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Evaluating the efficiency of a living wall facade as a sustainable energy-saving alternative in hot arid regions

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Abstract

Buildings can generate heat from a variety of sources, including building occupants, the sun, lighting and radiance, and cooling equipment, the energy consumed by which results in heat. Egypt is experiencing rapid economic growth, improvements in urban spaces, and a reduction in green space, all of which contribute to the occurrence of environmental problems such as pollutants, increased CO2 emissions, and increased energy consumption. Furthermore, the study focuses on the cases of architectural buildings that have been combined with living green facade as an innovative facade in order to address the energy crisis and climate change. The study on live greening techniques on building facades has raised a lot of interest. The primary purpose of this research is to utilize simulation software to manage the energy consumption usage of a green facade and compare energy demand levels to the basic scenario. Living green façades can offer zone-sensitive cooling on building facades, which is especially important during summer sessions in hot areas. Green facade cooling loads have an effect on interior air quality by keeping the façade from warming up. The research investigates the cooling impact of three types of living green walls in Egypt using Design-Builder simulation software. To estimate the energy consumption rates of the base case building, the Design-Builder simulation program was used in conjunction with the Energy Plus engine. According to the findings, the indirect green façade with planter boxes of green walls has reduced the high energy consumption compared to the buildings with direct and indirect green façade, increased thermal comfort, and reduced CO2 emissions. As a result of the estimation, it was determined that the energy demand standards of the living wall were lower than the energy demand standards of buildings without the living wall of the same measurement, saving 75% of the energy.

Keywords: Energy consumption, Living green wall, Saving energy, Thermal comfort, Hot, Arid climate

Introduction

The Egyptian building stock consists of approximately 12 million buildings, with nearly 60% of them being residential and 40% being commercial [1], indicating the importance of the residential building sector in total energy consumption and thus the priority of more analytical studies to make them green (Fig. 1). Furthermore, during the previous 5 years, the residential sector has been the fastest expanding sector in terms of power consumption [2]. This is mostly due to the growth of residential complexes and new communities, as well as the extensive usage of home equipment, particularly household air conditioners, as a result of hot weather during the summer months [3]. The main problem of this research is the lack of awareness of the importance of green Façades Technology and lacks its usage in Egypt; although very limited research focused on the application of green facades in Egypt, while it is greatly needed in our climate, however many researchers are adapting green facades and they are ignoring the types that are best for hot arid regions. Otherwise, the research's primary goal is to select the most energy-efficient green façade types for our climate.

The major goal of the research is to produce efficient residential structures in terms of thermal comfort, CO2 emissions, and energy consumption in a hot desert climate, utilizing New Cairo, Egypt, as the research case study. This will be accomplished on two fronts. The first is the existing situation, in which buildings will be judged based on their shapes. The second level consists of the present building's green wall techniques. The study employed an inductive analytical technique with the use of computer tools to get its results.

Safikhani et al. [4] describe the investigation of the thermal performance of vertical greenery systems. The living wall and green facade both decreased indoor temperature by up to 4.0 °C and 3.0 °C, respectively [5].

Perini and Rosasco [6] examine the costs and benefits of various vertical greening systems, such as living walls and green façades, from the standpoint of both individual and societal gains. Each assessed system's installation, upkeep, and disposal costs are weighed against the associated personal and societal benefits.

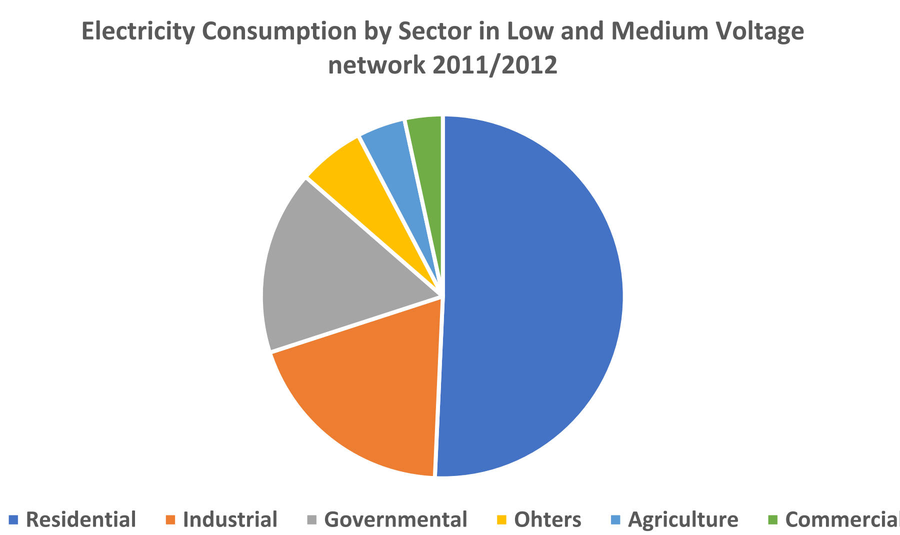


Fig. 1 Electricity consumption by sector at low and medium voltage network for 2011/2012 [3] (Egyptian Electricity Holding Company, 2013)

Residential sector problems

Residential consumption accounted for 41% of overall consumption in 2010/2011. This amount is utilized in 30% for lights and 70% for the usage of electrical equipment, particularly air conditioners in the summer [7].

According to the issues encountered in the development of façade designs, biological solutions should be clearly specified and incorporated into the design of energy-efficient facade systems. Additionally, it is advised that biomimetic project analysis be carried out using energy simulation software and energy performance calculation techniques in order to generate more trustworthy and understandable results [8].

Benefits of green facades and living walls

The successful deployment of green walls for both public and private patrols yields significant benefits [9]. Green walls have the ability to significantly enhance the environment in heavily populated metropolitan areas, given the enormous number of buildings that are suitable for these technologies [10] (Fig. 2).

Vertical plants may increase the energy efficiency of a structure by providing insulation, shade, and transpiration from leaf and substrate moisture. A number of architectural elements can determine how much vertical vegetation enhances energy efficiency [11].

Main types of green vertical garden

A green wall is a form of VGS that may be divided into green facades and living walls, as shown in Fig. 3. Green facades are made up of climbing plants or plants that are tied directly to the building walls or are erected with wires or trellis [12]. Green facades are further defined as classic green facades, double-skinned green facades, or green curtains and adjacent flowerpots, while living walls are further classed as biofiltration living walls or modular living walls [13]. Living walls are built using continuous or modular systems that include growth material and watering systems. Unlike the green wall, the green wall may be put to the top level, giving you additional plant alternatives, and it is suited for indoor use for high-rise buildings [14].

Living walls

A green wall is a method that not only connects vegetation to a building's front but also places both the plants and the planting material on the vertical surface of the outer wall, as seen in Fig. 4 [15].

Fig. 2 Examples of applications of GW, spontaneously or in façade retrofit

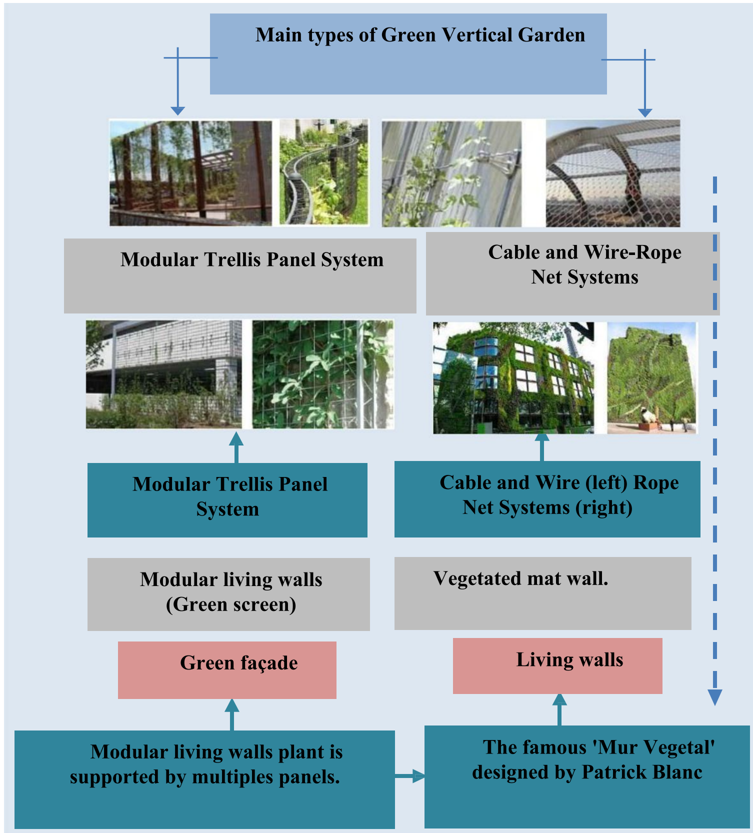


Fig. 3 Vertical greening systems: categories and examples [Ref., Authors]

Fig. 4 Vegetated Mat Walls, Madrid Spain. (https://www.museumofthecity.org2013, https://www.eyeonspain.com2013)

It works effectively in a variety of climates. Yet, the selection of superior species may adapt to the prevailing environmental conditions, making system maintenance easier. Self-automated irrigation and nourishment systems, in general, make living wall care simple [16].

