country like Malaysia - the VGS should be located on the South orientation. If the VGS shading coefficient value is less than 0.6, the best orientation for the VGS is located on the East orientation. Similarly, research performed by Jim [57] for the subtropical climatic region of Hong Kong, shows that the East and South wall orientation can provide higher cooling-effect as it has better exposure to solar irradiance compared to West and North. Another study conducted by Acero et al. [58] in Singapore, which has a similar tropical climate as Malaysia, stated that the highest thermal reduction on the facade surface temperature occurs on East facades orientations.

In this paper, the U-Value and shading coefficient of the VGS was based on previous research data available and simulated to predict outcomes for the hypothetical case studies. Therefore, to improve on this paper, further study based on the U-Value and shading coefficient of each of the greenery systems can be done by measuring the thermal transference reduction on a real building case study. The thermal reduction effect of the VGS prediction is only limited to the interior thermal reduction of the case studies, and implications to its surrounding thermal effect are out of the scope of this paper. These findings are also limited to Malaysia's geographical location and tropical climate conditions.

5. Conclusion

Vertical greenery systems (VGS) provide numerous advantages for occupants, the economy, and the environment. This study investigated the impact of the different VGS types on building OTTV and based on the calculations made in this study, VGS can substantially impact the interior building thermal performance. The findings of this paper highlighted that with the installation of VGS, a building OTTV can be reduced by up to 7.47 W/m^2 or 7.33%. This helps to reduce the overall cooling load demand, which is the highest percentage of the end-use energy consummation in a tropical climate. However, there are myriads of VGSs available in the industry where VGS can be installed with different design types, of plants, or the system used. In this paper, the U-value and shading coefficient of the VGS was based on previous research data that was used to predict outcomes for the hypothetical case studies. The Linear Green Wall calculation provided the best VGS thermal performance effect, achieving higher OTTV reduction in Malaysia's tropical climate condition and geographical location. Additionally, the VGS orientation also influences the VGS effectiveness for optimum OTTV

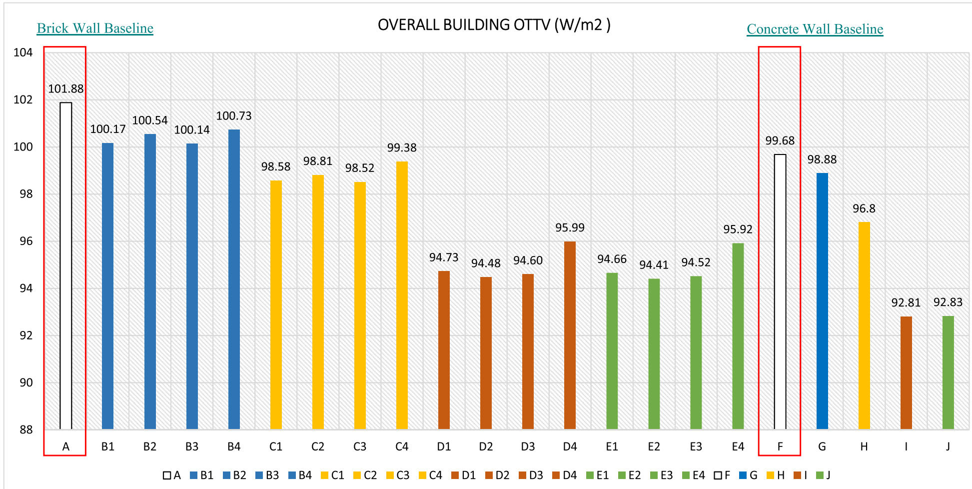

Fig. 4. Overall building OTTV for the theoretical case study buildings.

Table 9
OTTV reduction based on the type of building façade.

Type of VGS	Orientation	Case Study	Type of building facade	OTTV Reduction (W/m^2)	Percentage OTTV Reduction (%)	U-value of VGS (W/m^{2}K)
Direct Green Facades	West	B4	Brick wall	1.15	1.13	2.50
		G	Concrete wall	0.80	0.80	
Double-skin Green Facades	South	C3	Brick wall	3.36	3.30	1.66
		H	Concrete wall	2.88	2.89	
Modular Green Wall	East	D2	Brick wall	7.40	7.26	0.40
		I	Concrete wall	6.87	6.89	
Linear Green Wall	North	E1	Brick wall	7.22	7.09	0.24
		J	Concrete wall	6.85	6.87	

