PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(4): 1055-1064
https://doi.org/10.14719/pst.4814

HORIZON
e-Publishing Group

REVIEW ARTICLE

Green horizons: Exploring the potential of vertical green walls

Jeyasurya T[1], C. Subesh Ranjith Kumar[1*], P. Irene Vethamoni[2], K. Sivasubramanian[3] & M. Djanaguiraman[4]

[1]Department of Floriculture and Landscape Architecture, Horticultural College and Research Institute, TNAU, Coimbatore - 641 003, India
[2]Horticultural College and Research Institute, TNAU, Coimbatore - 641 003, India
[3]AIRCRP IFS, Department of Agronomy, TNAU, Coimbatore - 641 003, India
[4]Department of Crop Physiology, TNAU, Coimbatore - 641 003, India

*Email: subesh@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 26 August 2024
Accepted: 29 September 2024
Available online
Version 1.0 : 22 October 2024
Version 2.0 : 27 October 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Jeyasurya T, Kumar CSR, Vethamoni PI, Sivasubramanian K, Djanaguiraman M. Green horizons: Exploring the potential of vertical green walls. Plant Science Today. 2024; 11(4): 1055-1064. https://doi.org/10.14719/pst.4814

Abstract

The term "Green walls" also known as vertical gardens or living walls has emerged as a promising solution to combat the environmental challenges posed by rapid urbanization. This review explores the concept ornamental, plant choice suitable and benefits associated with green walls in urban settings. Utilising vegetation to cover vertical surfaces, green walls offer several benefits to the environment, society and economy. They contribute to improved air quality, noise reduction, energy conservation and biodiversity enhancement. Vertical greenery allows for the utilization of unused wall surfaces, creating green areas without occupying valuable ground space, which is often scarce in urban environments. Additionally, green walls offer aesthetic appeal, promote urban agriculture and create opportunities for community engagement. However, their implementation requires careful consideration of factors such as structural integrity, irrigation and maintenance. Despite these challenges, green walls offer a sustainable and innovative approach to enhancing the quality of urban life while mitigating the negative impacts of urban development on the environment. The current emphasis highlights the significance of green walls as an effective tool in sustainable urban planning, underscoring the need for further research and their integration into urban planning practices.

Keywords

green walls; ornamentals; air quality; pollution; vertical garden

Introduction

Indeed, cities of today are greatly impacted by tons of pollution, minimal open spaces, the urban heat effect and depleting air quality. These issues do not only ruin the environment but also the health and well-being of the people who live in urban areas. With these problems, green walls do provide a new solution. It also makes vegetation present on vertical surfaces, thereby improving air quality, extensive green spaces, mitigation of urban heat and biodiversity enhancement, making this a sustainable approach toward a healthier and more resilient urban environment (1). These vertical structures are covered in plants, creating a vibrant and lush "tapestry" on buildings and other surfaces. Unlike traditional horizontal gardens, green walls save space and add an aesthetic touch while also improving the environment. The layers of soil and plants on a green wall also provide thermal insulation, controlling temperatures inside it. The natural insulation may reduce the need for heating and cooling systems, thus saving money on energy efficiency as well as lowering the quantity of greenhouse gases (2). Its process of evapotranspiration also aids in keeping cooler temperatures surrounding plants and will consequently reduce energy use. As cities strive for sustainability, green walls are becoming a popular architectural feature. By incorporating nature into urban designs, these walls promote harmony between development and the environment. Green walls not only provide ecological benefits, but they also enhance urban aesthetics. Ecological benefits like improved air quality, thermal regulation, noise reduction, increased biodiversity, aesthetic appeal, space efficiency and stormwater management (3). This combination makes them an appealing solution for creating more sustainable and visually attractive urban spaces.

Green walls

A green wall is a great solution for those living in urban areas with little acreage (4, 5). It offers numerous benefits to small urban spaces for storm water retention, humidity regulation, acoustic buffer and temperature moderation. Especially for storm water retention in green walls can absorb rainwater, reducing runoff and decreasing the strain on urban drainage systems. This can be particularly beneficial in flood-prone cities. Proper proliferation on walls and buildings typically requires a support framework (6) . Plant blankets, vertical modules, or pre-vegetated panels attached vertically to a frame or structural wall are examples of green wall construction. The panels or geotextile felts that support the plants are typically composed of concrete, metal, clay, synthetic fabric, expanded polystyrene or plastic (7, 8). Geo textile sheets are defined porous fabric, utilized to cover a variety of goals in civil engineering, landscaping and agriculture applications. For this reason, it can be applied in filtration, drainage, separation, reinforcement and protection. It is manufactured from synthetic fibers either polypropylene or polyester but has come to be used in different forms-woven, nonwoven or knitted.

