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THE EFFECT OF VERTICAL GREENERY SYSTEMS ON BUILDING ENERGY PERFORMANCE: OVERALL THERMAL TRANSFER VALUE-BASED COMPARATIVE ANALYSIS

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ABSTRACT

The construction industry significantly contributes to world energy consumption, representing around 40% of overall energy usage and a considerable portion of greenhouse gas emissions. Tropical cities are exploring sustainable solutions, and passive cooling systems like Vertical Greenery Systems (VGSs) have drawn interest for their potential to enhance energy efficiency. This study examines the influence of VGSs on the energy performance of high-rise buildings in Sri Lanka, utilising the Overall Thermal Transfer Value (OTTV) as the key performance metric. Two high-rise buildings were evaluated: one with a VGS-integrated façade and the other with a standard design without vertical greenery. OTTV were computed using standardised procedures that consider local climate data and envelope features. The OTTV analysis indicates a favourable impact from VGS integrated building, as the average OTTV reduced from 3.681 W/m² in the VGS absence of VGS to 3.527 W/m² with VGS present. The nearly 4.18% reduction appears modest, indicating a considerable improvement in thermal performance. These findings suggest that while VGSs may not drastically reduce OTTV in isolation, they contribute positively to overall energy efficiency strategies in tropical urban settings. The findings offer robust empirical support for the integration of vertical green systems into urban construction plans in tropical environments. This study contributes to the limited body of knowledge on VGS applications in South Asia and advocates for the integration of nature-based solutions in urban building practices. It provides practical insights for architects, policymakers, and green building consultants aiming for energy efficiency and climate resilience in the built environment.

Keywords: *Building Energy Performance; High-rise Buildings; Overall Thermal Transfer Value; Tropical climate; Vertical Greenery System.*

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1. INTRODUCTION

In recent years, the swift pace of urbanization combined with global warming has intensified concerns over Urban Heat Island (UHI) effects and the rising energy demand for building cooling (Shah et al., 2023). At present, buildings account for approximately 40% of energy consumption (Martínez-Rocamora et al., 2016) and 39% of global greenhouse gas (GHG) emissions (Chen et al., 2023), largely resulting from fuel combustion to satisfy their energy requirements (Vijerathne et al., 2022). Consequently, energy conservation has become even more compelling (Demski et al., 2018). Given that air-conditioning (AC) cooling accounts for around 37% of total building energy use globally and up to 56% in tropical regions, increasing temperatures, partly driven by the performance of these AC systems, are expected to elevate energy consumption further, creating a self-reinforcing cycle (Katili et al., 2015). The building envelope, which separates indoor spaces from the external environment, can be optimized to reduce heating and cooling energy needs, as its design greatly impacts both the building's cooling demand and the surrounding environment (Al-Yasiri & Szabó, 2021; Pérez et al., 2017; Shah et al., 2023). Implementing efficient envelope systems can potentially lower total building energy consumption by more than 50% (Al-Masrani et al., 2018).

Energy-efficient technologies help reduce building energy consumption, lower costs, and lessen environmental impacts, including contributions to global climate change (Lee et al., 2015). Many design features in a building and façade characteristics hold huge potential in predicting energy use intensity for each construction (Martinez & Choi, 2017). The adoption of energy-efficient technologies in buildings offers a promising solution to reduce energy consumption, lower costs, and mitigate environmental impacts, particularly those linked to climate change (Lee et al., 2015). To investigate the correlation between the building façade characteristics and the energy efficiency of buildings, it was found that possibly much smaller energy use may result from determining the optimal combinations of façade attribute resolutions (Martinez & Choi, 2017). Accordingly, buildings that integrate green architecture and engineering principles, along with innovative energy-efficient technologies, enhance environmental sustainability, improve energy performance, and contribute significantly to climate change mitigation while remaining economically beneficial (Vijerathne et al., 2024). Green Architecture emphasizes integrating buildings with local ecosystems and the global environment, with a key passive design strategy being the development of an energy-efficient building skin that minimizes heat gain and captures cooling breezes (Haggag, 2010). In this context, passive cooling emerges as a fundamental approach, utilizing design features and technologies that reduce indoor temperatures with minimal or no energy consumption, thereby playing a critical role in enhancing building energy efficiency and thermal comfort (Oropeza-Perez & Østergaard, 2018). Accordingly, Vertical Greenery Systems (VGS), commonly referred to as green walls, have become vital elements of green infrastructure, delivering significant benefits for both current and long-term environmental goals (Jayasooriya et al., 2025), and stand out as one of the most promising solutions as a feature of passive green architecture. Green walls and roofs further offer multiple environmental benefits, including cooling urban areas, mitigating climate change, improving thermal comfort and air quality, reducing noise pollution and greenhouse gas emissions, enhancing heat transfer and thermal performance, and lowering annual energy demand, thereby decreasing the need for mechanical heating and cooling (Daemei et al., 2021). Accordingly, through the strategic use of shading, insulation, and vegetation, green walls can significantly reduce heat buildup, leading to indoor temperature drops of up to 10 °C (Jayasooriya et al., 2025). Moreover, the vegetation functions as a natural thermal barrier, which can cut energy consumption by up to 20% (Haggag, 2010).

