Mohammed
Journal of Engineering and Applied Science (2022) 69:99
https://doi.org/10.1186/s44147-022-00154-9

Journal of Engineering and Applied Science

RESEARCH Open Access

Employing systems of green walls to improve performance and rationalize energy in buildings

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Abstract

In the context of energy crisis challenges, climatic changes, rising temperatures, and the disappearance of green areas, all these have led to emerging thermally uncomfortable indoor spaces because their envelopes did not prevent the harmful effects of the outdoor climate. Hence, the urgent need to adopt the most effective methods to treat thermal performance and rationalize energy consumption in buildings has emerged. Consequently, the research aims to improve the environmental and thermal performance of building envelopes affecting their indoor environments by employing the systems of green walls. Accordingly, their types, design considerations, characteristics, technical elements, and indicators of sustainability aspects related to them were collected and investigated to ensure their success. Also, these systems' indoor and outdoor effects on buildings and two international experiments were analyzed for benefit when dealing with these systems. An analytical comparison was performed concerning their applications to guide understanding and utilization. The study devised a seven-stage framework to choose, design, evaluate, and attain the most appropriate green wall system according to the state and circumstances of the studied building. Finally, inspecting this framework was by the chi-square test, thus fostering the integration of the natural environment with the built environment, human comfort, and energy conservation.

Keywords: System of green wall (SGW), Green facades, Living walls, Performance, Envelope, Thermal comfort, Energy consumption

Introduction

The world is exposed to the energy problem and the depletion of natural resources, so it is necessary to turn to renewable energy sources and find solutions and alternatives to rationalize energy consumption, especially non-renewable energy. The building sector is one of the sectors that consume the majority of energy as one of the causes of climate change and is affected by it as well; the construction process consumes 36% of the used energy overall and 65% of the electricity consumption total [1, 2]. Many trends have emerged, and following Egypt's Vision 2030, the fifth goal—environmental sustainability—an integrated and sustainable ecology system, they push to design and construct sustainable and green buildings that are friendly to the environment. These trends aim to adapt projects to the surrounding environment, minimize non-renewable energy consumption, and benefit from renewable energy sources in operating and managing them [3]. These are due to climatic changes and rising temperatures that negatively affect the thermal performance of the building through its envelope, facades, or outdoor walls [4]. Reflective surfaces like facades also affect the microclimate surrounding the city, increase the temperatures around the buildings, and thus affect the discomfort felt and increase the amount of used energy [5]. Therefore, one of the possible solutions is using vegetal surfaces for the facades, which reduce the wasted energy by evaporation and thermal insulation, increase the sunlight scattering, and reduce the heat island effect [6–9]. Due to the lack of green open spaces in cities, planting trees and shrubs is often an unviable option; hence, building facades is a valuable option that utilizes the solid areas ignored or left during the façade design. The building must represent the shelter that protects man from those climatic changes that have become a reality; humanity is suffering from it now. The manifestations of climate change are constantly increasing, represented by rising temperatures and the subsequent rise in sea levels, tropical cyclones, and others [10]. Hence, the continuous rise in temperatures and how the building can adapt to that rise must be faced, besides the associated consequences on thermal comfort within buildings. The development of more complex shapes of buildings has accompanied the increase in energy demand [11]. The primary task of the building is to protect its occupants from the vagaries of the weather and extreme climatic conditions [5]. It is clear from the above that the importance of applying SGWs to the walls and facades of buildings that are an envelope separating two environments in constant transformation. Such a designed envelope sometimes contains fixed components and elements operating under different conditions and in the same manner, besides other factors that cause buildings to consume 40% of the required energy [2]. Facades are one of the main building elements that affect energy performance. So, designing the facade elements must meet the necessary flexibility and performance efficiency in terms of the flowed energy, the temperature of the outdoor environment, and human comfort [1, 8]. Since there are many SGW types, each system has features and characteristics that affect its quality and role in thermally and environmentally improving buildings' performance [7, 12–14]. These features and characteristics need to be emphasized, investigated, and illustrated before selecting and implementing such systems to be suitable for the state and conditions of a building. Hence, a methodology and a practical framework will be required for dealing with these systems to be the most suitable for use in buildings, consistent with their condition, and have an influential role in decreasing and rationalizing energy consumption and reaching thermal comfort.

Research problem

The emergence of indoor spaces that are not suitable for life (healthy, psychologically, and functionally) without seeking to make modifications in the facades and outdoor walls to control the outdoor climate effects upon such indoor spaces. For creating an environment with thermal performance being the most comfortable for users [4, 12]. Also, dark places waste daylight as energy as a friend to the environment despite the sun's brightness being permanent [2, 5]. In addition, the ecological balance disruption, besides global warming, absence of external shading, climatic changes, and their increasing deterioration with the gradual disappearance of green areas around buildings [3]. Thus, sick buildings have emerged, which consume more energy than necessary.

The aim and objectives of the research

The research aims to improve the environmental and thermal performance of the building's envelope for positively affecting the indoor environment and energy consumption of buildings through a proposed framework to design and employ systems of green walls, besides evaluating and developing these systems to be the most suitable for the considered projects. Accomplishing this aim is through the following objectives:

(1) To study the concept and role of SGWs, inventory their types, and consider their indicators concerning the three sustainability aspects to ensure the SGWs success when meeting their design considerations, technical features, and elements
(2) To investigate the indoor and the outdoor effect of SGWs on the thermal and environmental performance of the buildings and energy savings, thus understanding their application classes to utilize in buildings
(3) To devise and build a plan and guide as a framework for the designer to employ and deal with SGWs while selecting, designing, evaluating, applying, re-evaluating, and developing after actual implementation.