Vegetated mat living walls

Layers of fabric are installed on sturdy steel frames, cast-in-place concrete, or masonry supports to create plant mat wall modules. Nurseries grow plants in holes drilled in a layer of tissue that acts as a growth medium. Vegetated mats are soilless hydroponic systems in which irrigation pipes hidden below fabric layers provide water and nutrients to plant roots [17].

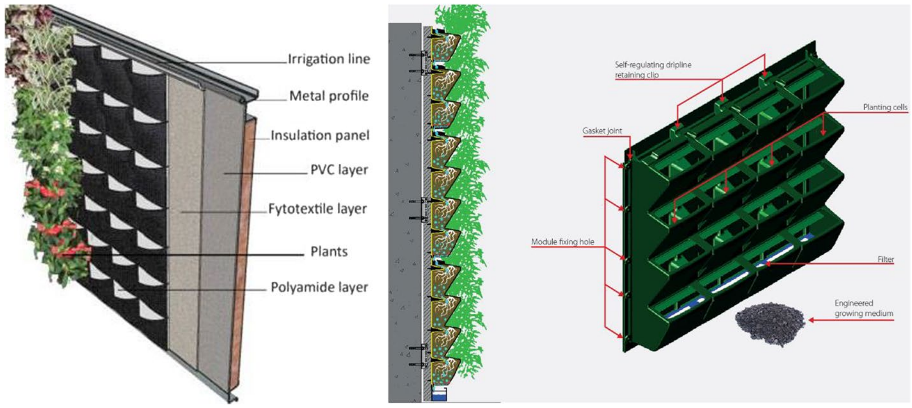


Fig. 5 Hanging pocket living walls and modular living walls system [18]

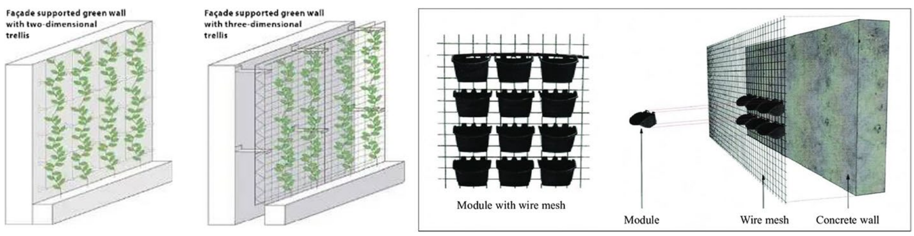


Fig. 6 Modular living wall system https://www.intechopen.com/books/advances-in-landscapearchitecture/vertical-gardens

Hanging pocket living walls

The hanging living bag wall is a cloth bag suspended on solid pillars. Plants grow in these pots, which are filled with soil or nutritional medium as shown in (Fig. 5).

Modular living walls

Modular living walls are solid rectangular containers filled with soil or growth medium that may be connected to or standalone from an outside wall (Fig. 6). Metal or lightweight structural plastic is used to make containers, which may be utilized as framed boxes, wire cages, or rigid boxes with pre-drilled holes. Containers are occasionally split into small individual cells that are perpendicular or sloped to the container's back wall.

Suárez et al. [19] illustrated the esthetic importance; ornamental grasses can be used in living wall or green roof. The plants in the green system benefit from the decorative grasses' varied colors, sizes, and flexibility of the leaves, which create distinctive textures, volumes, and movements. However, the designer must be aware of the species' growth and behavior patterns in order to include them in the design and prevent any conflicts with nearby species.

Vertical greenery system (VGS)

Vertical green systems have been considered for a long time; examples may be found in ancient Babylonian architecture dating back to 600 BC. The Hanging Gardens of Babylon was one of the ancient world's seven marvels [20]. Many perspectives might be seen in the vertical flora. A vertical greenery system, according to Pérez et al. [17] and Bass

Fig. 7 Vertical Greenery Systems classification [25]

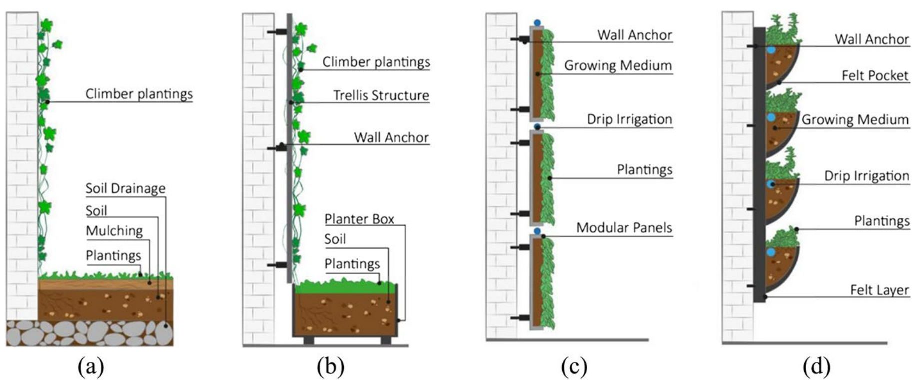


Fig. 8 **a** Direct green façade. **b** Indirect green façade. **c** Indirect green façade with planter box. **d** Green living wall [26]

and Baskaran (2003) [21], is a method of growing plants on, above, or inside the walls of a structure.

Moreover, external wall examinations on existing facades should be performed to check the integrity of wall components. The direct green facades of self-clinging climbers perform well on external walls with rough surfaces, such as brick and concrete. Vine species may grow on any type of external wall material (indirect green facades) [22, 23]. Vines can cling to wooden window frames and trimmings, which are common in older houses, unlike smooth glass or metal frames [24] as seen in Figs. 7 and 8.

According to the study by Shruti (2023), it is best to install a green facade in New Delhi's composite environment with a distance of more than 150 mm between the greenery system and the façade surface. However, the results demonstrate greater discomfort with higher relative humidity when the climate shifts from dry to humid. The study's findings attempt to bridge the gap of the influence of green facades in the Indian climate to see its applicability on a larger scale [27]

Fig. 9 Max Juvenal Bridge, France, after and before the green wall [29]

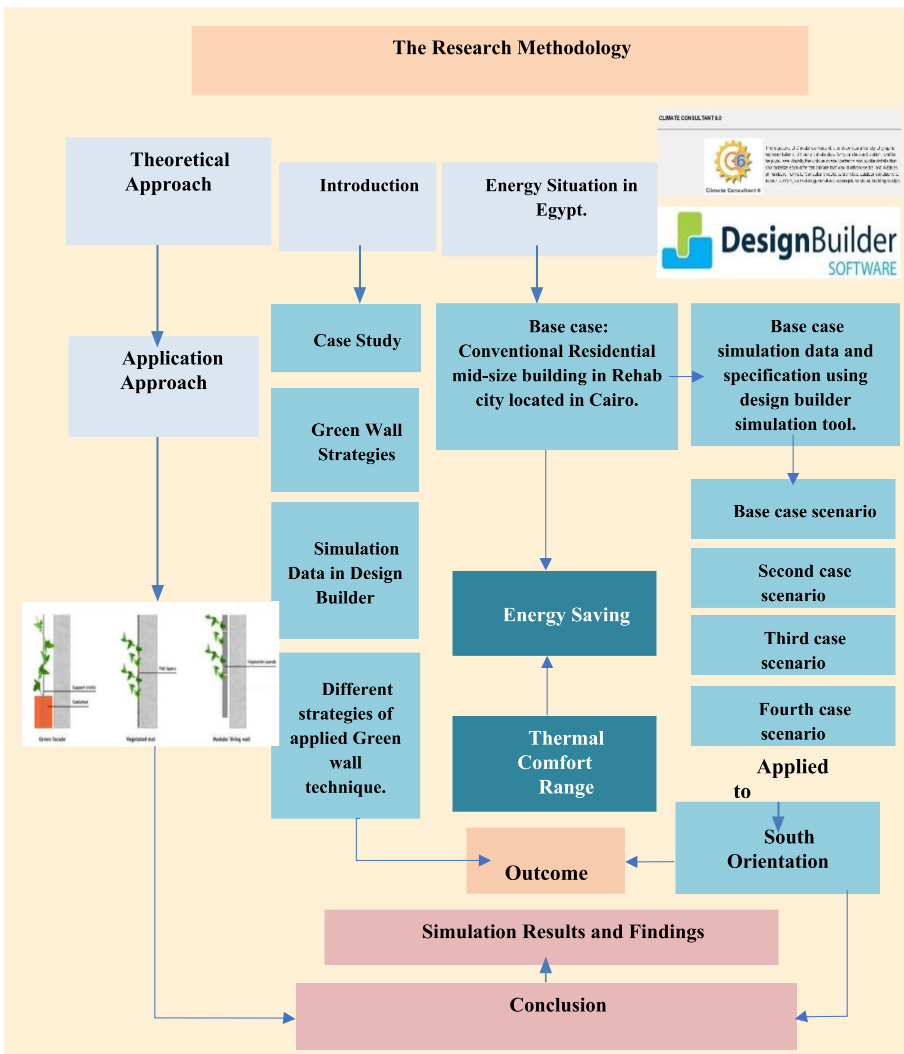


Fig. 10 Research methodology chart [Ref., Authors]