In building science, the VGSs are regarded as not only having aesthetic appeal but also forming an integral part of passive cooling design; thus, they can significantly enhance energy savings. Their application is particularly valuable in densely populated urban areas, where green facades are often integrated into building envelopes (Jim et al., 2011). The potential of VGS is especially notable in low- to mid-rise residential, industrial, and commercial buildings, where green facades can play a critical role in improving thermal performance (Widiastuti et al., 2018). As a passive energy-saving solution, green facades contribute to indoor comfort and reduce reliance on mechanical cooling systems, making them particularly suitable for warm climates (Coma et al., 2017; Convertino et al., 2022). The thermal benefits of VGS in enhancing comfort, reducing indoor temperatures, and cutting energy use remain underexplored, with limited research and technical knowledge available, particularly in tropical climates (Shuhaimi et al., 2022). However, despite these promising benefits, the thermal performance of VGS remains underexplored, with limited research and technical knowledge available, especially in tropical regions. While VGS shows great potential in enhancing the energy performance of buildings, particularly commercial ones, current findings are still limited and somewhat inconclusive. Although studies suggest VGS can increase thermal lag and lower cooling loads (Widiastuti et al., 2018), further research is essential to fully understand its effectiveness across various climates and building types.

Moreover, green walls are widely used internationally and, although still limited in Sri Lanka, are gaining popularity. Given this growing trend, it is important to evaluate their thermal performance, as the materials used can significantly affect a building's cooling demand (Senalankadhikara et al., 2022). The Overall Thermal Transfer Value (OTTV), which measures the average heat gain through a building envelope, is a widely adopted metric for promoting energy-efficient building design (Chan & Chow, 2013). It serves as a basis for comparing the thermal performance of different buildings. Accordingly, this study aims to evaluate the influence of VGS on the energy performance of high-rise buildings in Sri Lanka. A comparative analysis will be conducted using the OTTV of two buildings, one incorporating VGS and the other without, to assess the effectiveness of VGS in enhancing thermal performance and reducing energy demand. Accordingly, 03 objectives were formulated: (i) To review the importance of VGS as a passive mechanism for energy performance improvements in buildings, (ii) To identify measures and techniques to evaluate the impact of VGS on energy efficiency in Buildings emphasizing OTTV and (iii) To evaluate the effect of VGS on the building energy performance of high-rise buildings in Sri Lanka based on OTTV.