Methods

The study used the inductive-analytical approach to demonstrate and interpret the concept, role, and types of SGWs. Furthermore, the design considerations, technical features and elements, and the indicators of the three sustainability aspects of such systems were collected and itemized to ensure their success.

Hence, utilizing the analytical approach was in two stages; the first stage analyzed the indoor and outdoor effects of using these systems on buildings, whether positive or negative. Then, investigating the two international experiments was to reach a set of results and considerations to benefit in treating the thermal performance, rationalizing energy, and when choosing, designing, and evaluating SGW. These experiments have the same varied climate conditions between summer and winter as the climate in Egypt. In the second stage, the analytical comparison of the application classes of these systems was conducted to understand the usages of these systems, encourage applying them, and integrate the natural environment with the built environment. The analysis depended on the previous features, considerations, and sustainability aspects.

Finally, the deductive approach was to set a framework for identifying, designing, evaluating, applying, re-evaluating after executing, and developing the most appropriate SGW to employ and deal with efficiently. Then, utilizing the chi-square test and 5-point Likert scale to inspect the feasibility and reliability of the proposed framework. Hence, this framework will be a mechanism, a tool, or an implementation plan for the success of these systems.

Introducing the systems of green walls (SGWs)

The green envelope is one of the components of the adaptive facades [2]. Its walls use climbing and herbaceous plants to cover supporting structures or grow directly on the facade surface, as shown in Fig. 1. Utilizing these systems was to treat environmental problems caused by the lack of green spaces. Furthermore, they have an influential role in absorbing greenhouse gases and purifying the air of suspended pollutants [15]. The structural system of SGWs for green facades and living walls is either metal, wood, or plastic containers connected to walls by horizontal, vertical, or pivotal arbors. The structural system is either two-dimensional, such as cables, wires, and meshes, or three-dimensional, such as suspended frames. The cable grid system supports climbing the plant until it grows and creates green facades, while the wired grids support the slow growth of plants [3], as shown in Fig. 2. The wiring system is more flexible and provides broader areas of design applications that are better than the cable system. Also, it meets an infinite number of different sizes and styles that are adjustable in both vertical and horizontal directions.

Design principles, considerations, and technical elements for the SGWs

The surrounding conditions of a building and the environment require the designers to consider the following for SGWs [7, 12], as in Table 1.

Indicators of the three sustainability aspects for the success of SGWs

While following the previous considerations and activating the features and technical elements of SGWs, considering the three aspects of sustainability is necessary for these systems to succeed, as in Table 2.

The influential role of SGWs indoor and outdoor

Consequently, it is an adaptive system capable of changing its behavior synchronized with changes due to the natural characteristics of plants, design principles, considerations, and technical, besides its indicators according to the three sustainability aspects, as shown in Tables 1 and 2. Hence, such systems have positive and negative effects on humans, buildings, and the surrounding environment, indoors and outdoors. In the

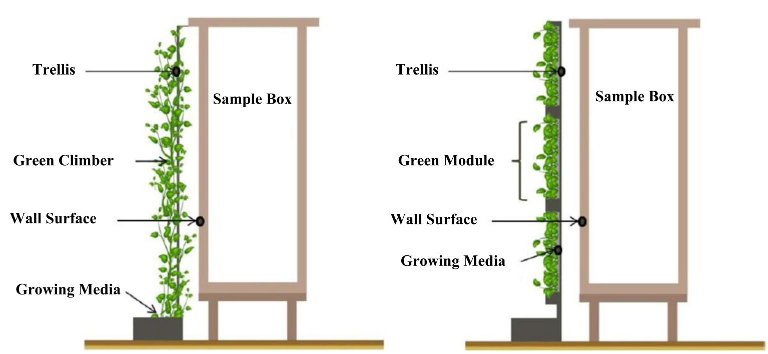


Fig. 1 The main concept of the green façade (left) and living wall (right) [8]. The green façade where plants are directly on the wall with roots in the ground or upon a net fastened to the wall with roots in the earth. The living wall where plants; their roots are on-wall-mounted units or upon a net fixed to the wall, and the roots do not extend into the ground

Fig. 2 The system of cables and wiring for the climbing plant [14]. The two systems use high-tensile steel cables and related equipment. The wiring system is more flexible than the cable system and allows for greater design space. It may be adjusted in both vertical and horizontal dimensions to accommodate an endless number of different sizes and styles

Table 1 Principles, considerations, features, and technical elements of SGWs [1, 6, 9, 11–17]

No.	Design concept	Architecture	Construction
1	Orientation	Coverage area	Green system structure
2	The green system plant type	Irrigation system	Structural load
3	Water insulation systems	Describing type	Technical staff
4	Green design standards	Shape	Feasibility and economy
5	Rehabilitation and exchange	The facade affected	Maintenance
6	Environmental affected systems	Aesthetics	Security and safety
7	Shades and shadows	Thermal performance	Soil type

outdoor environment, the percentage of green vertical levels added to cities equals many times the horizontal areas that can be difficult to provide within a crowded city [15]. Thus, the air is purified from carbon dioxide and suspended pollutants, produces oxygen, and provides a good general picture of streets, better health, and a habitat for birds and living organisms; being a friend to the environment gives better character to the building's personality, helps enjoy nature, and increases the aesthetic value of buildings [12, 13]. If the ratio between the height of a green wall system and the road width is equal to one, the amount of dust and fine particles is reduced by 30%, and by doubling the ratio, it reaches 45% [11]. Thus, it positively affects the city's local climate, the temperature around the buildings, and the heat island phenomenon. SGWs scatter the sun's rays, provide shading, control daylight, absorb rainwater, and cool air by evaporation during the transpiration process [4]. In the indoor environment, they improve the thermal performance of the building facades, especially in hot areas, purify and cool the air before entering the space, and reduce noise inside the building at acceptable rates [16]. They scatter and absorb sound waves from the environment, and they recycle drain water by absorbing and exploiting the remainder after purification [11]. The most important disadvantages of these systems are constant maintenance, pruning, cleaning, renewal