Evolution and History

Green walls are an extremely ancient concept, dating about 2500 years back with one of the Seven Wonders of the Ancient World, namely the Hanging Gardens of Babylon. Among the most striking pieces of work, often considered a predecessor of modern green walls, was said to be erected by King Nebuchadnezzar II in about 600 BCE in the ancient city of Babylon, close to the modern-day country of Iraq. Therefore, as the legend says, these terraced gardens were constructed in the image of green hills of media as a gift to Amytis-wife of a king who was beloved and longed for. The gardens are an architectural as well as a wonderful engineering display as they have developed in a gradual sequence of stone tiered constructions decorated by many crops containing trees, shrubs and flowers that created an image of cascading greenery. Although the existence and details concerning the Hanging Gardens can never be confirmed to historians, they are oftentimes envisioned as related to current green wall systems that strive to integrate nature into the urban space through vertical planting and innovative design. The ancient gardens represented an ethos for a world where nature and human structures were connected-an ethos that modern sustainable architecture and urban greening practices draw upon today. The French botanist Patrick Blanc is credited with creating the current concept of green walls in the recent past. He is known as the Father of the Vertical Garden and is well-known for his exceptional "Mur vegetal" green walls (9).

Classification

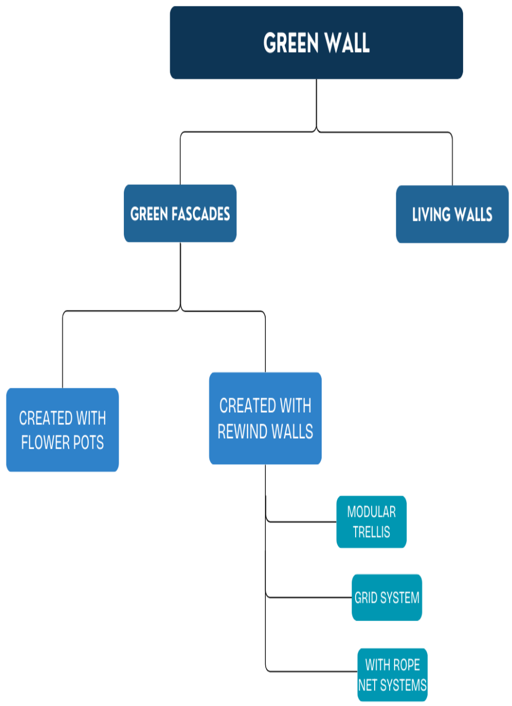

Fig. 2. Classification of green walls.

The Fig. 2. illustrate the 2 main categories of green walls: green façades and living walls. Green façades involve climbing plants that either grow directly on a wall or are supported by specially designed structures. The supporting materials like freestanding frames, planters or containers, hooks, wire, stakes and cages are used for the green wall. These plants are rooted in the ground, with their shoot systems growing vertically along the building's surface. In contrast, living walls consist of modular panels, typically made of polypropylene plastic containers, geotextiles, irrigation systems, growing medium and vegetation, all working together to create a vertical garden.

There are many commercially available living wall systems and they can be categorized in terms of different parameters. It was classified the living walls into 3 systems namely trellis, modular panel and felt layer systems (13). Trellis is structure used in gardening and providing support for climbing plants. Trellis enable gardeners to grow plants vertically, making efficient use of limited space (10). Modular panels of vertical greenery systems are pre-constructed units that can be used on a building façade, providing benefits both aesthetically and ecologically. It states that they are usually made from materials like plastic, metal or recycled products

Fig. 1. Setting up a felt - integrated living wall.

a) Planting in module (b) Sheet is covered with foliage

Fig. 1. (a) A trial planting was conducted using a geotextile sheet, which was secured in place with hooks for support. The growing medium used in this setup consisted of a mixture of coco peat and perlite in a 2:1 ratio.

Fig. 1. (b) It took two months for the plants to fully cover the sheet after planting.

and are very easy to interchanged or expanded according to needs (11). Felt layer systems have benefits like easy installation, lightweight structure and flexibility in plant selection, making it the best answer for vertical greening options to establish in the urban area (12). They can be decorative elements in gardens, adding visual interest and structure to outdoor spaces. This classification is based on the characteristics of the plant box (13).

Layers of green wall systems

The typical components of a green wall system are a growing medium, container, irrigation system, waterproofing layer and structural support (13, 14). The application of a waterproofing layer is crucial for vertical green walls to prevent water seepage. This can be achieved using materials such as APP membrane, waterproof coatings, cement-based polymers and acrylic-modified coatings. These solutions effectively safeguard the structure by creating a barrier against moisture intrusion (15).