2. LITERATURE REVIEW

Many factors have a major influence on reducing the energy consumption in the building sector such double glazed windows, vertical greenery systems (VGS), integrating of semi-transparent photovoltaic device with architectural design of buildings, energy saving by using heat reflecting coating, passive climate control methods, energy saving by shading, building energy performance enhancement by using optimisation technique, double skin green facade, etc. (Akram et al., 2023). Accordingly, two primary energy-saving techniques are employed to reduce the energy load on buildings: active energy-saving techniques and passive energy-saving techniques (Chetan et al., 2020). Active energy-saving techniques are mechanical devices that employ heat and electricity as a power source to meet a building's cooling needs that are not naturally provided (Oropeza-Perez & Østergaard, 2018). Passive energy saving is a design or technical feature used to improve the energy efficiency of buildings by cooling them with minimal energy consumption (Geetha & Velra, 2013). Passive energy-saving mechanisms include shading devices like overhangs and self-shading façades to reduce heat gain, and advanced glazing systems that limit heat transfer while allowing daylight (Aldawoud, 2013). Natural ventilation strategies, such as solar chimneys and nighttime cooling, improve airflow and indoor air quality (Carli & Giuli, 2009). Phase change materials help stabilize temperatures by storing and releasing heat, while radiant heat barriers reflect solar radiation to enhance insulation (Al-Yasiri & Szabó, 2021). Innovations like eco-evaporation cooling and adaptive façades further boost energy efficiency and indoor comfort without relying on mechanical systems (Amirifard et al., 2019). VGS has emerged as a significant passive energy-saving mechanism in urban environments, contributing to energy efficiency and sustainability. Vertical vegetation creates a more aesthetically pleasant and improved environment, which has the greatest social relevance (Leong et al., 2021). VGS is a crucial part of urban planning as studies show that being among greenery may enhance mental health and well-being (Poulsen et al., 2020). The health and well-being of urban dwellers can be improved by vertical landscaping as plants in vertical gardens can absorb pollutants and particulate matter, serving as natural air filters (Yu et al., 2016). According to Jaafar et al. (2011), the cooling impact of VGS can result in significant energy savings, especially in high-rise structures where conventional cooling techniques might not be as successful, and buildings can become more energy-efficient by using less energy for cooling because of the shadowing that vertical flora provides (Campiotti et al., 2022).

2.1 THE EFFECT OF VGS ON ENERGY PERFORMANCE

VGS significantly enhances building energy performance by shading facades and mitigating the effects of direct solar radiation (Widiastuti et al., 2018). In tropical regions, VGSs help to regulate interior temperatures, reducing the cooling energy demands and improving overall building efficiency (Wang et al., 2016). These systems lower surface temperatures by up to 20°C compared to conventional building materials, thereby decreasing the cooling energy requirements during hot weather (Cuce et al., 2018). Additionally, the cooling effect of plants, facilitated through processes like evapotranspiration, further reduces the dependence on air conditioning (Pan et al., 2020). During colder months, VGSs function as windbreaks, minimizing heat loss and reducing heating energy consumption by around 25% (Cuce et al., 2018). VGS contributes to energy savings at both the building and urban levels by minimizing active cooling loads (Pérez et al., 2017). Studies highlight that passive cooling from vertical gardens reduces the energy loads of air conditioning systems, which are typically energy-intensive (Davis et al., 2019). In urban settings, VGSs mitigate UHI effects, reducing surface temperatures and curbing heat transfer to building envelopes (Coma et al., 2017). Comparative analyses of green walls and green façades reveal variations in energy efficiency based on daily solar irradiation and environmental factors, with substantial reductions in AC energy consumption observed in Mediterranean climates (Perini et al., 2017).

2.2 MEASURING THE EFFECT OF VGS

The assessment of the influence of VGS on energy efficiency in buildings is a complex study domain (Coma et al., 2017). Diverse technologies and approaches have been established to evaluate the efficacy of VGS in improving energy efficiency in buildings (Akram et al., 2023). VGS enhances heat resistance primarily through the insulating qualities of the vegetation and substrate materials (Blanco et al., 2018). Research indicates that the heat resistance (R- R-value) of VGS can be affected by several aspects, such as the species of plants utilized, the substrate thickness, and the system's design (Blanco et al., 2018). According to Evangelisti et al. (2015), thermal resistance of a layer can be calculated by Ri=$di\lambda i$, where Ri is thermal resistivity; di is the thickness of the specific layer; λi is its thermal conductivity. Further, total thermal resistance can be calculated by $Rtotal$= Rsi+ΣRii+Rse, where $Rtotal$ is the total thermal resistance including the internal and external surface resistances Rsi and $Rse,$ respectively.