Table 2 The indicators of the three sustainability aspects are related to SGWs [9, 10, 12]

No.	Social	Economic	Environmental
1	The social, physical, and cultural levels.	Estimating the construction budget and the initial cost and all costs must be calculated for each building separately.	In this appropriate plant type for the climatic nature, if the coastal environment, the soil saline, and acidity increase.
2	Some facades deteriorate and need restoration.	Many variables affect the capital required, such as the plant type, facade conditions, transporting materials, and availability of materials.	It is essential to avoid plants that produce a large amount of water vapor through the transpiration process, thus increasing the relative humidity.
3	Agricultural awareness and culture.	To reduce cooling loads and energy costs.	The suitable plant type is selected according to wind features not to harm the structural loads.
4	The population is ready to do the necessary maintenance periodically.	It requires more capital, but this difference returns to the owner through the economic life cycle, so the budget shows recovering the cost difference by saving.	The density of the plants' leaves and their nature (deciduous-evergreen) according to the direction, the permeation of moist air during hot periods, and the prevention of dust-laden winds and direct sunlight from entering.
5	Social cohesion among residents.	The cost of staff qualified in all phases technically.	The plant type is according to the available water, irrigation methods, and drainage.
6	To enhance the psychological state and reduce the stress of living.	Many variables affect the maintenance costs, such as the facade condition after use, the cost of transporting materials, and the availability of materials.	Balancing the use efficiency of plants and environment preservation is by choosing the appropriate plant type for the surrounding environment, climate, and prerequisites for water use and drainage, especially in dry areas.
7	Aesthetic values	To increase the value of a building.	Recycling rainwater and greywater are for irrigation.

impediment of facades, falling leaves, dark rooms, and damaged walls, plus increasing insects, theft due to easiness, climbing, more dirt inside buildings, and clogging gutters and drains [6].

Accordingly, the examination and control of the thermal and environmental performance of SGWs impact considerably on energy rationalization and human comfort, as an integration between the built environment and the natural environment, taking into account the aesthetic, acoustic, and economic performance of those living systems.

The thermal performance behavior of buildings and energy rationalization in case SGWs for human comfort

Conducting experiments have been on the climatic effects of plants on buildings by combining vegetation cover on walls, ceilings, and open spaces in the building context [6]. Numerous studies have proven that the vegetation cover of the façade benefits the thermal and environmental performance levels of a building. Furthermore, two investigated international experiments have the same varied climate conditions between summer and winter as the Egyptian climate, as shown in Table 3. The analysis results can be employed to understand the behavior of the thermal performance of buildings and how to select, design, and implement such systems.

Conducting the first experiment was at the Institute of Physics of Humboldt University, Berlin, Germany, which sought to combine rainwater management and energy savings with natural air conditioning through vegetation walls, as in Fig. 3 [10, 18]. The shade generated by plants as a cooling effect affects the building energy consumption to become a passive air conditioning system natural. From monitoring the solar radiation on a plant surface during the summer months, temperature measurements show that 58% of the plant surface makes transpiration for evaporation, which contributes to cooling the environment compared to traditional roofs. In the summer, plants act as a heat barrier for the indoors by 60% more than the usual roof as the vegetation contributes to the evaporation process. Hence, SGWs still have a significant impact on the energy balance.

The second experiment is Bioshader at the University of Brighton, Britain. A comparison was between units of windows not covered with plants and others covered with plants, as in Figs. 4 and 5. The result was as follows: the room with the covered windows with plants decreased the temperature to 3.5 °C, while the other room not covered with plants increased the temperature to 5.6 °C. The decrease in the thermal

Table 3 The similarity of varied climates between the summer and winter of the two international experiments to Egypt's climate

Location	Climate description	Average summer temperatures	Average winter temperatures	Average sunshine hours per the year months
Egypt	Hot desert climate—semi moderate	23 to 44 °C	17 to −2°C	3 to 12 h
Germany, Berlin	Moderately continental	22 to 32 °C	4 to −2 °C	3 to 12 h
Britain, Brighton	Moderate climate—abundant rainfall throughout the year	24 to 38 °C	22 to −11 °C	4 to 11 h

Fig. 3 The facades of the Institute of Physics at Humboldt University, Berlin, Germany [10]. Its facades include rainwater management and energy savings with natural air conditioning through plant walls

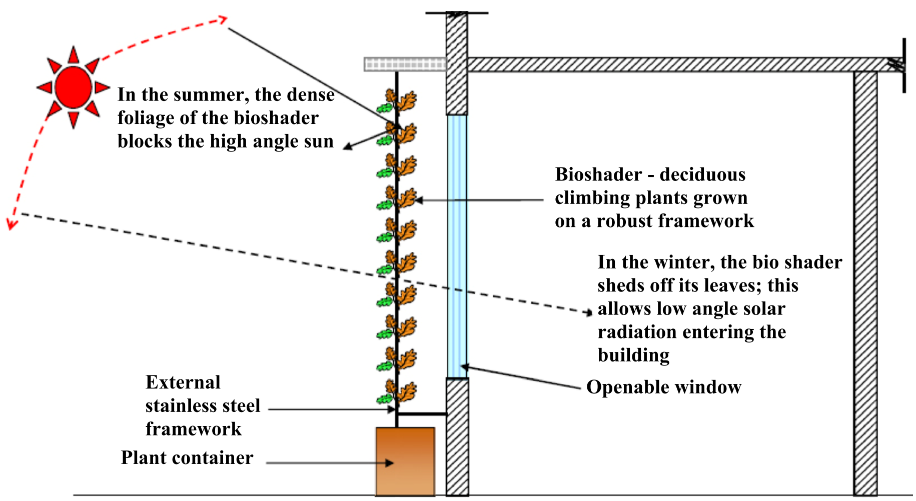


Fig. 4 Section of Bioshade [10]. Its facades include rainwater management and energy savings with natural air conditioning through plant walls

energy of the penetration of solar rays of one layer attains 37% and with the five layers of leaves reaches 86%. The penetration degree measurement of solar radiation on single-layered leaves reaches 0.3, while five-layered leaves reach 0.14 [10, 18].