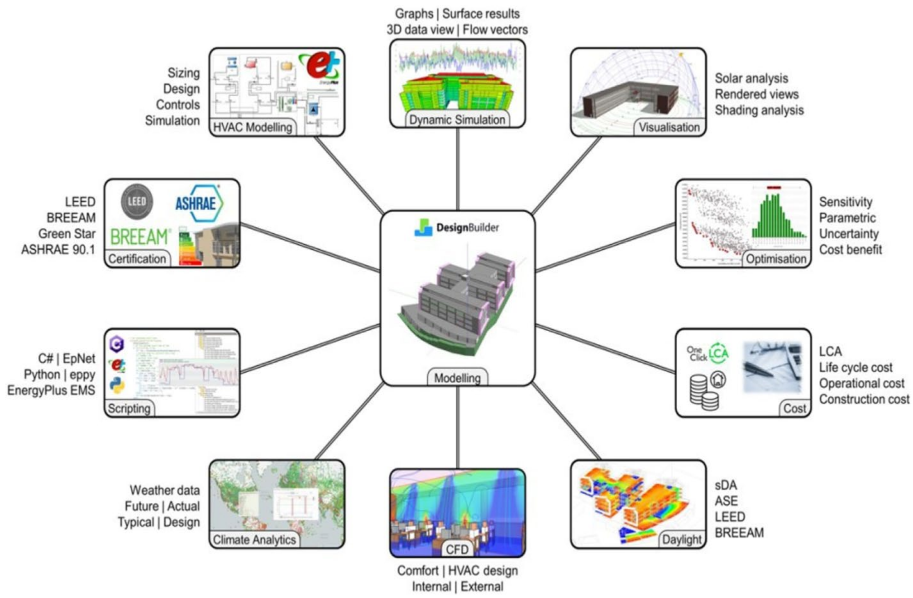


Fig. 11 Energy plus design-builder graphical user interface [31]

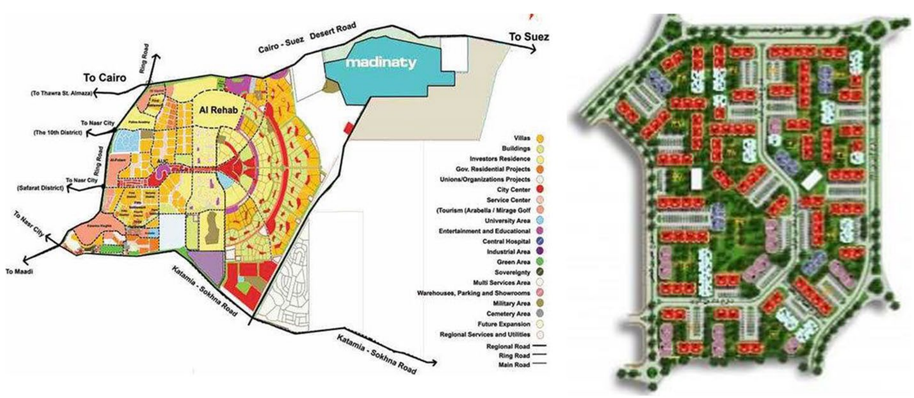


Fig. 12 Location of Al Rehab City masterplan, Cairo, Egypt

Vertical greenery plant selection

Particular attention should be given while selecting plants for green walls. Plants growing on vertical surfaces are more exposed to the elements, particularly high winds, than plants growing on the ground. Hardy plant species local to the temperature zone in which the structure is located are most suitable for green walls as shown in Fig. 9 [28].

Methods

The research was conducted using the “Design Builder”- [v.7] programmed connected to (Energy Plus), which is extensively used, popular, dependable, and accurate simulation engine among modern thermal and visual simulation tools. As the “base case” model, we develop an existing building simulation model and conduct many runs for each housing alternative using different green wall tactics for the same orientation. The purpose of this research is to investigate the influence of green wall technology on lowering electricity consumption, thermal comfort, and CO2 emissions by examining its impact on yearly energy consumption and temperature in a typical Cairo urban area. Several parameters of every vegetated layer may be identified using the program, including soil depth, soil conductivity, plant density, plant height, stomatal conductance, and embodied carbon.

Research methodology as shown in (Fig. 10), compromises between both of:

- Theoretical approach

This article provides a literature study on building retrofits as well as the country's current energy position as it applies to the residential building sector.

- Application approach

Employ the "Design Builder" application in conjunction with information technology validation tools on a 'base case' model of a real-world home to depict the many implications of home remodeling options [30].

Fig. 13 **a** View of 3D of a residential building in Al Rehab City. **b** Floor plans for the family four-story housing prototype masterplan, Cairo, Egypt

Table 1 Residential building architectural data

Function	Rate
Building (usage) type	Residential type sector/fully finished spaces
Occupant's rate	Reception space (8) persons/bedrooms (2) persons
Building floors	Ground floor + (5) typical floors
Floor height	3.30 m (slab to slab), 3.00 m ~ 3.0 m (clear height)
Building height	24 m^2
Building total height	(3.30 m × 5 floors) + 1.4 m parapet of façade = 18.00 m
Ground floor area	15.0 m × 21.0 m = 315.00 m^2
Typical bedrooms floor area	24.0 m (8.0 m × 3 typical units) × 24.0 m (8.0 m × 3 typical units) = 576.00 m^2
Ventilation system	"Base-Case" model: artificial mechanical ventilation (Full HVAC) a system with a set point (24 °C)
Sun exposure angle	Egypt (30° N 31°E) sun's altitudes in middays (12:00 PM) ranged between 36.6° and 83.4°
location on the field	Egypt-Cairo-Rehab-Rehab City Second Phase(Group 24)
Window gap ratios	Preferred heights 40%

Simulation process

The Energy Plus tool from the US Department of Energy was used to simulate energy use. Energy Plus is software that simulates the energy usage of a complete building and includes a green roof module. The energy use of the planned structure will be calculated accurately with and without the use of green walls using its energy modeling tools, allowing for comparison (see Fig. 11).

Egypt's first privately created city, Al Rehab, is recognized as one of the most efficient residential city concepts. It is located 20 min from downtown Cairo and 10 min from Heliopolis and Nasr City, at the intersection of the Cairo/Suez Road and the Eastern Ring Road. Figure 12 depicts how well connected it is to the neighborhood's urban core. Figure 13, "Al Rehab City," was to be erected in six phases, each taking up 240 feddans, and was eventually enlarged to 10 phases upon completion. There are residential villages, residences, villas, five-star hotels, and golf courses on the property.

A simulation was used to conduct a comparative examination of two case study buildings in Cairo, Egypt: the as-built building (base-case) and the green wall methods for the same structure (modified case) as shown in Table 1. The case study's residential building is located in Cairo, Egypt's Rehab City. The structure has four levels and a total size of 1750 m^2, with four flats on each floor. Design Builder, an easy-to-use modeling tool, allows you to work with virtual building models. Among the environmental performance parameters available are energy usage, carbon emissions, comfort levels, daylight lighting, peak summertime temperatures, and HVAC component sizes.