Vegetation layer

The vegetation layer is also known as plant canopy layer is the aesthetic layer of living walls, and probably the most important part that identifies a living wall as an environmentally friendly product. The vegetation layer is the critical element for all the environmental benefits of living walls (16). Because of the core role of the vegetation layer in the living walls, it is necessary to understand the requirements for plants survival, such as light and microclimate. The vegetation layer Improves air quality by absorbs CO_2 and other pollutants while releasing oxygen and photosynthesis. Plant can filter particulate matter and volatile organic compounds, leading to cleaner air in urban environments (17). This shall serve as a natural insulator, thus lowering the absorption of heat in summer and heat loss in winter. Such thermal regulation can result in lower consumption of energy for heating and cooling (18). The vegetated areas provide habitats for several species, thereby contributing to urban biodiversity. They generate ecological corridors that help the movement of wildlife into a more resilient ecosystem and environment (11).

The plants, if chosen correctly, require attention only 3 to 4 times a year to remove dust, wilting foliage and dead plants (19) (For example, Pothos, *Philodendron* spp., *Syngonium* spp. and Bird nest fern). In different greening systems, the plants should be selected accordingly. When choosing the climbers for the indirect greening system, the height should be considered. Some climbers can grow 5 to 6 m high; others can grow up to 10 m and some species can even reach 25 m (20). For the modular panel system, the plant type is normally evergreen (14). Since evergreen plants photosynthesize year-round, they continuously absorb carbon dioxide and release oxygen, which contributes to air purification. In addition, their foliage provides heat control for the buildings, reducing energy demand for heating and cooling all through the year (12). Evergreen species tend to be more durable and require less upkeep than deciduous plants, since evergreens do not lose their leaves seasonally. It decreases the need for frequent servicing and is far better suited for vertical and rooftop installations (21).

Selecting plants for green walls

The following criteria should be taken into account for plant selection (21).

Based on orientation of wall

The orientation and placement of the wall should be taken into account while selecting the perfect plants (20). The amount of heat and solar radiation that the wall absorbs will depend on its orientation. East-facing walls are more affected by temperature swings in the morning and west-facing walls absorb the most heat in the afternoon. While south-facing walls continually retains heat during the day and stay at higher temperatures for the longest, north-facing walls stay reasonably cold throughout the day. The longest stretch of high temperatures usually occurs in regions that face south (22).

Based on amount of sunlight received

The exposure of a part of the green wall should influence the choice of plants since it usually receives more direct sunlight than at ground level, as there are no trees or shrubs to provide shade or evaporative cooling. Sun-tolerant plants that can tolerate high temperatures and strong winds tend to flourish in the most exposed areas and some of the examples of Sun tolerant plants like *Cordyline* spp., *Philodendron* spp., *Coleus* spp. and succulents. Concomitantly, shade and moisture-loving plants would be set up on the bottom of the wall, thriving on light conditions that are lower and cooler (23).

Based on morphological and physiological attributes of the plant

Relatively less height, mat formation or dense tufting is often required to prevent the plants from wind damage and uprooting. Plants anchoring into the substrate with fibrous roots or underground storage organs are ideal for small amounts of substrate material and are often less prone to drought damage. Succulent leaves, compact twiggy growth, small evergreen leaves, leaves with a thick cuticle-are all adaptations to water loss that become necessary when exposed to green wall conditions. Rolled leaf margins or glaucous foliage colour reduce the angle of impact from solar radiation (20). Based on these trials in Singapore, over a 6 months period, a list of suggested plants for vertical greening in the tropics was given (24). The plants are *Scindapsus pictus, Tristellateia australasiae, Cryptanthus bivittatus* and *Nephrolepis falcata*. Generally, the suggestions are for the adoption of plants that can bear high temperatures and high sunlight input together with low soil moisture. Those with thick and dense coverage and that resort to crassulacean acid metabolism were considered preferable. CAM (Crassulacean Acid Metabolism) is a special photosynthetic pathway that some plants have-in particular those which thrive in extremely hot and dry regions. They do not use carbon dioxide (CO_2) during the hot day or sunshine but instead absorb CO_2 at night time, when it's cooler. They store this CO_2 within the plant as an acid, which they will later use during the day for photosynthesis. This process has the advantage of conserving water and proves a good strategy for arid habitats.

According to a study, ideal green wall plants should possess fibrous root systems, strong stem-to-root connections, resistance to wind buffering and good growth habits (25). Plants naturally found on cliff tops or cliff faces are particularly well-suited for vertical gardens, as these environments share similarities in terms of substrate scarcity, wind exposure and water availability. Examples of such plants include species like *Sedum* spp. and *Saxifraga* spp, which thrive in rocky, vertical environments. Caution against the use of monocultures in green walls, as these bear a high risk of failure through problems in cultivation or pathogen attack, plant growth habits and stress tolerance (20). Instead employing a range of species is recommended to combat the microclimate differences that are likely to exist within the one wall. Plants that have a clumping rather than an upright growth habit are recommended. However, it's advisable to avoid high-vigor species as they may overshadow neighbouring plants and place excessive strain on the support structure. Opting for dwarf varieties could help minimize the need for costly pruning in a vertical garden system. For new vertical green systems, incorporating stress-tolerant species that are well-suited to the local climate could help meet the goal of reducing the energy requirements associated with this cultivation technology (26).