Based on forgoing study sections and through the two experiments, the following can be deduced, derived, and illustrated:

(1) Vegetation creates for itself a completely different climate from the surrounding conditions. This climate influences the indoor space depending on the height, orientation, and location of the surrounding buildings. Not exposing the façade

Fig. 5 Bioshader wall in the summer [18]. The units of windows are not covered with plants, and others are covered with plants and the utilized equipment to carry out the Bioshader experiment

to extreme fluctuating temperatures is hot during the day and cold during the night, and the plant type differs according to the different climates.

(2) The green wall mechanism depends on the distance between the facade and the vertical layer cultivated if direct and indirect cultivation systems. The indirect planting system contains a layer of stagnant air that has an insulating effect; accordingly, vertical greening can work as an additional insulator of the façade efficiently.

(3) The vegetation layer blocks direct sunlight and can be an effective method for impeding solar radiation, ensuring the temperature is lower indoors. Using plants to provide shade is an effective way to control solar radiation measured in the shaded area of trees 100 W/m^2 which is much less than the area without shade 600 W/m^2.

(4) The physiological process that occurs in the plants aims to moderate the outdoor and indoor temperatures; thus, it contributes to energy savings.

(5) Vegetation and greenery contribute to the vertical mixing of air as warm air rises above hard surfaces and is replaced by fresh air, reducing the heat island effect. Vegetation improves local air quality by reducing smog, producing oxygen with lower airborne particles, and lowering the temperature.

(6) In the winter, the SGW works to isolate the thermal radiation of the indoor walls by the green layer and reduce energy consumption by 50% during winter, as the vegetation layer acts as an insulator and disperses the wind moving along the building surface.

(7) Experimental studies focus on the shading and cooling presented by SGWs. However, there is a set of factors that affect the extent of green facade shading: the quality and type of support structure, facade orientation, and whether the climber is deciduous or evergreen; also, the expected lowering of wall surface temperature ranges from 5 to10 °C.

(8) Experiments have shown that the daytime temperature difference between a wall without vegetation and a green wall is consistently higher by 5 °C, with its

peak at 13 °C. During the day, the temperature difference is positive between a wall without vegetation and a green wall, which decreases the building's cooling load. Nevertheless, at night, the negative temperature difference means that, in the absence of the green wall, the exterior surface cools more quickly than the green wall. Also, the indoor walls of the green systems are always cooler than walls without vegetation cover.

(9) According to the studies, electricity consumption ranges from 5 to 10% to cool buildings to compensate for temperature increases ranging from 0.5 to 3°C. Therefore, each decrease in the indoor temperature by 0.5 °C can reduce electricity usage by about 8% of conditioning air in the summer. Planting urban areas with trees, green roofs, and green facades can reduce the energy consumption of conditioning air by 20%;

(10) Increasing vertical planting or greening by 10% in a city led to reducing the energy value of heating and cooling capacity by 5 to 10%.

(11) At peak times, the indoor temperature ranges from 45 to 47°C in the case of SGWs, which is far from the thermal comfort ranges of 26 to 28°C. Hence, that indicates that although the SGW reduced the cooling load by a certain amount, there is still a need for mechanical cooling besides this reduction. Nevertheless, the advantage comes from lowering the energy consumption of the air conditioning system, which continuously reduces the mechanical cooling system dimensions, resulting in lower capital and operating costs for the cooling system over the building's life.

Comparative analysis of application classes of SGWs

Based on the above demonstration, the study conducted an analytical comparison among the SGWs, as in Table 4. It aims to identify and interpret their classes for considering them as new methods of saving energy, reducing the heat island phenomenon, encountering deterioration climatic, and controlling the building performance: thermal, environmental, acoustic, and visual. In addition, it would aid in understanding the SGWs application, using them, and integrating the natural environment with the built environment. The analysis will depend on the features, considerations, and sustainability aspects collected and itemized, as shown in Tables 1 and 2 (11 points), to be a guideline to specially select and design the appropriate system for the building's case.

A proposed framework to design, employ, evaluate, and develop a system of the green wall (SGW)

Accordingly, a framework can be formulated or devised as an execution plan to select and design the most suitable SGW according to the state and circumstances of the studied building. Furthermore, it is a tool to implement and evaluate SGW and work to develop it after completing its growth, as in Fig. 6, which consists of seven stages. Consequently, assessing the selected system performance can predict the full performance capabilities of the building under this living system:

Table 4 The analytical comparison of application classes of SGWs [7, 9, 11]