Case study investigation

Geographic and climatic outlines

Climate consultant software examines a wide range of aspects that contribute to climate change. The Psychrometric Chart depicts how several climatic data may be displayed

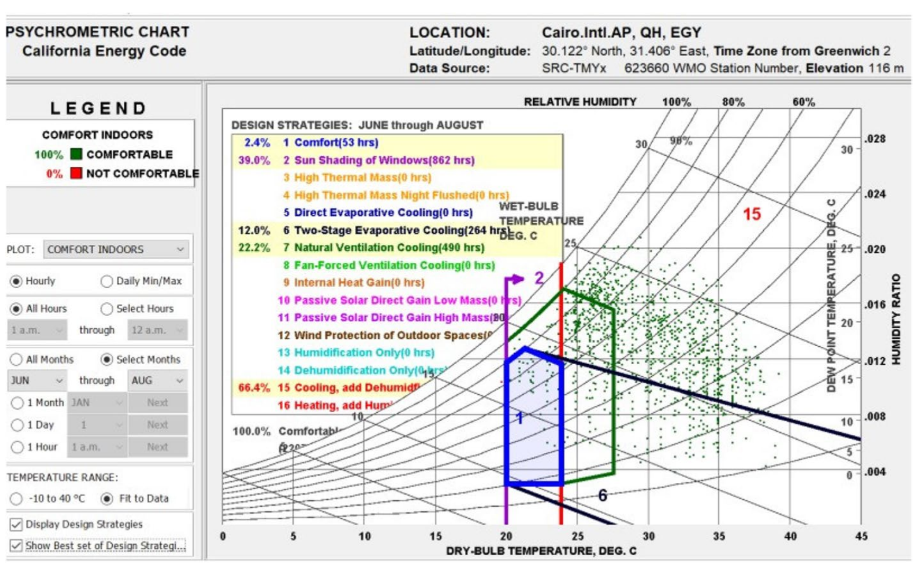


Fig. 14 Psychrometric chart shows just the 4 months starting from June to September high with the best eight design strategies shown in the above psychrometric chart

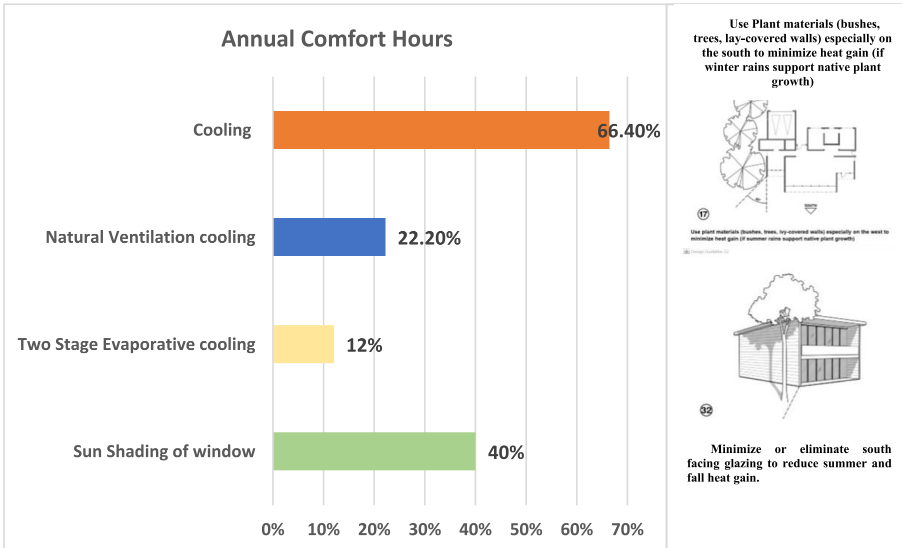


Fig. 15 **a** Analysis of climatic strategies using the psychrometric chart using Climate Consultant software. **b** Climate Consultant building design strategies [31]

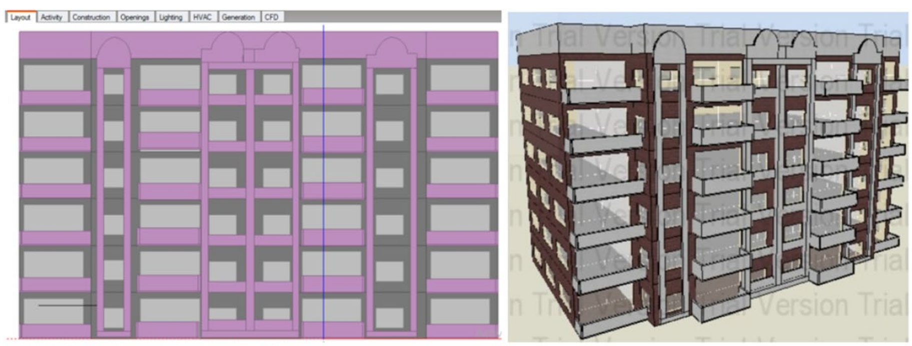


Fig. 16 The graphical user interface of Design Builder (simulation model of the case study)

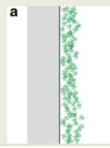
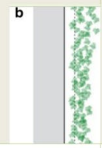
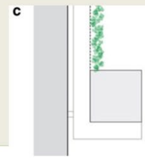
concurrently to illustrate whether individuals would feel at peace in regions with these qualities. A handful of the graphs will highlight the usefulness of Climate Consultant 6.0. (Figs. 14 and 15).

In principle, significant summer gains must be avoided for passive solar cooling advantages to be effective, necessitating shading measures appropriate for each location's solar altitude. Different levels of cooling, sunshades as a green wall, and other external sources of cooling are required at various times depending on the site-specific tactics used. These were recorded by charts and graphs, such as the one shown in Fig. 15. The authors are concerned with yearly thermal comfort research since the major purpose of this article is to assess the space thermal performance during the warmest month of the year (Fig. 16).

Green wall façade's performance

The energy performance simulation was done utilizing various construction materials for both the basic case and the modified scenario. Both examples have the same

Table 2 Comparative analysis of green wall systems of sample buildings

Comparative Analysis of green wall systems				
The function of the Green Wall	Energy efficiency	√	√	√
	Air-Conditioning	√	√	√
	Noise control	√	√	√
	Efficient usage of day-		√	√
Number of Green Wall	G.W at all facades		√	√
	G.W at some facades	√		
Type of Ventilation	Natural	√	√	√
	Mechanical			
	Hybrid	√	√	√
Ventilation mode of the facade	Outdoor air curtain		√	√
	Indoor air curtain		√	√
	Supply air	√	√	√
	Exhaust air		√	
	Buffer zone	√	√	√
Air cavity of facade	Narrow (10-20 cm)		√	
	Wide (20-300 cm)		√	
Windows of internal skin	Fixed	√	√	√
	Openable		√	
Service-maintenance possibility	Adaptive in Egypt	√	√	√
	Non-Adaptive in Egypt			

footprint, which is 1750 m^2. Moreover, both examples contain four above-grade stories. For green façades, climbers are connected directly to the building surface, as in traditional architecture. The work is supported by the cables or trellis employed in the second-case scenario. The material used to support climbing plants is steel. The third case study is an indirect greening system that incorporates planter boxes at different façade heights. If the rooting space is inadequate to calculate the cavity depth at the worst orientation, the system requires a watering system, and the best techniques are then used on a green wall.

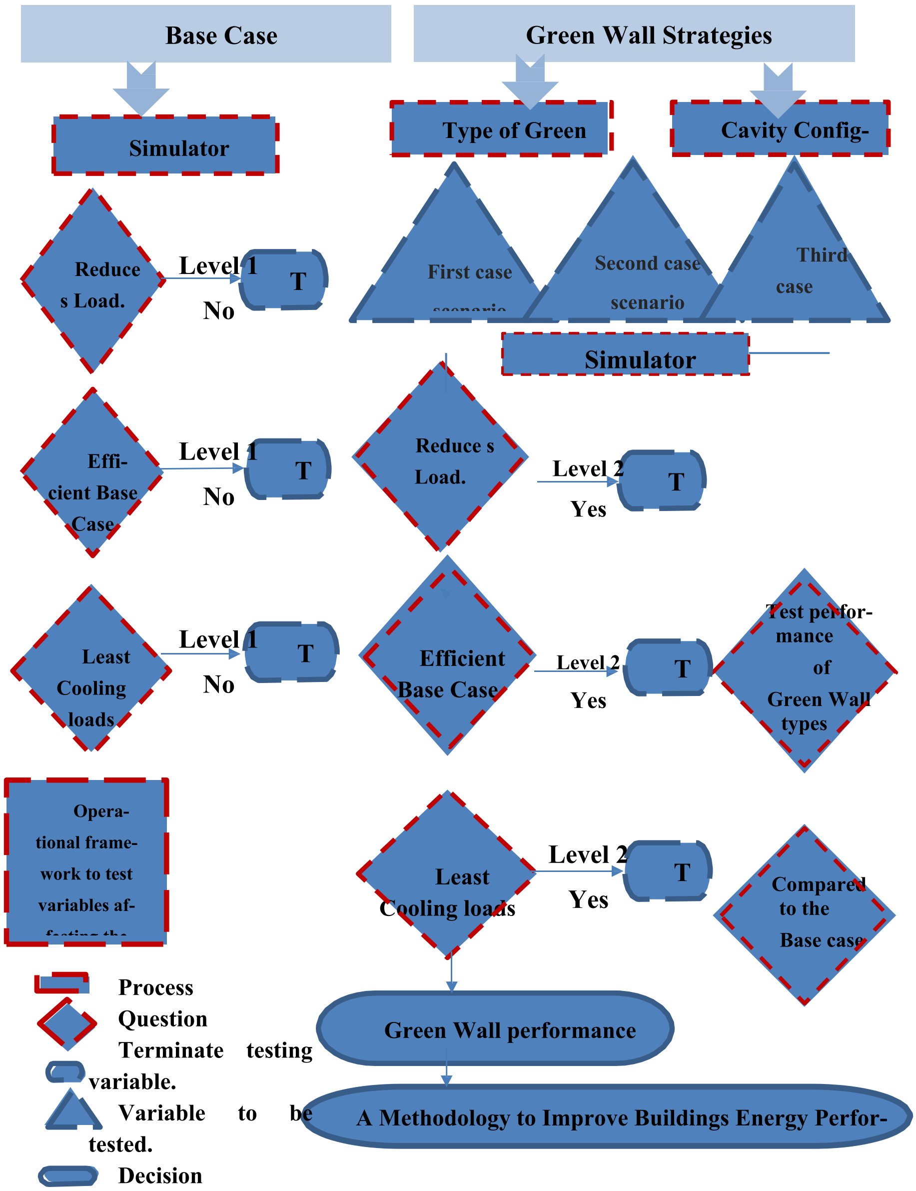
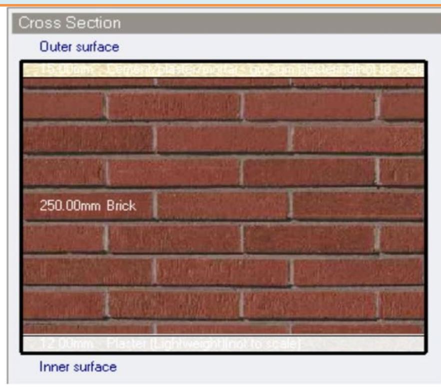
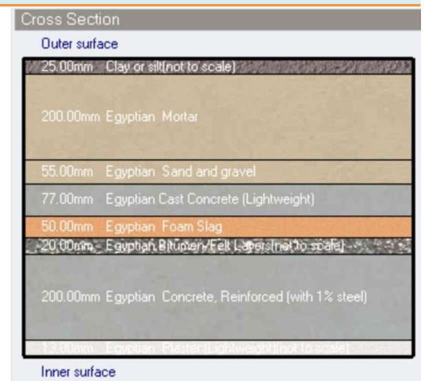