A desirable rooting system provides good anchorage for the plant, binding the substrate together. To combat erosion, this is done by the action of strong winds or heavy rainfall. It is best achieved by the use of species with a shallow, dense rooting system that have stems that root into the substrate as the plant grows (20).

A study suggested that use of modules pre-cultivated in nurseries can be a good potential solution for vertical gardening and reported that full efficiency of vertical vegetation can only be achieved by a high leaf area index per facade unit (27).

Relative water content has been identified as a more significant indicator of water status than other parameters under drought stress circumstances and green wall plants should be drought tolerant. Because of its close relationship to volume, it more accurately represents the equilibrium between the rate of transpiration and the water supply to the leaf (28). Numerous leaf physiological parameters, including turgor, growth, stomatal conductance, transpiration, photosynthesis and respiration are closely correlated with the water status of the leaves (29).

Since the plant species grown in green walls are exposed to extreme temperature in tropical conditions, The Chlorophyll Stability Index (CSI) is an indicator of heat and other stress tolerance capacity of plants and is a measure of integrity of membrane. Recommended the usage of plants with higher heat tolerance and water stress for green walls under tropical conditions (24).

Plant species suitable for green walls

Green walls support many plants, including climbing plants, ferns, shrubs, ground covers, perennial flowers and edible herbs (30). According to a study, the plants suitable for outdoor green wall are limitless (23). The choice of plants varies with local climatic conditions, the rates of growth and structural aspects of each species. Tested the adaptability of *Myrtus communis* L. to vertical cultivation in a

Mediterranean climate (26). The modular living wall system REVIWALL® (Reviplant Nursery, Revigliasco, Turin, Italy) was used. The trial was carried out from April 2010 to November 2011 at Antibes (France). On each of the 4 exposures (North, South, East and West), 3 repetitions of 3 modular panels (40 x 50 cm) with 18 plants were prepared. The plants used in the experiment were grown in pots of 13 cm diameter and pruned at the end of the first vegetative period. The automatic fertigation system was programmed according to environmental conditions. Data was collected every 3 weeks from June to November over a span of 2 years. The measurements taken included growth index, coverage index, ornamental value and both fresh and dry weights. No significant differences were observed in growth index and coverage index across the 4 treatments during the 2 growing seasons. By the end of 2010, plants achieved full coverage of panel surfaces in all exposures, demonstrating excellent ornamental qualities. The conclusion drawn is that *Myrtus communis* is a promising species for vertical greening, potentially making a significant contribution to the spread of this innovative technology in Mediterranean urban landscapes. A study mentioned the usage of plants such as *Ficus* spp., *Schefflera, Rhoeo discolor, Pandanus* spp., *Philodendrons* spp., *Nephrolepis* spp., *Pilea, Syngonium podophyllum, Ophiophogons* spp., *Chamaedorea* spp., *Spathiphyllums* spp., *Pepromia* sp. and *Sanseveria* spp. in tropical green wall conditions (23).

The advantages of using this vertical garden include faster plant growth, lesser plant infections and diseases, lighter cultivation media and the possibility to recuperate drainage to be recirculated (31-33).

Growing medium

The growing medium affects both the thermal performance and water retention of green vegetation (34). Additionally, it gives plants the nutrients and water they require for biological processes (8). In order to resist wind force and other harsh weather conditions, the plant roots will penetrate and become stronger inside the medium.

The growing medium in the green roof systems has a high content of porous minerals and low organic matter content, to balance weight against performance (35). The growth medium in green walls has the same basic properties, for it provides the vegetation with its needs of nutrition. Regular natural growth medium is soil. However, soil can have clay and organic particles which may be heavy when saturated, since the nutrient in the soil is limited, its replacement will bring up more cost and hassle (16). Many producers are creating their own growing media in response to that constraint. Around the world, hydroponic systems in living walls are common systems for plants growing without soil. In such case, nutrients are provided through irrigation water (36).

Plants in a hydroponic system release microorganisms into the root zone that are simulated by carbon and grow in the rhizosphere. The ability of the hydroponic growing medium to hold water and have air-filled porosity is the 2 most crucial properties needed for root production (37). In hydroponic growing media, 3 porous materials-grow stone, expanded clay and activated carbon-are utilized to investigate the effectiveness of living walls in enhancing indoor air quality. Researchers from Canada and New Zealand assessed the use of biochar as a hydroponic growing medium. Enhancing nutrient retention and reducing greenhouse gas emissions from soil, like nitrous oxide (N_2O) and methane (CH_4) were 2 benefits of biochar (38).