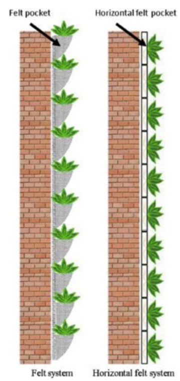
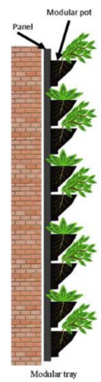
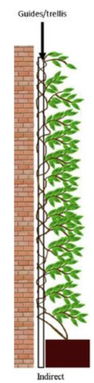
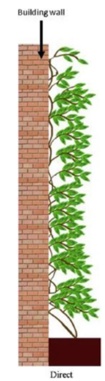
Po.	Features	Classes of Systems of Green Walls (SGWs)			
		Living walls		**Green facades**	
1	**Description**	Plants and their roots are in fixed units on walls.	Plants are up a net fixed to the wall and have roots not extending into the ground.	Plants are up a net fixed to the wall and have roots in the ground.	Plants are directly on the wall and have roots in the ground.
2	**Shape**				
3	**Impact on facades**	There is no effect of plants on walls as there is no direct contact as the units act as a buffer between plants and a wall.	The negative impact of plants on walls is less severe since the grid on the wall touches the facade walls less relatively.		The negative impact of plants on the walls is more severe since they directly touch the facade walls, such as moisture and insects.
4	**Irrigation system**	There is no effect on walls and foundations because the plants are watered by irrigation systems evolved.		In the case of not providing an isolated box for cultivation, there is a negative impact because irrigation is executed directly on the ground, which affects walls and foundations.	
5	**Rehabilitation and exchange**	It is easy to replace the damaged part without affecting the rest of the system.	The system is connected to the grid installed on it, but this does not prevent interference among plants, which hinders replacing and renovating parts of such systems.		The entire system is interconnected as one unit, so it is difficult or impossible to replace parts and is required to be replaced and renewed completely.
6	**Aesthetics**	It has an organized aesthetic shape, and color and size are controlled.	An organized aesthetic shape sometimes can be obtained.		An organized aesthetic shape is difficult to be acquired.

Table 4 (continued)

Po.	Features	Classes of Systems of Green Walls (SGWs)			
		Living walls		Green facades	
7	**The environmental impact on the system**	It is more resilient, and damages are partial.	It is relatively resilient to the plants holding onto the structure installed on the building.		It is quickly affected by the weather from wind and rain.
8	**Shades and shadows**	Shadows are from the units holding the plants.	The carrier grid controls the shadow shape.	Shades are provided to the facade equally by the plants themselves, and the shading degree depends on the plant density degree.	
9	**Technical staff**	High experiences		Intermediate experience	No experience
10	**Economy**	High cost	Medium cost		Low cost
11	**Types of buildings in which it can be applied**	It is suitable for making landscapes for aesthetic tall buildings and logos.	It is suitable for tall buildings; units can be repeated horizontally and vertically.	It is suitable for public and administrative buildings of limited height.	It is more suitable for residential buildings of limited height.

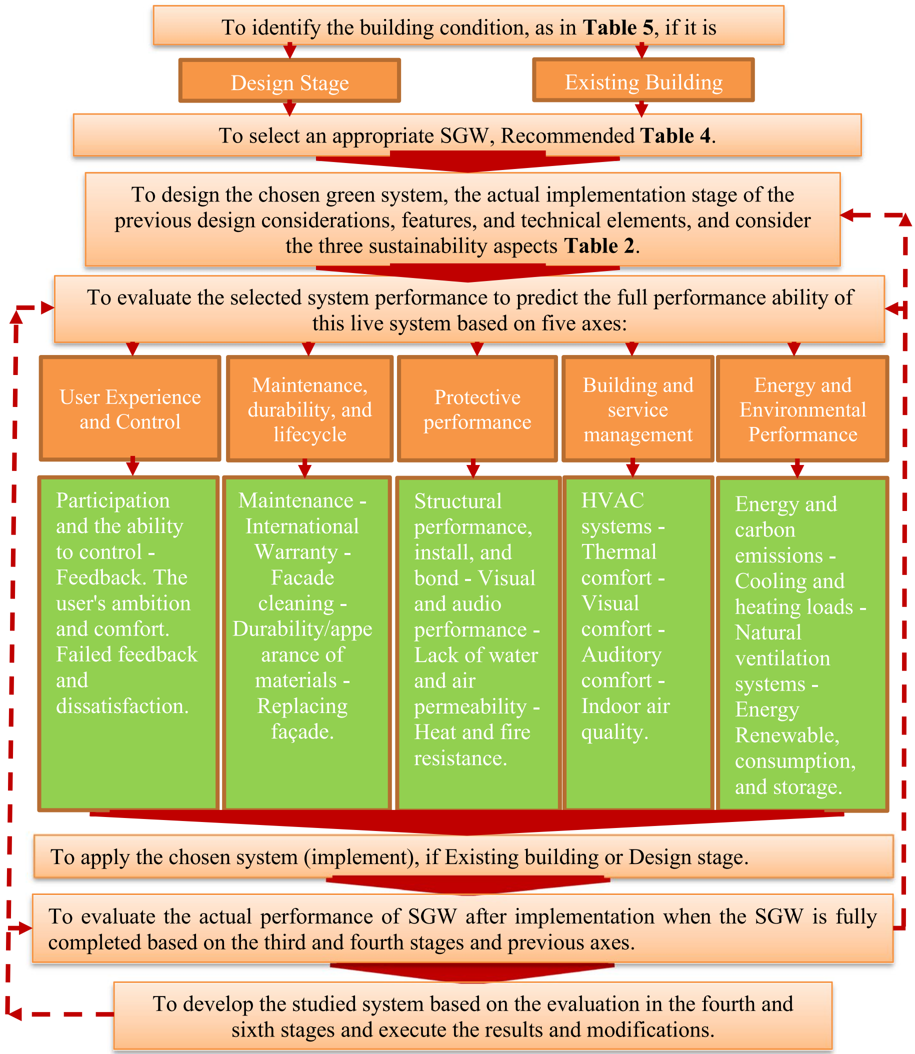


Fig. 6 The proposed framework of employing and dealing with systems of green walls (SGWs) efficiently to be the chosen system is the most suitable. The framework provides an implementation strategy for selecting and designing the most appropriate SGW for the circumstances and condition of the examined building, as well as a tool for implementing, evaluating, and working to improve SGW when it is completed