Fig. 17 Operational frameworks to test variables affecting the thermal performance of green wall façade

The operational frameworks examine factors impacting the thermal performance of the green wall façade, as indicated in Fig. 17. Table 2 highlights the benefits of each kind and the green wall's energy efficiency usage rate is increasing as time goes on due to its advantageous features such as minimizing heat loss in buildings, positively impacting from the sun in a controlled manner, maintaining an optimum balance between inner and outer climate, thus drawing more benefits from the space close to a window, contributing to sound insulation, and offering the option of natural ventilation.

Table 3 Thermophysical properties of the building envelope of the case building

Traditional External Walls & Roof	
Walls	**Traditional Roof**
	
• Brickwork Outer (25 cm) • Plaster (0.13 cm)	• Brickwork Outer (25 cm) • Bio-PCM (2.0 cm) • Plaster (0.13 cm)
U-Value(W/m2-K)	
• 1.637	• 0.978
Ground Floor Slab	**Typical Floor Slab**
	
• Ceramic tile (2 cm) • Cement/Plaster/Mortar (2 cm) • Sand and gravel (4 cm) • Bitumen (2 cm) • Concrete,cast-dense (7 cm) • Concrete, Reinforced (15 cm)	• Ceramic tile (2 cm) • Cement/Plaster/Mortar (6 cm) • PCM insulation board (7.6 cm) • Air Mass (0.15 cm) • Bio-PCM (0.18 cm) • Concrete block (15 cm)
U-Value(W/m2-K)	
• 1.810	2.379

Construction materials input

The first is the as-built case, which uses conventional Egyptian building materials as follows: as stated in Table 3, the roof was constructed using conventional Egyptian roof layers (0.15-m reinforced concrete, 0.02-m getting damp insulation, 0.04-m heat insulation roofing board, 0.05-m sand, 0.02-m cement mortar, and 0.01-m concrete

Table 4 Design Builder input data for the residential case study

Activities	Residential home
Number of occupants	0.0196 (people/m^2)
Construction	Solid slab
Opening	30% window-to-wall ratio
HVAC system	Mixed mode ventilation (split fresh air + natural ventilation)
Lighting	2.00 w/m^2–200 lx

tiles). The typical floor layers are 0.12 reinforced concrete, 0.05-m sand, 0.02-m cement mortar, and 0.01-m ceramic; the envelope walls are 125-mm-thick red brick, and the outside fenestration is 6-mm clear glass as shown in Tables 3 and 4.

Results and discussion

First-stage simulation results

The first stage of the simulation process has been applied by identifying the building type and loading the local climate data. Three models were simulated on DesignBuilder Software and test them in the summer months in south orientation the overall assessment of the green walls model benefits on the simulated model was made by comparing the results obtained for the VGS models and the reference model analyzing external surface temperatures and operative temperatures, fuel totals, internal gains fuel breakdown, Co2 emissions, thermal comfort range, and fabric and ventilation as shown in Table 5.

Second-stage simulation results

Simulate the impact of the vertical green system by the different scenario: (a) direct green façade; (b) indirect green façade; and (c) indirect green façade with a planter box on reducing the high energy consumption, the lowest annual predicted mean vote model (PMV) and finally the least Co2 emission through the building.

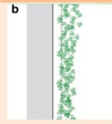
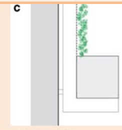
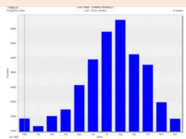
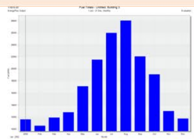
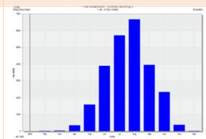
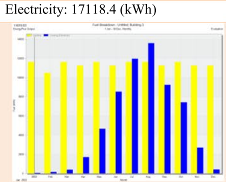
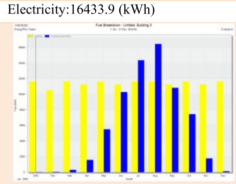
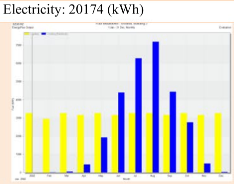
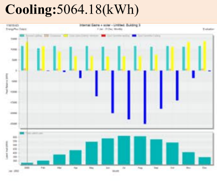
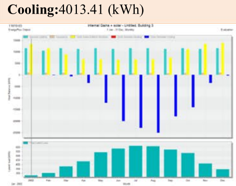
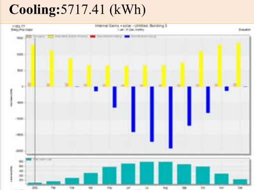
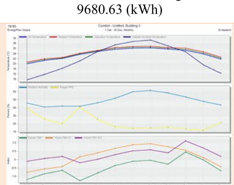
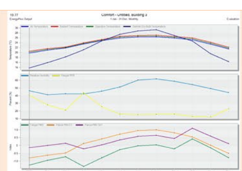
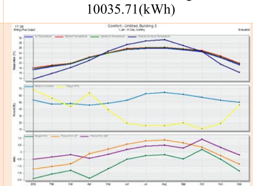
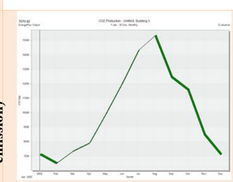
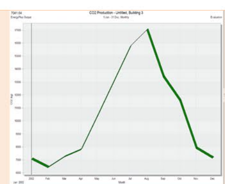
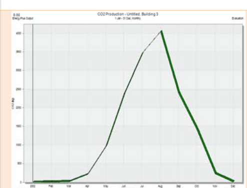
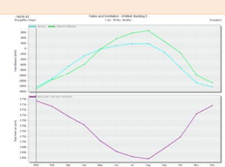
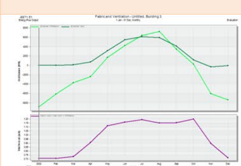
Fuel totals

The graph depicts the electricity (total building electricity usage), in which the first case scenario produces 17,118.4 kWh, the second case scenario produces 16,433.9 kWh, and the third case scenario produces 20,174 kWh.

Internal gains

The graph shows the sensible cooling effect on the zone of any air introduced into the zone through the HVAC system, in which the first case scenario achieves 9680.63 kWh, the second case scenario achieves 6679 kWh, and finally, the third case achieves 10,035.71 kwh as shown in Table 5.