Container

The growing medium and the vegetation are supported by the container in the living wall system. Plants in trellis systems are typically started in flowerpots and work their way up the trellis. The flower pot may be placed on the ground next to the façade or at various heights within it (13). In modular panel systems, containers of various sizes and types are typically affixed to the wall structure or a vertical support. There are generally 2 main types of modular containers. The first type is the true box system, which consists of empty square containers made from materials like plastic or metal. The number of plants per box varies depending on the species and box size, typically ranging from 6-15. These boxes usually measure around one square foot and are a few inches thick, though sizes can vary by manufacturer. The second type comprises plastic or metal trays with multiple slanted cells. These slanted cells help secure the plants and facilitate irrigation. These trays are commonly placed side by side and stacked to increase height (36).

The felt pocket in the felt layer system is often connected to a waterproofing layer before being fastened to the rear of the building (13). Patrick Blanc designed a distinctive green wall system featuring 2 layers of synthetic fabric with felt pockets (23). This fabric is mounted on a frame and reinforced with a waterproofing layer at the back (9). In summary, the materials commonly used for containers include fiber, plastic, felt, aluminium, steel and wood. Each material can have varying impacts on environmental sustainability. Factors such as durability, cost, thickness and weight of these materials can affect both the functional and aesthetic qualities of the containers (39).

Irrigation system

The irrigation system is essential because it represents the fact that water and nutrients are provided to the vegetation by a certain mechanical or natural irrigation system. Because of this, it is crucial to introduce some sort of control and timing of the irrigation system to ensure there is regular and safe provision of water (13). Various irrigation systems are available for different living wall setups. Traditionally, irrigation was done manually, but nowadays, drip systems using gravity have become a common alternative. An experiment was conducted using a timer-controlled irrigation system to evaluate the thermal performance of a vertical living wall (40). By maintaining a fixed irrigation schedule, the moisture level was kept between 20 % and 45 % throughout the study to optimize cooling effects. Gravity guided the moisture distribution within the growing medium. To ensure optimal plant conditions, moisture sensors must be installed in the growing medium. In the commercial market, various irrigation systems are available for different living wall setups, including computerized vertical drip systems, individual drip irrigation systems and water-retaining irrigation systems.

In order to irrigate 1 m^2 of plants on a vertical surface, an efficient irrigation system might dispense roughly 2.5 L twice a day. This is comparable to the typical landscaping usage rate of 4 to 5 L m^{-2}. A vertical garden's top or bottom can be used to collect and store rainwater in a storage tank. Maintaining the water source and storage tank at the top allows for gravity-based irrigation, which also saves energy. The excess rainfall can then be pumped up and used again after collecting on trays or catch basins at the base (41). It has been demonstrated that the substrate moisture content of a modular green wall panel varies from 15 to 45 % (v/v) at the top and bottom (40).

As a study suggested, for a living wall watering occurs 3-5 times a day, depending on the season and the vertical garden's exposure (23). Each watering lasts for 1-3 min depending on the height to be irrigated. In order to maintain a mineral balance throughout the root systems, a highly diluted nutritive solution 0.2 to 0.3 g^{-1} is distributed with the help of a mechanical dispenser or a fertigation unit.

Structural layer

The structural support serves as the living wall system's framework. In general, the elements differ and are not the same in outdoor and interior settings. The structural layer must support the loads from every other layer. If the living wall is situated outside, the structural support must also withstand additional loads from wind, rain or snow. To support the climbing plants, the trellis system often includes mesh structures, wired structures or modular trellises (8). This system is simple without too many components; thus, the support structure does not need to support extra weight in addition to plants. The felt layer system and modular system are similar in structural support as both felt layers and modular panels are attached directly to the structural frame. Highlighted the possibility of using non-rusting metals such as stainless steel, aluminium or galvanized steel to provide structural support for felt layer or modular systems (36). If the pricing is right, hard wood might make a stronger structural support for both indoor and outdoor areas because it is more environmentally friendly than steel and plastic (39).

Waterproofing layer

Typically, a waterproofing layer is applied to the building wall to create a protective membrane. Since this layer is usually attached to the structural support, it prevents moisture from penetrating behind the waterproof membrane and impacting the building façade (36). The waterproofing layer ensures that the whole irrigation system can work normally without leakage since leakage in an operational living wall system may consequently require it to be removed altogether. Traditional waterproofing materials are PE, fleece and low-density polyethylene- (LDPE) (39).