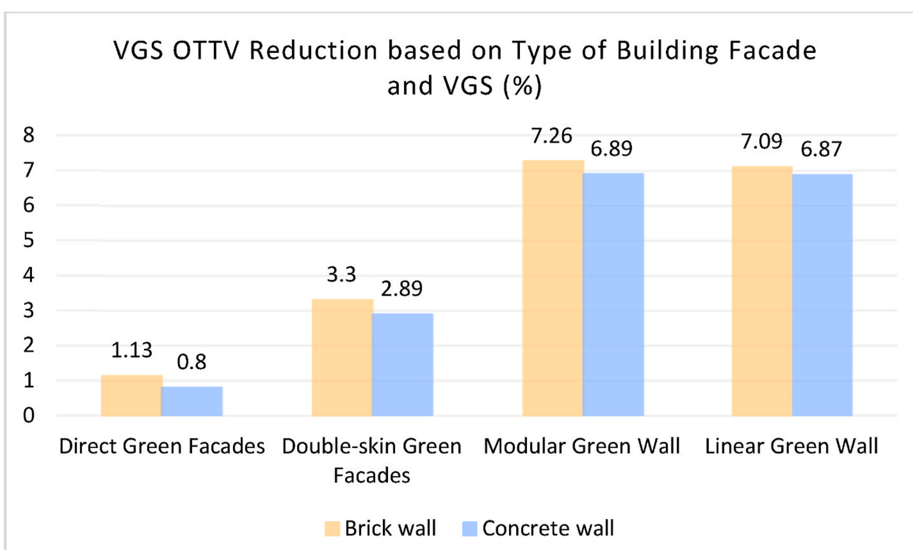

Fig. 5. OTTV reduction based on the type of building facade and VGS.

reduction with differing orientation factors affecting the shading coefficient value. Thus, for a VGS with more than 0.6 shading coefficient value, the best orientation for the VGS is the South orientation, based on the geography of Malaysia. If the shading coefficient values of VGS are less than 0.6, the best orientation for the VGS will be an Eastern orientation. Therefore, this paper has presented new insights for OTTV reduction and thermal influence of VGS in tropical climates that can increase public and building stakeholder's awareness regarding the benefits and advantages of VGS. Additionally, this paper provided technical knowledge and guidance on data computation using basic calculations with Microsoft Excel software. Thus, this data computation method can be easily replicated for other researchers in the tropical climate using the same OTTV formula. The findings of this paper provided various options for the Malaysian stakeholders based on the existing types of VGS available in the industry and their corresponding thermal benefits.

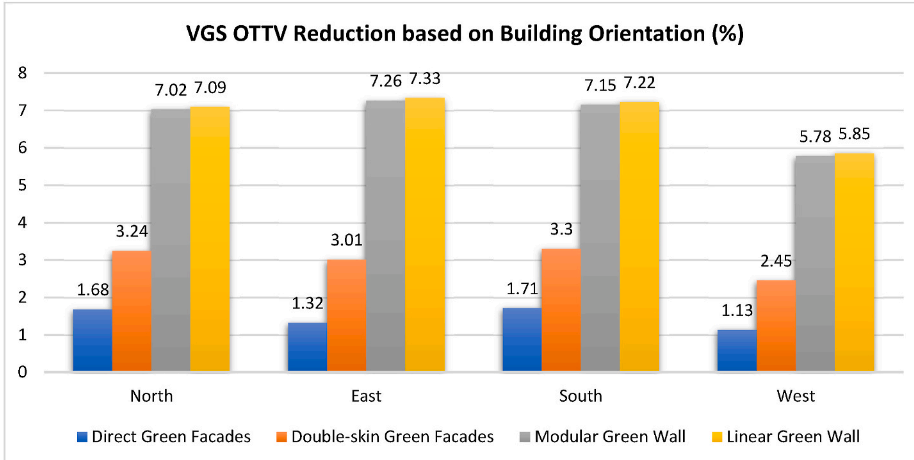

Fig. 6. VGS OTTV reduction based on the Building Orientation.

Table 10
Shading coefficient (SC) of VGS and building orientations.

Case Study	Type of VGS	Orientation	Shading coefficient (SC)	Total U-value (W/m^{2}K)	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

Table 11
Average of VGS OTTV Reduction based on Type of VGS.

Type of VGS	U-value of VGS (W/m^{2}K)	Average VGS OTTV Reduction (%)
Linear Green Wall	0.24	6.87
Modular Green Wall	0.40	6.82
Double-skin Green Facades	1.66	2.97
Direct Green Facades	2.50	1.32

Table 12
VGS OTTV Reduction based on Shading Coefficient.

Type of VGS	Case Study	Orientation	Shading coefficient (SC)	VGS OTTV Reduction (%)
Linear Green Wall	E2		0.55	7.33
Modular Green Wall	D2	East	0.55	7.26
Double-skin Green Facades	C3		0.62	3.30
Direct Green Facades	B3	South	0.67	1.71

Statement of authors role

Nur Dinie Afiqah Mohammad Shuhaimi: Main content writing, Data analysis and editing.

Suzaini Mohamed Zaid: Main content writing, Data analysis and editing

Masoud Esfandiari: Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data

Eric Lou: Verification of the overall reproducibility of results and other research outputs

Norhayati Mahyuddin: Verification of the OTTV formula based on MS1525:2019 and all the OTTV calculations

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper titled *The Impact of Vertical Greenery System on Thermal Performance in Tropical Climate.*

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