Table 5 Simulation Output of the green wall strategies in the building

	First Case Scenario Direct green façade	Second Case Scenario Indirect green façade	Third Case Scenario Indirect green façade with planter box
Layers (In design-builder)			
Fuel Total (Monthly results of Building-Energy consumption			
	Analysis for Fuel Total: Average value achieved		
	Electricity: 17118.4 (kWh)	Electricity:16433.9 (kWh)	Electricity: 20174 (kWh)
Fuel Breakdown (Monthly results of Building Energy consump-			
	Analysis for Fuel Breakdown: Average value achieved:		
	Lighting:11369.75 (kWh) **Cooling:**5064.18(kWh)	**Lighting:** 10400.98 (kWh) **Cooling:**4013.41 (kWh)	**Lighting:** 17118.4 (kWh) **Cooling:**5717.41 (kWh)
Internal Gain (Monthly results of Building Energy consumption (kWh))			
	Analysis for Internal Gain:		
	Zone Sensible Cooling: 9680.63 (kWh)	Zone Sensible Cooling: 6679 (kWh)	Zone Sensible Cooling: 10035.71(kWh)
Thermal Comfort (Monthly results of Building Thermal Comfort range)			
	Fanger PMV: -0.56	**Fanger PMV:** -0.34	**Fanger PMV:** +1.6
Co2 Emissions (Monthly results of Building CO2 emission)			
	Analysis for Co2 Emissions:		
	Co2 Emissions:10373.74	**Co2 Emissions:**9958	**Co2 Emissions:**12578
Fabric and Ventilation (Floor, Ceilings, Floors, Roofs, Natural Ven &)			
	Analysis for Fabric and Ventilation:		
	Glazing:4036.4 (kWh) **Walls:** 9254.591 (kWh) **Ceilings:**431.31 (kWh) **Floors:**598.92 (kWh) **Roof:**2243.7 (kWh) **ExternalInfiltrations:**6595.0(kWh)	**Glazing:**3036.4 (kWh) **Walls:** 8254.591 (kWh) **Ceilings:**331.31 (kWh) **Floors:**498.92 (kWh) **Roof:**1957.7 (kWh) **ExternalInfiltrations:**5095.0(kWh)	**Glazing:**4636.4 (kWh) **Walls:** 9554.591 (kWh) **Ceilings:**471.31 (kWh) **Floors:**618.92 (kWh) **Roof:**26743.7 (kWh) **ExternalInfiltrations:**6895.0(kWh)

Fuel breakdown

Electricity consumed by room equipment other than lights (computers, equipment, process, etc.). is shown in Table 5.

CO2 emissions

Cumulative carbon dioxide emissions for buildings, based on data available at the building level, are 10,373.74 kg in the first case scenario, 9958 kg in the second case scenario, and 12,578 kg in the third case scenario.

Thermal comfort range

Fanger expected mean vote and operational temperature (the mean of the zone air and radiant temperatures) were determined, as these are the two most important factors influencing thermal comfort. The first scenario reaches − 0.56, the second scenario obtains − 0.34, and the third scenario achieves + 1.6. The projected mean value (PMV) metric scale is used to assess the amount of thermal comfort obtained in a particular area [32]. According to the Egyptian energy code, this metric's value should range from 1 to − 1 to achieve the comfort zone.

Fabric and ventilation

Fabric and ventilation elements were also investigated. According to their figures, employing the green roof resulted in a clear, considerable drop in all numbers. The numbers in Table 5 also show a link between the building's ventilation and airflow and the heat losses caused by glass, walls, roofs, ceilings, and outside infiltration. Table 4 depicts the total heat transfer to the zone from the outer glass and wall.

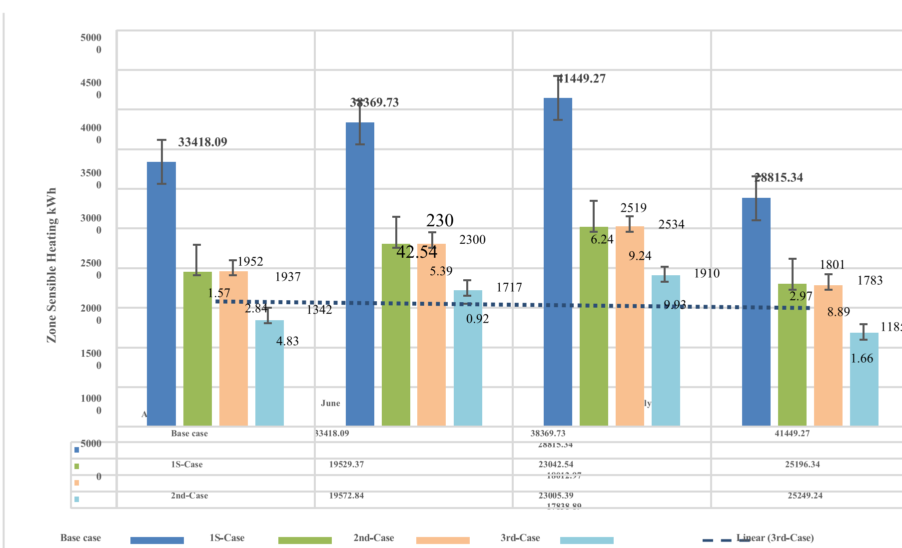


Fig. 18 Monthly simulation energy consumption for the four scenario strategies

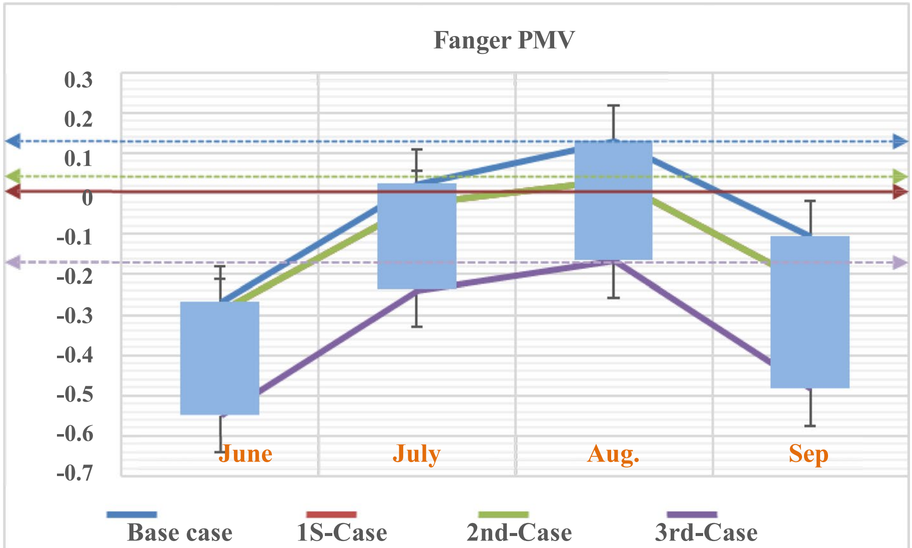


Fig. 19 Annual indoor PMV in classroom base case result

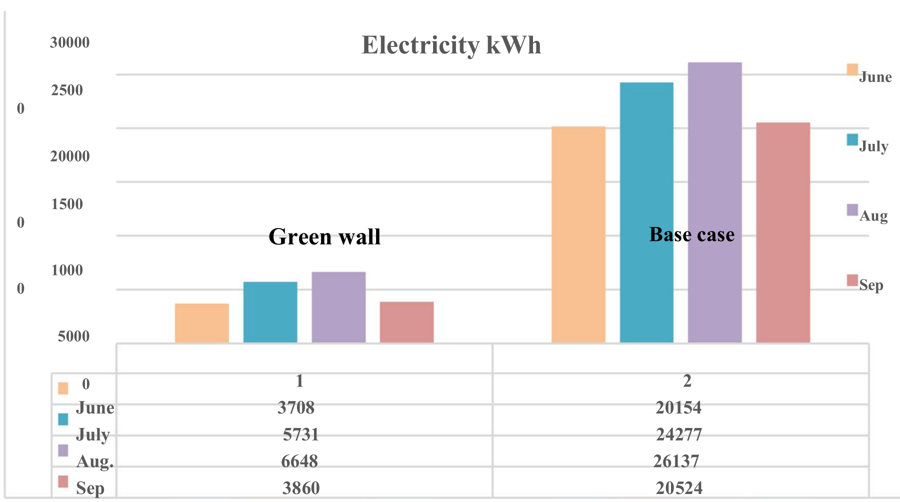


Fig. 20 Comparison between the modified model and the initial case in terms of electricity load

Results

The findings of the various simulations are grouped into four distinct scenarios: monthly energy consumption (kWh), thermal comfort, and energy conservation.

Energy performance simulation

The energy performance simulation was carried out for the basic case and the modified scenario employing green wall methods. Just by merging the green wall with the thickness of the existing base wall of the south facade, the yearly cooling load may be reduced from 41,449 to 19,109 kWh (see Fig. 18).

Annual predicted mean vote model

The predicted mean vote model (PMV) is a well-known thermal comfort concept that was first established by Fanger, ISO 7730, and ASHRAE 55 standards. The PMV is an index that forecasts the mean value of a large group of people's votes on a 7-point thermal sensation scale based on the human body's heat balance. The allowable thermal comfort range for a PMV, according to ASHRAE 55 guidelines [33], is between − 1 and + 1. The average yearly PMV for the residential areas study was computed using E + based on the metabolic rate, occupancy rate, and garment characteristics. Figure 19 forecasts the average monthly PMV during the warmest month of the year.