Research reveals that VGS can dramatically lower interior air temperatures, hence minimizing the cooling demand on buildings (Perini et al., 2017). Additionally, the efficiency of VGS in decreasing cooling loads is impacted by the interior heat loads of buildings, as emphasized by Coma et al. (2017). who discovered that energy savings might reach up to 58% when VGS are implemented successfully (Coma et al., 2017). According to Pan et al. (2020), the cooling load of VGS can be calculated by Qfabric = U·A·ΔT = U·A· (T out – T in), where U is the heat transfer coefficient, in W/m2 ºC; A is the surface area of each wall, in m2; while ΔT is the difference between Tin and Tout, in ºC (Pan et al., 2020). Another essential part of analysing VGS implications is the use of OTTV estimations (Alghamdi & Alviz-Meza, 2023). Research by Bahdad et al. (2021) expressed that OTTV in their study of vertical green walls, emphasizing how these systems might increase cooling efficiency in residential buildings. Additionally, the study by Pérez et al. (2017) analysed numerous VGS applications and their passive energy-saving potential, emphasizing the relevance of OTTV in assessing the thermal performance of these systems. In addition to that, Kunchornrat et al. (2009) express the OTTV equation by considering 3 main elements. Such as conduction of heat through opaque walls, heat conduction of glass windows, and glass window solar radiation. According to that Singhpoo et al. (2015) expresses the OTTV equation as, $OTTV$= $TDeq$×(1−WWR)×Uw+ΔT×WWR×Uf +SF×WWR×SC, where, OTTV= overall thermal transfer value (W/m^2), WWR= window-to-wall ratio, Uw= thermal transmittance of opaque wall (W/m2 ◦C), Uf = thermal transmittance of fenestration (W/m2 ◦C), TDeq = equivalent temperature difference (◦C), ΔT = temperature difference (◦C), SF = solar factor (W/m^2), and SC = shading coefficients of fenestration.

In addition to these techniques, the Leaf Area Index (LAI) has been discovered as a relevant metric in analysing the shading impacts of VGS (Pérez et al., 2022). The study by Pérez et al. (2017) emphasized the importance of LAI and facade orientation on the shadow effect, which directly influences energy savings by limiting solar heat gain. Although the LAI is one of the most important factors influencing a VGS's thermal impacts, previous research has rarely looked at and compared how LAI affects VGSs' thermal performance (Bakhshoodeh et al., 2022). According to Perera et al. (2021) the LAI can be expressed as LAI=Leaf area/ Ground area. The Solar Heat Gain Coefficient (SHGC) is also applied for analysing the thermal performance of VGS in buildings (Basher et al., 2022). Research has demonstrated that the incorporation of VGS may considerably modify the SHGC of a building's façade (Ahn et al., 2023). The SHGC is calculated as the ratio of Qtotal to Qin, where Qin is the amount of solar radiation entering the building through the glazing, and Qtotal is the total solar radiation incident on the glazing surface; this ratio can be influenced by the specific characteristics of the Vertical Greenery System (VGS) applied to the façade (Ahn et al., 2023). Research reveals that VGS can successfully reduce ambient temperatures through evapotranspiration, hence boosting thermal comfort in urban environments (Blanco et al., 2018). Further evidence for the cooling effect comes from Campiotti et al. (2022) who observe that VGS can function as natural temperature regulators, successfully reducing surface temperatures through transpiration's cooling effects, which can be used as a gauge of VGS's energy efficiency.

Furthermore, the incorporation of VGS into building design is commonly tested by simulation models, tools, and software that anticipate energy consumption and thermal comfort levels (Convertino et al., 2022). For instance, research applying EnergyPlus models has shown that VGS may lead to large energy savings, with anticipated reductions in cooling loads ranging from 35% to 90%, depending on the climatic setting and building orientation. Such simulations can combine many aspects, including climatic data, building orientation, and plant characteristics, to offer a thorough assessment of energy performance (Shuhaimi et al., 2022). These measures were used to evaluate the effect of VGS on building energy performance. Among them, OTTV-based comparative analysis of the effect of VGS on building energy performance will be presented in this paper.

3. RESEARCH METHODOLOGY

The choice of research approach significantly influences the research design, as it determines how data will be collected and analysed. Since Research approaches indicate how data will be gathered and evaluated, the research approach selection has a big impact on the research design. Common research approaches include inductive and deductive reasoning. Inductive approaches involve generating theories based on observations and data, while deductive approaches test existing theories through hypothesis-driven research (Ravishankar & Komarasamy, 2022). The use of a deductive approach within a quantitative research design is well justified in this study, as it enables the investigation to build upon established theoretical frameworks and empirical studies, particularly those examining the relationship between VGS and the thermal performance of building envelopes, which is typically measured using the OTTV (Shuhaimi et al., 2022). The OTTV is selected for this study as it provides a standardized and practical measure of the average heat gain through building envelopes, making it suitable for evaluating and comparing the thermal performance of façade systems, including VGS, in the context of energy-efficient design (Akram et al., 2023; Bahdad et al., 2021; Chan & Chow, 2013; Kunchornrat et al., 2009; Shah et al., 2023; Vighio et al., 2025).