(1) The first stage (identification) is to identify the building circumstances or state if it exists or is in the design stage, where each case has unique considerations and actions, as shown in Table 5. It should be relied on the indicators of the three aspects of sustainability, as in Table 2, to ensure the success of SGWs while following their design considerations and activating the features and technical elements of such systems in the third stage.
(2) The second stage (selection) is to select the appropriate system, as in Table 4.
(3) The third stage (design) is to design the chosen system, as in Table 5. It is the stage of considering Tables 1 and 2 to ensure the success of such systems.
(4) The fourth stage (evaluation): after the identification, selection, and design stage, the performance evaluation of this chosen system comes. The SGW evaluation is

Table 5 Considerations and actions according to the building's condition, the second stage will depend on them to select SGW [6–9, 11, 13, 16, 17]

No.	Actions	Condition	
		Existing building	**New building (design stage)**
1	**Orientation**	The climatic conditions of each region and its thermal influence must be considered, and the adequate orientation to employ the SGW over the west and southwest facade in the case of the hot region.	
2	**Green system structure**	The vegetation system that grows on a structural system installed on the facade should be identified with the presence of a cavity, considering the reasonable insulation for the structural system of facades.	Both systems can be applied; plants that grow directly on the facade or plants that grow on a structural system installed on the facade with a cavity.
3	**The plant type used in the green system**	Climatic nature, in the case of the Egyptian climatic, it is preferable to use runners and ivy plants with an average Leaf Area Index (LAI) = 0.002 to 0.0065; The structural system type, the roots of plants growing directly on the facade or in containers hanging; and The used plant life cycle should not be less than 30 years, with the possibility of landscape renewal and modification.	
4	**Water insulation systems**	It should be selected systems integrated into insulation techniques to ensure that plant roots do not extend inside walls and existing openings.	There is the freedom to select the insulation system used according to the nature and concept of design.
5	**Structural load**	Plants' loads must be calculated in the climbing system directly on the facade, the steel installed with plants, or the suspended system with structural systems installed to ensure the building bearing.	Live and dead loads must be considered during calculating building loads to ensure the safety of a building.
6	**Facade coverage area**	If the design concept of the green facade systems includes 100% of the facade area, recommended using cable systems.	If the coverage area of the green facades ranges from 60 to 40%, recommended using modular units with the possibility of using cable and wire systems.
7	**Irrigation system**	In two conditions, the drainage nets of the green facade systems must be integrated into the building drainage, with developing a water management strategy, and considering utilizing gray water in the design.	
8	**Maintenance**	Maintenance is done once a year for the structural system to ensure its safety and twice a year to ensure the insulation quality. Yearly maintenance includes four courses to ensure that plants do not penetrate the facades and openings, preserve natural lighting, and provide the soil with the nutrients necessary for plants. A contract is to be made with the residents for 5 years after handing over the facility to sensitize residents about maintaining the planted facades and plants that have fully grown and fulfilled their purpose.	
9	**Follow green design standards**	Select the site to orient and produce the energy toward the sun's rays without obstruction; the topography is flat. Examine how the local climate affects the design. Simplify the building form to be the least complicated for easily insulating walls well. Design solar shading strategies and elements of the roof and facades provide shadiness and allow the sun's rays to heat different parts of them in winter. Determine the thermal insulation coefficient for thermal comfort.	

another major challenge after applying it to the facade. This adaptive facade type that reacts to outdoor influences and indoor needs requires an evaluation framework for its reliable use in new buildings or existing building renovation. The performance evaluation of the SGW is a standard that must be considered and established for predicting the full performance capabilities of this living system and how is the dynamic behavior of this system predictable and quantifiable. Improved standards and rigorous testing of components and dynamic behavior of any SGW are needed. That requires a combination of assessment methods and tools with new approaches to explore such green systems in the context of actual operation with buildings. It can rely on five axes that include a set of standards and performance indicators proposed for them, as shown in Fig. 6.

(5) The fifth stage (implementation) is to apply and execute the SGW, whether the building is existing or new (design stage).
(6) The sixth stage (evaluation after implementation) is the penultimate stage that must be executed either after 3 to 5 years as the maximum time limit starting from implementing the SGW or when covering the entire façade, whichever is closer to assessing the actual performance of the system when completed on the studied facade. This stage depends on the third and fourth stages to specify the criteria, considerations, indicators, features, elements, and axes utilized in the evaluation after implementation.
(7) The seventh stage (development) is to develop and treat the fully executed SGW based on the fourth and sixth stages to put the results into effect and make the required adjustments.

Inspect the feasibility and suitability of the proposed framework of SGWs

The practical survey aims were:

(1) To ascertain the feasibility and significance of the concluded framework
(2) To measure the suitability of the axes and stages of the proposed framework
(3) To explore if the concluded framework needs to develop or add another stage or benchmarks
(4) To appraise the competence of the application mechanism when handling these systems (SGWs) during all their life stages to be the most convenient

Through nine questions were seven questions related to the seven-stage of the deduced framework, as in Table 6, one question about the feasibility and significance of the concluded framework, and one question concerning the competence of the application mechanism. These questions ordered in the questionnaires were presented to the specialists and practitioners of the design and execution of green and sustainable buildings. Seventy-three persons were invited. Ultimately, only sixty-two (18 academics, 24 architects, and 20 practitioners) engaged in the survey study. Questionnaire answers relied on a 5-point Likert scale (5= strongly agree and 1= strongly disagree). They were examined and analyzed by the Statistical Package for the Social Sciences (SPSS). The descriptive statistics were computed and employed to interpret, organize, explain