Electricity consumption

The graph (Fig. 20) depicts the variance in the number of kWh utilized by equipment, cooling, and lighting systems. The power in the room varies, including a varied daily and weekly schedule that accommodates changes in occupancy and activity throughout the period. For the months of June through September, the straight line reflects lower power use to account for the summer vacation in domestic spaces. The base case achieves 3708 Kwh, 24,277 kWh, 26,137 kWh, and 20,524 kWh, while the indirect green façade with planter box achieves 3708 kWh, 5731 kWh, 6648 kWh, and 3860 kWh through June, July, August, and September respectively.

CO2 emissions

The CO2 emission graphs for the identical simulation procedures demonstrated considerable reductions when employing the green wall option, as shown in Table 4.

CO2 emissions were above 15,839 kg/month when the green wall was used; when the G.W construction was used, CO2 emissions surpassed 4029 kg/month during the hot summer months, which was decreased by more than 85%. Green wall solutions, on the other hand, will cut emissions to slightly more than 11,810 kg/month, as indicated in Table 5.

Modular green façade type-cavity width (south-west)

The entire energy usage inside the residential space is assessed in relation to the influence on cooling loads caused by the use of various modular green façade layouts, systems, orientations, and depths. By adapting the indirect green façade with a planter box with the different air cavities, the energy consumption linked to cooling demands for a

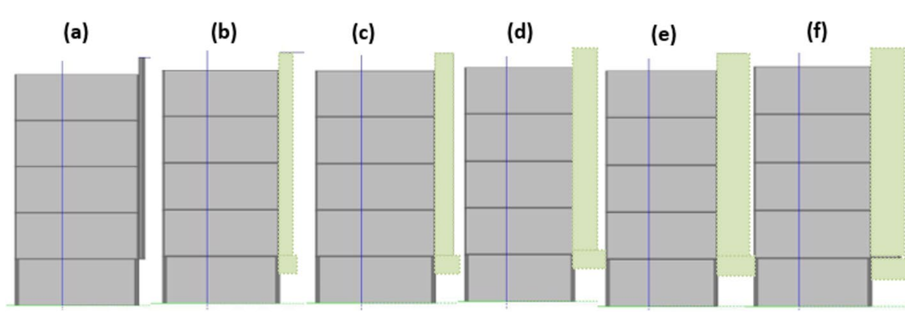
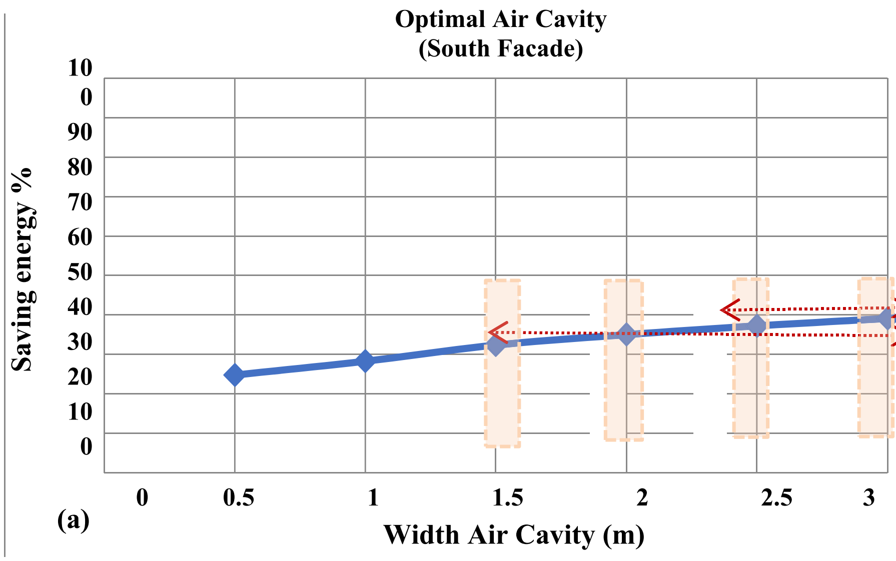


Fig. 21 **a** Base case. **b** 0.5 m VGF. **c** 1.0 m VGF. **d** 1.5 m VGF. **e** 2.0 m VGF. **f** 2.5 m VGF



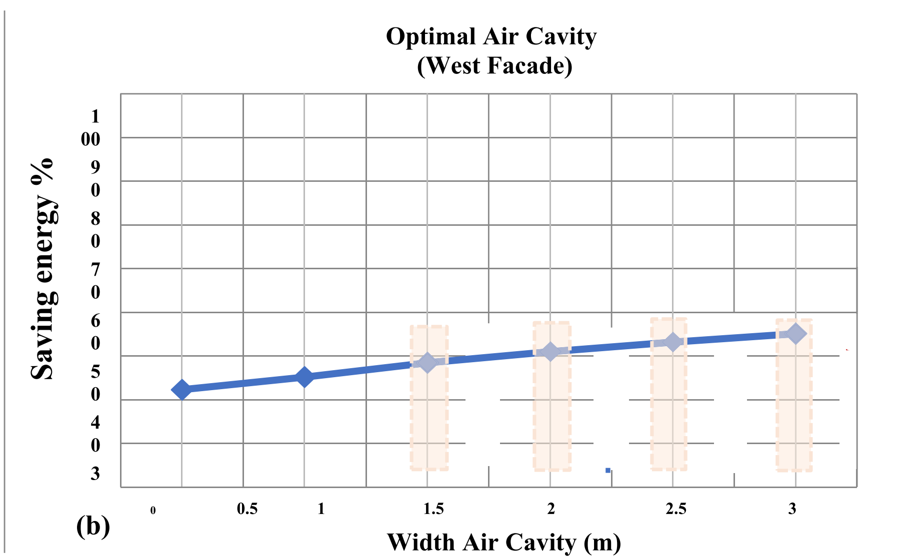


Fig. 22 **a** Optimal air cavity of cooling (electricity) for indirect green façade with planter box wall at south facade. **b** Optimal air cavity of cooling (electricity) for indirect green façade with planter box wall at west facade

retrofitted façade is examined to offer an appropriate cavity start from 0.5 to 3.0 m in the southern and western façade comparison of findings as shown in (Figs. 21 and 22).

Figure 22a shows that the south façade air cavity widths of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 m accomplish and save energy of 24%, 28%, 32%, 35%, 37%, and 40% accordingly. On the western façade, it was 22%, 25%, 28%, 31%, 33%, and 35% (Fig. 22b). According to both results, air gaps ranging from 50 to 100 cm saved the least amount of energy while air gaps ranging from 50 to 100 cm saved the most (150 to 200 cm). While air gaps greater than 2.00 m saved energy, the increase was not particularly noticeable.

Figure 23 depicts the saving energy rise for direct, multi, and box green wall types with varying air cavity widths (0.5, 1.0, 1.5, 2.0, 2.5%3.0) m for the four façade orientations