A case study strategy was adopted as the most suitable approach for this investigation, as it allows for an in-depth, context-specific analysis of real-world buildings. The study focused on two high-rise office buildings located in Colombo, Western Province, Sri Lanka. Both buildings were comparable in function, height, orientation, and occupancy type but differed in one key design feature: Building A was constructed using conventional design without vertical greenery, while Building B integrated a Vertical Greenery System (VGS) on selected exterior façades as a passive cooling measure. This comparative case selection was based on purposeful sampling, ensuring that both cases were functionally and climatically similar to isolate the effect of the VGS on thermal performance. The VGS in Building B consisted of modular green wall panels installed on the western and southern façades, designed to provide shading and reduce heat absorption. The buildings were selected to allow a controlled comparison of OTTV values under similar operating and environmental conditions, ensuring the reliability of findings.

Three semi-structured interviews were conducted for each building with industry professionals directly involved in design, operation, or sustainability assessment. Participants were selected through convenience sampling, focusing on professionals with hands-on experience and technical knowledge relevant to energy performance and façade systems. The profile of interviewees is shown in Table 1.

Table 1: Profile of interviewees

Cases	Designation	Years of experience
Case A building without VGS	Energy Consultant	06 years
	MEP Engineer	05 years
	MEP Engineer	08 years
Case B building with VGS	Sustainability Executive	05 years
	MEP Engineer	06 years
	Operations Manager	09 years

The numerical data necessary for calculating the OTTV of the two case buildings were collected from the respondents. The OTTV of each building was then determined using the following equation mentioned below, as recommended and validated in Chan and Chow (2013), Shah et al. (2023), and Vighio et al. (2025). These studies focus on the evaluation and monitoring of OTTV in tropical climates, examining the effects of passive design strategies, façade materials, and green roof applications on building thermal performance.

$$TV = TD_{eq} \times (1 - WWR) \times U_w + \Delta T \times WWR \times U_f + SF \times WWR \times SC \qquad \textit{Equation (1)}$$

Where, OTTV = overall thermal transfer value (W/m^2), WWR = window-to-wall ratio, U_w = thermal transmittance of opaque wall (W/m^2 ◦C), U_f = thermal transmittance of fenestration (W/m^2 ◦C), TDeq = equivalent temperature difference (◦C), ΔT = temperature difference (◦C), SF = solar factor (W/m^2), and SC = shading coefficients of fenestration.

The OTTV of both cases was compared, and the variation in OTTV due to the effect of VGS was subsequently determined. Secondary data sources included documents providing key performance metrics, material information, and other parameters necessary for calculating cooling load values, thermal resistance (R-values), and OTTV before and after the installation of VGS.

4. KEY RESEARCH FINDINGS

As aimed in this study, the OTTV values of both cases were separately calculated as shown below.

4.1 CALCULATION OF OTTV OF CASE A BUILDING

The data collected to calculate the OTTV through interviews are shown in Table 2.

Table 2: Parameters and data collected from the Case A building (without VGS) for OTTV calculation

Parameter	Details Required	Data Provided
Wall Heat Transfer		
Wall Area (m^2)	Total area of the walls	220 m^2 (North and South), 250 m^2 (East and West)
Window Heat Transfer		
Window Area	For the ratio of window area to wall area	78 m^2
Glass U-value ($W/m^2 \cdot K$)	Overall heat transfer coefficient for windows	5.8 $W/m^2 \cdot K$
Other Parameters		
Sol-air Temperature (T_e)	Surface temperature due to solar radiation	106°F (41.11°C)
Shading Coefficient (SC)	Shading coefficient of fenestration	0.4
Solar Factor (SF)	Solar factor for the fenestration	56.5 W/m^2
Thermal Transmittance of Opaque Wall (U_x)	Uw – Wall U-value	0.09 $W/m^2 \cdot °C$
Thermal Transmittance of Fenestration (Uf)	Uf – Single-pane glass	1.12 $W/m^2 \cdot °C$