Table 6 Questionnaire questions were relied on in the survey study

No.	Question about	Survey question
1	**Aim**	The components of the framework support the goal of improving the environmental and thermal performance of building envelopes.
2	**Stages**	The seven stages of this framework are sufficient to produce a suitable green wall system.
3	**Evaluation**	The role of the stage of evaluation of the selected system performance is to predict the full performance ability of this live system based on five axes and support the life cycle of the studied green wall system.
4	**Support**	The framework works on adjusting and developing the life of the green wall system that the study is working on to be the most suitable. Or the framework supports these systems with a certain percentage.
5	**Integration**	The framework supports the integration with the building, especially in the second stage, after checking via the fourth stage (the stage of evaluation) to realize the environmental and sustainable concept and improve the thermal performance.
6	**Green value**	This framework reflects sustainability and green value to be more suitable for the buildings that will be applied to and to have an influential role in reducing energy consumption and achieving heat comfort.
7	**Conceptual**	This framework develops the conceptual design toward improving thermal performance, reducing energy consumption, and achieving heat comfort.
8	**Mechanism**	These stages are considered a logical sequence of the framework for dealing with these environmental treatments, which are considered sustainable design treatments that are environmentally friendly and support the thought, concept, and trends of sustainability.
9	**Design**	The effectiveness of the devised and proposed framework in this study comes from its reliance on design considerations. As well as the technical features and elements of such systems and indicators of the three aspects of sustainability.

the data, and investigate frequency distributions of the responses through the questionnaires to identify and rate the significance of the stages and axes, besides the feasibility and mechanism. Finally, the statistical inference test was run through the chi-square test, as in Table 7.

The matched non-parametric chi-square test was utilized in this survey study because the not completed parametric hypotheses and the variables were measured on the ordinal scale to diagnose and explain the results. The chi-square test describes and demonstrates convergence and agreement in many of the responses; in case they tend more to any of the five points used by the Likert scale in the questionnaires. The chi-square test inspects and demonstrates the differences and agreements between expected frequencies and those observed or collected in surveys and questionnaires, whether a coincidence or an existing relationship among the studied variables [19]. Therefore, if the number of frequencies of responses related to a specific answer grows notably, the significance level and confidence degree in the results will increase.

Results and discussion

The framework with its seven stages, Fig. 6, is a tool that assists in achieving one of the strategies or methods of treating building envelopes and providing solutions to environmental problems in buildings. These stages are considered a logical sequence for dealing with such treatments that are sustainable treatments and friendly to the environment. Also, they support the thought, concept, and trends of sustainability. This framework optimizes the thermal performance of the building and its envelope, mitigates the heat island phenomenon, achieves human thermal comfort, and minimizes energy consumption in the shade of no strategy or implementation plan to deal with

Table 7 The descriptive statistics and chi-square test of the practical survey results of the questionnaires were computed by SPSS

No. of question	Question about	Minimum	Maximum	Mean		Std. deviation	Chi-square	df	Asymp. Sig.
		Statistic	Statistic	Statistic	Std. error	Statistic			
1	Aim	3	5	4.87	0.049	0.383	134.942a	2	0.000
2	Stages	3	5	4.76	0.059	0.468	94.861a	2	0.000
3	Evaluation	3	5	4.16	0.052	0.413	66.813a	2	0.000
4	Support	4	5	4.77	0.054	0.422	96.129a	2	0.000
5	Integration	4	5	4.94	0.031	0.248	155.806a	2	0.000
6	Green value	4	5	4.82	0.049	0.385	111.661a	2	0.000
7	Conceptual	4	5	4.68	0.060	0.471	71.161a	2	0.000
8	Mechanism	4	5	4.73	0.057	0.450	82.629a	2	0.000
9	Design	4	5	4.76	0.055	0.432	91.403a	2	0.000

Minimum and maximum, the chosen value of the answer is composed of 5 points used by the Likert scale about questions; *Mean—Statistic*, this indicates that the answers are closer to which point than 5 points on the Likert scale; *Mean—Std. error*, the maximum allowed error in estimating the mean is less than or equal to the standard error of the exploratory sample calculated by the researcher, which is one degree of importance equal to 0.1105; *Std. deviation*, the questions that have a lower value. The difference in views about the question is less; this indicates convergence and agreement in the responses; *Chi-square*, this value summarizes the difference between our data (observed) and our independence hypothesis (expected). There is a considerable degree of agreement among the respondents about one answer; *a*, 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 15.5; *df*, the degree of freedom is a number that determines the exact shape of the distribution. It is calculated by the number of rows and columns in the table frequencies of the questionnaire; *Asymp. Sig.*, the *p*-value is less than 0.05 indicating that there is a significant statistical difference that confirmed the convergence and agreement in the answers. There is a correlation between the participations' answers

such treatments (SGWs). The evaluation stage of the comprehensive performance of these systems (SGWs) at any stage during their life cycle comes to ascertain the effectiveness and comprehensiveness of this proposed framework as an implementation plan and a supportive methodology for dealing with envelopes, whether walls or facades. The efficiency of the devised framework is its reliance on design considerations. In addition, the features, principles, and technical elements of such systems and the indicators of the three aspects of sustainability that were deduced, collected, and classified from previous studies as in Tables 1 and 2 must be considered. Also, the green design standards must be followed for the success of SGWs when specifying the SGW type and its construction system according to the conditions, state, type, and function of the building, as in Table 5. Making an analytical comparison among SGWs was to identify, collect, and itemize the application classes of SGWs, as shown in Table 4, to be an aid for the designer in understanding the application of these systems, encourage their subsequent application, and integrate the natural environment with the built environment.