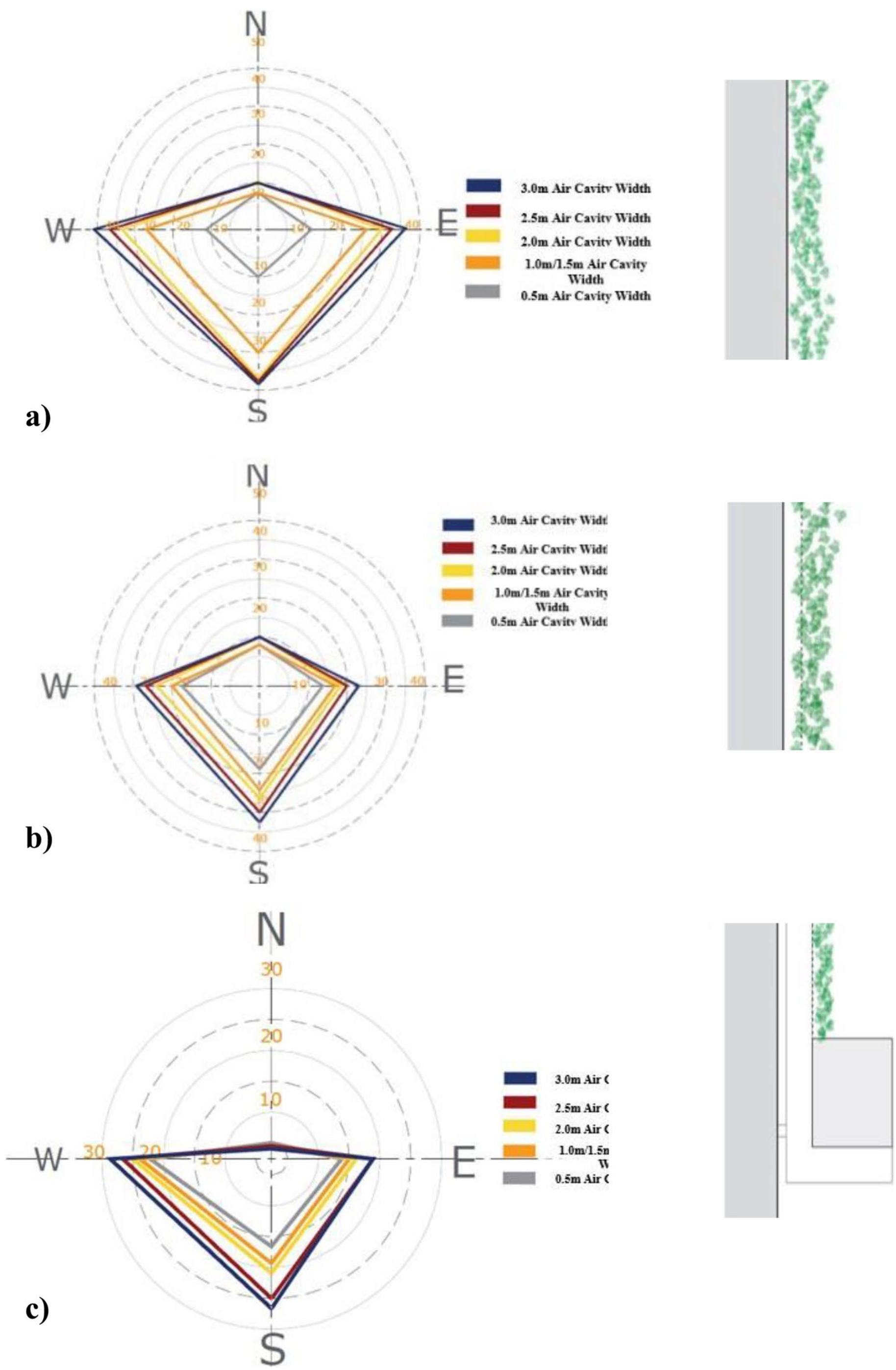
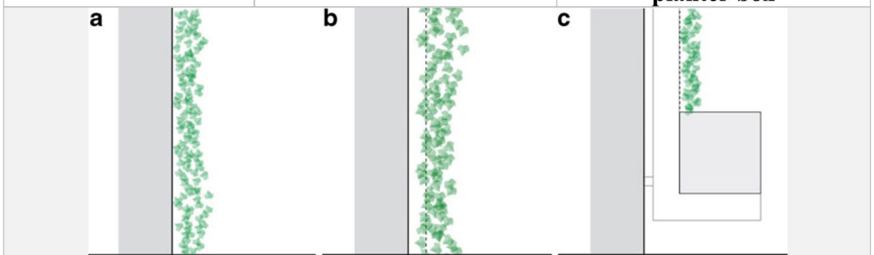


Fig. 23 Saving energy % rose of **a** direct green façade; **b** indirect green façade; and **c** indirect green façade with planter box with different air cavities

(East, West, North, and South), demonstrating that the wider the air cavity, the larger the energy saved. This would be up to a 2.5-m air cavity width; above this, the energy saved was not noticeable.

Table 6 Simulation output of the green wall strategies in the building

First Case Scenario Direct green façade	Second Case Scenario Indirect green façade	Third Case Scenario Indirect green façade with planter box



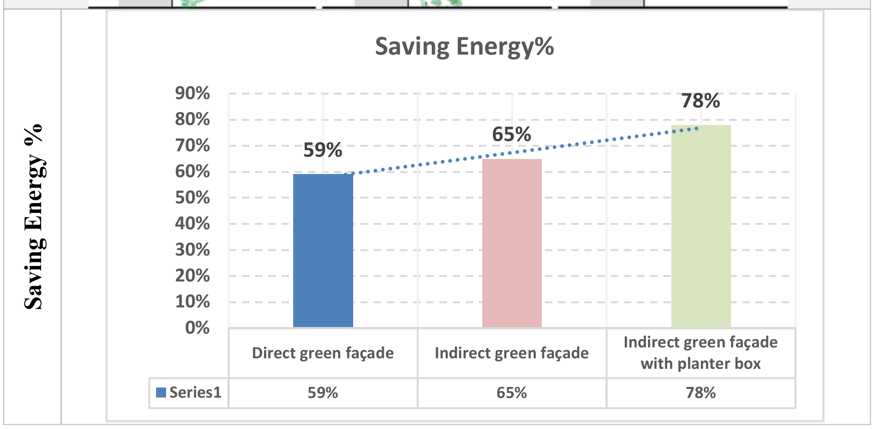


Figure 23 indicates the saving energy % rose that shows the configuration of the different types of green wall with the optimum air cavity widths (2.0 m) saving energy% rose for the South facade's orientation where it clearly shows that the indirect green façade with planter box façade achieve the best value of energy consumption (annual sensible cooling KWh).

Discussion

Building efficiency of a green vertical facade

Simulation results for cooling, heating, lighting, and total energy consumption of the direct green façade, indirect green façade, and indirect green façade with planter box building have been evaluated to find the optimum integrated usage of a vertical green system with respect to energy efficiency.

The thermal effects of plants on the façade and fenestration are directly related to how well a green wall reduces energy consumption. The primary benefit of plants during the day, especially during the cooling season, is the significant energy savings caused by reduced solar radiation from vegetation shading, which results in a drop in temperature.

Table 6 shows the effect of applying VGS on Saving Energy with a 2.0-m air cavity width, it reached 78%, 65%, and 59% for the south orientation respectively.

Several materials can be used for indirect greening systems and direct greening systems combined with planter boxes. Since only vegetation is involved, the environmental benefits are the same for all materials used, but the environmental impact can vary greatly (stainless steel has a much higher impact) and the costs can also vary greatly.

Conclusions

According to studies, the advantages achieved are quite substantial and long-lasting in comparison to the cost contribution of green walls, hence validating the notion of green walls as a sustainable urban design. Green façades are not only visually appealing, but they also improve the efficiency of indoor and outdoor air, preserve power, reduce thermal load, and increase building amenities. To ensure system maintenance and safeguard buildings from water pollution, maintenance problems should be addressed on a continuous basis with the owner prior to construction policy. The level of maintenance that the customer provides influences the type of systems and plants used.

Green techniques have a high potential for energy savings and mitigation, according to simulation data. Complete adoption of the recommended green methods will lower the case study's yearly cooling demands and CO2 emissions by approximately 78%. In terms of level two, building design, two separate methodologies were applied to a building envelope, once again using design-builder software. The structure is located in New Cairo, Egypt. The first strategy was to use the present building situation, which resulted in a high yearly total amount (60% less than the base case without the green wall technique in electricity with a high thermal comfort range and an annual average Fanger PMV). The second strategy was to use a green wall system, which resulted in an annual average overall decrease in power use of 75%. With an annual average Fanger PMV of − 0.4, this large decrease will be achieved while maintaining an acceptable range of thermal comfort. Moreover, CO2 emissions were reduced by an extra 45% on an annual basis. As a result, the study advises that green walls be used in hot, dry climates as a superior strategy for higher sustainability advantages.

Limitations

With the aid of case study data and literature research, this study tested a methodology for achieving vertical green system in hot arid climates that can be used as a guide when making decisions during the design phases.

Since some of the concluded or estimated key variables are susceptible to change depending on the circumstances of a particular project, uncertainty analysis was not covered. These variables include firstly, maintenance, for example. It is crucial to think about the added maintenance needed before deciding to install a living green wall in your new house. Secondly, if you choose the wrong plants, they could harm your house. Thirdly, watering vertical gardens can be difficult.

Abbreviations

Co2 emissions	Carbon dioxide emissions
Fanger PMV	Predicted mean vote
VGS	Vertical greenery system

Acknowledgements

The authors of this study used software such as the design-builder to analyze the effect of using green facades to enhance the buildings internal environment in relation to thermal comfort, energy consumption, and Co2 levels. The authors further acknowledge the reviewers and associate editor of the *Journal of Engineering and Applied Science* (JEAS) for their insightful remarks and recommendations.

Data collection and analysis

The authors state that the findings in this study were prepared specifically for this study and that no prior research by the authors of the current work or anyone else could be compared in terms of research design or findings.

Authors' contributions
Prof. AHM came up with the idea for the current study's problem, oversaw the technical process and removed any roadblocks, and then reviewed the manuscript. AMR contributed to the formulation of the methodology, carried out the simulations, gathered the literature required for the current study, shared the problem suggestions, prepared the final draft of the manuscript, and performed the data analysis. The final manuscript was read and approved by the author(s).

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Availability of data and materials
The authors will provide the datasets used and analyzed during the current study upon reasonable request. The study's supporting data, according to the authors, are included in the journal and its supplemental materials.

Declarations

Competing interests
The authors declare that they have no competing interests.

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