The thermal transmittance (U-value) of the glass, taken as 5.8 $W/m^2 \cdot K$, was referenced from the study by Kou et al. (2021), which provides empirical data on single-glazed window performance (Kou et al., 2021). Other measures (assuming the measurement is taken on the peak time of 12.00 noon as per the ASHRAE standard)

Total wall area = Northern wall area + Southern wall area + Eastern wall area Western wall area

Total Wall Area = $220\ m^2 + 220\ m^2 + 250\ m^2 + 250\ m^2$

Total Wall Area = $940\ m^2$

Total Window Area = $78\ m^2$

Window to Wall Ratio (WWR) = $\frac{78m^2}{940\ m^2}$

Window to Wall Ratio (WWR) = 0.083 (8.3%)

According to Singhpoo et al. (2015), the equivalent temperature difference (TD_{eq}) can be expressed as,

$TD_{eq} = T_e - T_i$ *Equation (2)*

Where TD_{eq}= equivalent temperature difference, T_e = sol-air temperature and T_i = indoor temperature.

$$TD_{eq} = 41.11°C - 26\ °C$$

$$TD_{eq} = 15.11\ °C$$

Hence,

$$OTTV = (TD_{eq} \times (1 - WWR) \times U_w) + (\Delta T \times WWR \times U_f) + (SF \times WWR \times SC)$$

$$OTTV = (15.11°C \times (1 - 0.083) \times 0.09\, W/m^2\, °C + (32°C - 26°C) \times 0.083 \times 1.12\, W/m^2\, °C + 56.5W/m^2 \times 0.083 \times 0.4$$

$$OTTV = 15.11°C \times 0.917 \times 0.09\, W/m^2\, °C + 6°C \times 0.083 \times 1.12\, W/m^2\, °C + 56.5W/m^2 \times 0.083 \times 0.4$$

$$OTTV = 1.247W/m^2 + 0.558\, W/m^2 + 1.876W/m^2$$

$$\boldsymbol{OTTV = 3.681W/m^2}$$

4.2 CALCULATION OF OTTV OF CASE B BUILDING

The data collected to calculate the OTTV through interviews are shown in Table 3.

Table 3: Parameters and Data Collected from Case B Building (with VGS) for OTTV Calculation)

Parameter	Details Required	Data Provided
Wall Heat Transfer		
Wall Area (m^2)	Total area of the walls	280 m^2 (North and South), 250 m^2 (East and West)
Window Heat Transfer		
Window Area	For the ratio of window area to wall area	80 m^2
Glass U-value ($W/m^2 \cdot K$)	Overall heat transfer coefficient for windows	5.8 $W/m^2 \cdot K$
Other Parameters		
Sol-air Temperature (T_e)	Surface temperature due to solar radiation	106°F (41.11°C)
Shading Coefficient (SC)	Shading coefficient of fenestration	0.4
Solar Factor (SF)	Solar factor for the fenestration	56.5 W/m^2
Thermal Transmittance of Opaque Wall (Uw)	Uw – Wall U-value	0.09 $W/m^2 \cdot °C$
Thermal Transmittance of Fenestration (Uf)	Uf – Double-glazed with ¼" air space	0.68 $W/m^2 \cdot °C$

Total wall area = Northern wall area + Southern wall area + Eastern wall area + Western wall area

Total wall area $= 280\ m^2 + 280\ m^2 + 250\ m^2 + 250\ m^2$

Total wall area $= 1060\ m^2$

Total Window area $= 80\ m^2$

So, Window to Wall Ratio (WWR) $= \frac{80m^2}{1060\ m^2}$

Window to Wall Ratio (WWR) = 0.075 (7.5%)

According to Singhpoo et al. (2015) the equivalent temperature difference can be expressed as,

$$TD_{eq} = T_e - T_i$$

Where TD_{eq}= equivalent temperature difference, T_e = sol-air temperature and T_i = indoor temperature.