Social and environmental benefits

The benefits of green vegetation have been the subject of numerous claims in contemporary literature. Enhancing human health and well-being, lowering energy costs, lowering noise pollution, improving air quality, enhancing water-sensitive urban design (WSUD), boosting urban biodiversity and food production and lessening the impact of the urban heat island effect (UHI) are just a few of the environmental advantages of green vegetation, which includes living walls and green roofs (7, 40, 42-48).

Air quality improvement

It is evident that vegetation of living walls can clean the air. A study claimed that airborne pollutants including nitrogen oxides, volatile organic compounds (VOCs) and dust can be reduced by potted plants because they can absorb carbon dioxide, produce oxygen through photosynthesis and improve air quality (47). Plants could therefore greatly enhance interior air quality. At the University of Technology Delft also found that green vegetation can reduce the number of particulates (<10 μm) that are a threat to human health in the long run (39). The green vegetation present within an area also helps reduce the pollution of air by absorbing the toxic gas coming out from the vehicles. Based on one indoor gas heater-based indoor studies of air quality conducted in UK, found that 6 or more potted plants in the house could reduce one third of nitrogen dioxide (NO_2) levels (49). In a study of Korean native indoor species, showed that indoor plants absorb and metabolize sulfur dioxide (SO_2) (18). Some additional studies showed that plants effectively reduced levels of particulate matter, ammonia, formaldehyde, benzene and nitrogen oxides (50). Additionally, by releasing moisture into the air, plants can raise the relative humidity inside and improve comfort in enclosed spaces (51).

It was reported that vegetation in living walls and green roofs helps reduce air pollution through photosynthesis (45). In this process, 155 m^2 of plant surface area can generate enough oxygen to sustain one person for 24 h. Additionally, living walls and green roofs naturally filter the air, reducing the concentration of harmful gases and particulate matter such as nitrogen dioxide, sulfur dioxide, ozone, carbon monoxide, dust and ash. It is estimated that 1 m^2 of green roofing can remove 0.2 kg of airborne particulates from the air annually.

Thermal regulation and insulation properties

Green roofs and living walls contribute to the cooling and insulation of a building. Green roofs may reduce heat loss from the building in winter and heat gain into the building during summer; they also add thermal mass, which will help in maintaining constant internal temperatures throughout the year (52). According to research, green roofs can save non-insulated buildings up to 37 % on energy costs (53). Due to the insulating effect of the air layer between the facade and the living wall, the living wall adds another layer of insulation to the building envelope. In warmer climates, the phototropism effect produced by the living walls can filter sunlight, assuring a cooling impact. 5 to 20 % of the sunlight that strikes the leaves is used for photosynthesis, while the remaining 15-20 % is reflected, 20 to 40 % is used for evapotranspiration, 10 to

50 % is converted to heat and just 5 to 30 % of the sunlight gets through the leaves.

Studied that even when the sun sets, the interior climate can be impacted by the green vertical cladding since it may lessen the effects of solar heat (54). Living walls can provide shade, which can lower interior temperatures considerably in the summer and save up to 23 % on energy bills. (27).

An experiment conducted in Greece during the winter compared the thermal performance of a bare concrete wall with that of a plant-covered building façade (22). The study found that the surface temperature of the bare wall sections was significantly higher than that of the plant-covered sections, with the plant-covered areas experiencing a temperature reduction of up to 10.8 °C.

A research conducted in Singapore's Hortpark on a free-standing wall (41). The findings demonstrated that the vertical greening system might lower temperatures up to 11.6 °C. It was found that a key strategy for lowering the amount of energy used for heating and cooling a structure is to add greenery to the building envelope (55). The energy savings might range from 35 to 90 %, depending on the type of climate and the quantity and placement of plants on a building.

Insulated walls increase a building's interior temperature in the summer, putting more strain on cooling systems and consuming more energy. A green wall's surface temperature can drop up to 10 °C when it is covered in plants and wet soil. Research on green walls was published in 1979 by Akira Hoyano, a pioneer of low-energy and passive architecture from Japan. It revealed that the amount of heat energy traveling through a green wall was significantly less than that of a concrete wall.

Coverage of a concrete wall with modular vegetated panels reduced exterior wall temperatures up to 16 °C in summer. In terms of internal wall temperatures, the authors found a difference of more than 2 °C maintained even late at night, indicating that green walls have significant ability to reduce power consumption for building cooling (41). A study shown that in a system consisting of solar panels, a living wall and a green roof, the cooling factor of the living wall and green roof could increase the performance of the solar power harvest from 2 to 12 % (56).