The performance of the selected system is evaluated based on five axes: energy and environmental performance; building and service management; preventive performance; maintenance, durability, the life cycle of the building, and the system itself; user experience and control. These axes are the most important results of the study to predict the full performance ability of such living systems. Consequently, the SGW performance evaluation stage constitutes a significant challenge, which is the fourth stage of the proposed framework. Such adaptive facades react to outdoor influences and indoor requirements that demand an evaluation framework for their reliable use in new buildings or renovations of existing buildings.

The possibility of applying and implementing these vertical green walls does not require high technologies and can be executed in developing countries. Their installation will harm buildings and users and bring opposite harmful effects indoors and outdoors, in case of absent supervision, engineering follow-up, and sufficient expertise, whether natural or constructed.

Through investigation and analysis, the two international experiments have the same variation of Egyptian climate to benefit from them while employing green wall systems during all stages of building:

- They demonstrated that the vegetation covering a facade is effective at thermal, acoustic, and visual performance levels both indoors and outdoors and energy equilibrium.
- The decrease in thermal energy resulting from penetrating solar rays is related to the thickness of the green wall system and the air cavity or the insulating space between the building and green wall system for one layer up to 37%, and with the five layers of paper up to 86%. The penetration measurement of the solar radiation of single-layer leaves equals 0.3, and for five layers of leaves equals 0.14.

According to previous studies, the electricity consumption is 5 to 10% used for cooling the increment of 0.5 to 3°C [5, 12]. Therefore, each decrease in the indoor temperature by 0.5 °C may reduce the electricity consumption by 8% of air conditioning in the summer. Also, vegetation can reduce energy consumption by 20%.

Studies have confirmed the exposure of vertical greening to many pests and insects for several reasons, and among the natural methods of pest control are the following [6, 12]:

- Plants' biological diversity
- Using insect-repellent plants
- Attracting predatory insects against agricultural pests

Many studies have addressed green wall systems regarding thermal performance; they have not considered operational and design performance over the system's life and after completing its growth [4, 16]. That is what the study tried to bridge and embrace in the proposed framework by evaluating and developing the comprehensive performance of SGWs.

Previous studies have considered these systems as a group of elements and classifications put upon the facades [11, 12, 17]. Nonetheless, they did not handle them as architectural treatments have environmental and parametric features that need mechanisms and design approaches that consider their life cycle and final form.

Several studies have shown that indoor temperatures have become close to the thermal comfort of 26–28 °C [5, 6, 10]. That minimizes the dimensions of the cooling system generally and decreases the capital and operating costs during the building life.

Previous studies have indicated that increasing vertical greening by 10% in cities reduces overall heating and cooling capacity by 5 to 10% [8, 12].

Conclusions

The main conclusion is the proposed framework to employ, utilize, and deal with systems of the green walls (SGWs) efficiently while choosing, designing, implementing, evaluating, and developing such systems to be the most suitable according to the circumstances and the state of a building. These SGWs improve the environmental and thermal performance of the building envelope that affects indoor environments and human comfort, conserving energy, rationalizing consumption, and reducing heat islands. This proposed framework is structured and built in seven sequential and overlapping phases to ensure succeeding SGWs. Consequently, the framework considers a mechanism, an execution plan, and a tool for evaluating SGW and working on its development throughout the building life, as a guideline to understand applying these systems, encourage their utilization, and integrate the natural environment with the built environment. The analytical comparison of the application classes of SGWs was conducted based on the features, considerations, and indicators of the three sustainability aspects associated with them, which were collected and itemized within the study sections. Also, the set of the concluded results and considerations from two international experiments had the same conditions as the Egyptian climate was discussed and investigated to benefit while choosing, designing, and evaluating SGW. The indoor and outdoor effects of SGWs were analyzed regarding the thermal performance, buildings' behavior, and surrounding environment and then classified into positives and negatives, whether indoor or outdoor, to emphasize the concept and role of SGWs. Accordingly, the vegetation becomes efficient concerning the buildings' performance (thermal, environmental, visual, acoustic, and economic), lowers the environment's temperature, increases the green areas, and achieves users' thermal comfort. Also, the negative impacts will be lower resulting from global climate change, energy consumption and electricity in the construction industry, and management and operation. There will be opportunities for further research and surveys on how to raise and improve the comprehensive performance of buildings or projects through these green systems and technologies for processing envelopes. Furthermore, there will be a need to adopt more effective methods for comprehensively handling such performance by relying on renewable energy sources and sustainable concepts and achieving the maximum possible savings in energy sources.

Abbreviations

SGW	System of green wall
SGWs	Systems of green walls
Bioshader	In Southeast UK, two—climbing plant canopies—were installed in an existing project and observed over 2 years
LAI	The leaf area index. This dimensionless quantity defines plant canopies, the one-sided green leaf area per unit of ground surface area
SPSS	Statistical Package for the Social Sciences. SPSS Statistics is a software package used for interactive or batched statistical analysis

Acknowledgements
Not applicable.

Author's contributions
The author read and approved the final manuscript.

Funding
This study had no funding from any resource.

Availability of data and materials
All data, models, and code generated or used during the study appear in the submitted article.

Declarations

Ethics approval and consent to participate
The submitted work is original and has not been published elsewhere in any form or language. The ideas, views, innovations, and results presented in the manuscript are mine unless otherwise referenced in the text. The works of others necessary for evaluating the study presented in this manuscript are referenced within the text and accurately listed at its end. The participation of respondents in the questionnaire during this survey was voluntary. All participants were over 22 years old. The article does not define the participants in any way and does not include any of their personal information. The author informed participants of the study objectives before agreeing to conduct the questionnaires.

Consent for publication
All participants of the questionnaire gave informed consent to participate.

Competing interests
The author declares no competing interests.

Received: 18 August 2022 Accepted: 12 October 2022
Published online: 27 October 2022

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