$$TD_{eq} = 41.11°C - 24\,°C$$

$$TD_{eq} = 17.11\,°C$$

Hence,

$$OTTV = (TD_{eq} \times (1 - WWR) \times U_w) + (\Delta T \times WWR \times U_f\,) + (SF \times WWR \times SC)$$

$$OTTV = (17.11°C \times (1 - 0.075) \times 0.09\,W/m^2\,°C) + ((32°C - 24°C) \times 0.075 \times 0.68\,W/m^2\,°C) + (56.5W/m^2 \times 0.075 \times 0.4)$$

$$OTTV = (17.11°C \times 0.925 \times 0.09\,W/m^2\,°C) + (8°C \times 0.075 \times 0.68\,W/m^2\,°C) + (56.5W/m^2 \times 0.075 \times 0.4)$$

$$OTTV = 1.424W/m^2 + 0.408\,W/m^2 + 1.695W/m^2$$

$$\boldsymbol{OTTV = 3.527W/m^2}$$

The OTTV analysis confirms a positive contribution of VGS, as reflected by a slight decrease from 3.681 W/m² in the VGS-free building to 3.527 W/m² in the building with VGS. The absolute reduction of OTTV appears modest (approximately 4.18%), however, it is the cumulative effect of reduced heat transfer through opaque walls, fenestration, and solar radiation absorption heat transfer. The relatively small variation of OTTV compared to other calculations might be attributed to the calculation method, which estimates an average effect across the entire envelope and adjusts for many components (walls, windows, shading), as opposed to just the façade with the VGS treatment. Even a slight decrease in OTTV can result in notable long-term energy savings, particularly in energy-intensive buildings, reinforcing the value of VGS as an effective passive design strategy for improving thermal performance.

5. CONCLUSIONS AND A WAY FORWARD

This study assessed the influence of VGS on the energy efficiency of commercial high-rise buildings in Sri Lanka, concentrating on thermal performance as measured by the OTTV. The findings revealed a positive impact of integrating VGS, with the average OTTV decreasing from 3.681 W/m² in the building without VGS (Case A) to 3.527 W/m² in the building with VGS (Case B), indicating a 4.18% improvement in the thermal envelope efficiency. The numerical difference appears moderate, carries substantial implications for long-term energy savings, particularly in densely populated urban areas and tropical regions with constantly elevated cooling demands.

The findings confirm that VGSs significantly enhance passive cooling by improving the insulating characteristics of building façades, diminishing direct solar heat gain, and decreasing thermal transmittance via walls and windows. These technologies additionally facilitate overarching environmental goals by mitigating urban heat island effects and enhancing urban microclimates. In addition to energy efficiency, the integration of vertical greenery provides supplementary advantages, like enhanced air quality, diminished noise levels, and greater psychological well-being for inhabitants. This study addresses a significant gap in the South Asian context by presenting empirical data on the thermal efficiency of VGSs in commercial high-rise structures in tropical climates. It enhances the expanding corpus of knowledge that advocates for nature-based solutions in urban planning and sustainable construction.

While this research offers valuable insights, it is limited to two buildings and focuses solely on OTTV without accounting for dynamic occupant behaviour, HVAC system efficiency, or long-term vegetation performance. Future research should expand to include a wider variety of building typologies, climatic zones, and incorporate long-term monitoring, maintenance, and cost-benefit analyses. The integration of advanced simulation tools with real-time energy monitoring will further enhance understanding of VGS performance over time. Additionally, studying the effects of different plant species, substrate types, and management practices will provide a more comprehensive evaluation of VGS thermal behaviour.

The demonstrated benefits of VGS highlight the need for its integration into national building codes, green building rating systems, and urban development policies. Encouraging the widespread adoption of VGS through incentives, guidelines, and regulatory frameworks can accelerate the transition toward energy-efficient and climate-resilient buildings across Sri Lanka's construction industry. Policymakers, architects, urban planners, and developers should collaborate to incorporate vertical greenery as a standard practice in façade design, especially in high-density urban centres facing rising cooling demands and urban heat challenges. Promoting VGS at an industry-wide level will support national sustainability targets, reduce environmental impacts, and enhance the liveability of urban environments.

Future studies should broaden this approach to encompass a wider array of building typologies and climatic zones, while also addressing long-term performance, maintenance considerations, and cost-benefit assessments. The integration of sophisticated simulation tools and real-time energy monitoring systems can enhance the comprehension of VGS performance over time. In conclusion, although VGS may not alone resolve energy concerns, it constitutes a significant element of a comprehensive design strategy focused on improving thermal performance and environmental sustainability in urban architecture.

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