Urban Heat Island Effect

With urban expansion areas, the prevalence of building materials and the reduction of vegetation have significantly altered city climates. These changes have led to an increase in temperature, especially in the inner or central parts of cities, a phenomenon known as the Urban Heat Island (UHI) effect (57). Urban Heat Island effect is the phenomenon by which the urban surroundings experience a higher temperature than their rural environment, mainly caused by human activities and infrastructures. Generally, rural surroundings are more towards vegetation and their infrastructure is less dense as in an urban setting, hence it reduces the UHI effect due to reasons like coverage by vegetation, lower impervious surface, lower population density and natural landscapes. The same case does not occur in the rural area because the evapotranspiration produced by trees and plants is of great support in regulating the ambient temperature (58). By evapotranspiration, it is the process by which water moves from the land to the atmosphere. This is when water from surfaces like soil and water bodies turns into vapor and rises into the air. The green vegetation tends to lower temperatures, which helps to mitigate the Urban Heat Island effect. The average temperature difference between a building facade covered with flora and one that is bare is 5.5 °C, according to academics from Lleida, Spain. However, in September, the difference can rise to a maximum of 17.6 °C in the northwest of the structure of Spain features diverse landscapes, including mountains and valleys, which can influence local climate conditions. Elevation changes can lead to cooler temperatures in some areas while others may heat up more (59).

A study quantified the performance of green vegetation in the hottest month in Hong Kong; these results indicated that an urban canyon could have up to an 8.4 °C maximum temperature decreases if it is 5-15 m wide, 5-10 m high and with vegetation on both walls and roofs (55).

Sound absorption

Hard surfaces in urban areas tend to be more reflective to sound, whereas plants can absorb sound waves depending on the characteristics of the substrate and vegetation (44). Plants contribute to sound absorption, diffraction and reflection, with the effect varying based on the sound frequency and the nature of the space. At lower frequencies, plants may cause sound to diffract, while at higher frequencies, they may reflect sound onto other surfaces, which can then absorb it (60). According to a

Table 1. Common plant used in different types of vertical gardens (66).

Types	Plant list
Green Facades	*Aristolochia* spp., *Jasminum officinale, Polygonum bauldschianicum, Lonicera* spp., *Hedera helix, Clematis* spp., *Passiflora caerulea, Parthenocissus* spp., *Hydrangea petiolaris,* etc.
Living Wall	*Syngonium* spp., *Philodendron* spp., *Scindapsis pictus, Tradescantia zebrina, Thaumatophyllum xanadu, Euonymus fortune, Cotoneaster hedera, Maranta* spp., *Tradescantia* spp., *Chlorophytum* spp., *Haworthia* spp., *Dracaena, Phalaenopsis* spp., *Cordyline* spp., *Parthenocissus, Fittonia* spp., *Asparagus sprengeri, Kalanchoe, Gardenia* spp., *Nephrolepsis, Clematis, Asplenium nidus.*
Exterior Wall	*Rosmarinus* spp., *Thymus* spp., *Lavendula* spp. or *Salvia* for full sunlight while *Fuchsia* spp., *Asplenium* spp., *Davallia* spp., *Begonia* spp. and *Arum* spp. for shady locations.
Interior Wall	*Begonia* spp., *Epipremnum* spp., *Saintpaulia* spp., *Columnea* spp., *Aeschynanthus* spp., *Philodendron* spp. or different ferns like *Pterisandmany* spp., *Nephrolepis* spp., species of *Peperomia.*

study, green walls can lead to a consistent and significant reduction in sound, particularly in areas where only diffracted sound waves are present (61).

Sound absorption coefficient was calculated in a study conducted at Hort Park, Singapore, with the involvement of 8 living walls. The results indicated that vegetation on living walls possesses one of the highest sound absorption values compared to other regular building materials. Vertical green walls, with their layers of soil and vegetation, can effectively reduce sound transmission. The porous nature of the growing medium and the irregular surfaces of plants disrupt sound waves, absorbing more sound than hard, flat surfaces like concrete or glass (62). In addition, the value of the sound absorption coefficient increases at higher frequencies (63). Once more, it was noticed that the coefficient of sound absorption rises with higher vegetation cover (62).

Aesthetic and psychological benefits

Plants and greenery can provide uplifting and calming effects on people whilst having a positive impact on stress -related illnesses. Studies have shown that viewing of greenery increases workplace productivity and patient recovery rates in hospitals (64). In that biophilic design is an architectural and planning approach that seeks to connect people with nature through the integration of natural elements into the built environment. This concept emphasizes the importance of nature in enhancing human well-being, promoting psychological benefits and improving overall quality of life (63).

Ecological preservation and beautification

Besides this, it also contributes to the preservation and protection of habitat, flora and fauna because the living wall replaces the land taken up by buildings and therefore preserves the biological diversity. It thus enhances the urban habitat for birds and butterflies. Its movement, color, sound and texture of plants add to the general health and well-being of the citizens, beautify the barren eyesores of our cityscape and provide unique opportunities for design and creativity as well as health and horticultural therapy applications (19).

It was explained that by using selected plants, a green wall can significantly increase both the number and variety of insects and birds in an area and help return a more sustainable ecosystem to urban ecosystem (65).

Green walls can function as part of ecological corridors that connect fragmented habitats in urban areas. This connectivity allows for the movement of wildlife, including pollinators and small mammals, between green spaces, parks and gardens.

Conclusion

In summary, green walls provide significant advantages as sustainable solutions to urban environmental challenges. They improve air quality, reduce noise, save energy, attract wildlife and enhance aesthetics, fostering healthier cities. As urbanization and climate change create pressing issues, integrating green walls into urban planning is essential for promoting sustainability. Ongoing research, innovation and collaboration are crucial to maximizing their potential and benefits.

Acknowledgements

The authors acknowledge the company M/S. Grand Gover Horticulture L.L.C Dubai for funding the research and providing fellowship for the student and materials sponsored for research by Verdure India Landscapes, Chennai.

Authors' contributions

TJ collected literature and wrote manuscript, CS helped in securing research funds, editing, summarizing and revising the final manuscript, PI helped in approved the manuscript, KS helped in summarizing and revising the manuscript, MD helped in summarizing and revising the manuscript. All authors read and approved the final manuscript

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

References

1. Palermo S, Turco M, editors. Green wall systems: where do we stand? IOP Conference Series: Earth and Environmental Science; 2020:IOP Publishing. https://doi.org/10.1088/1755-1315/410/1/012013
2. Köhler M. Green facades-a view back and some visions. Urban Ecosystems. 2008;11:423-36. https://doi.org/10.1007/s11252-008-0063-x
3. Sheweka SM, Mohamed NM. Green facades as a new sustainable approach towards climate change. Energy Procedia. 2012;18:507-20. https://doi.org/10.1016/j.egypro.2012.05.062 .
4. Utami S, Jayadi R, editors. Vertical gardening for vegetables. Ist International Symposium on Sustainable Vegetable Production in Southeast Asia 958; 2011. https://doi.org/10.17660/actahortic.2012.958.23
5. Binabid J. Vertical garden: The study of vertical gardens and their benefits for low-rise buildings in moderate and hot climates. MBS, University of Southern California. 2010;126. https://doi.org/10.1515/9783034610452.9
6. Green B. A guide to using plants on roofs, walls and pavements. Mayor of London Greater London Authority. 2004. https://doi.org/10.4324/9781843146575-81
7. Wuolo AA, Emilsson TT. Plant performance in living wall systems in the Scandinavian climate. Ecological Engineering. 2014;71:610-14. https://doi.org/10.1016/j.ecoleng.2014.07.027
8. Franco A, Fernández-Cañero R, Pérez-Urrestarazu L, Valera D. Wind tunnel analysis of artificial substrates used in active living walls for indoor environment conditioning in Mediterranean buildings. Building and Environment. 2012;51:370-78. https://doi.org/10.1016/j.buildenv.2011.12.004
9. Roofs G. Introduction to green walls technology, benefits and design. Estados Unidos: Greenroofs org. 2008. https://doi.org/10.2307/j.ctv3dnqpr.6

10. Hansen G. Arbor, trellis or pergola- what's in your garden? A Mini-Dictionary of Garden Structures and Plant Forms University. 2010. https://doi.org/10.32473/edis-ep432-2010
11. Primmer E, Jokinen P, Blicharska M, Barton DN, et al. Governance of ecosystem services: a framework for empirical analysis. Ecosystem Services. 2015;16:158-66. https://doi.org/10.32473/edis-ep432-2010
12. Ottelé M, van Bohemen HD, Fraaij AL. Quantifying the deposition of particulate matter on climber vegetation on living walls. Ecological Engineering. 2010;36(2):154-62. https://doi.org/10.1016/j.ecoleng.2009.02.007
13. Loh S. Living walls-a way to green the built environment. Environment Design Guide. 2008;1-7. https://doi.org/10.1016/j.dibe.2021.100043
14. Perini K, Ottelé M, Haas E, Raiteri R. Greening the building envelope, façade greening and living wall systems. Open Journal of Ecology. 2011;1(01):1. https://doi.org/10.4236/oje.2011.11001
15. Brock L. Designing the exterior wall: An architectural guide to the vertical envelope: John Wiley and Sons; 2005. https://doi.org/10.1080/00038628.2012.697863
16. Bianchini F, Hewage K. Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach. Building and Environment. 2012;58:152-62. https://doi.org/10.1016/j.buildenv.2012.07.005
17. Tzoulas K, Korpela K, Venn S, Yli-Pelkonen V, Kaźmierczak A, et al. Promoting ecosystem and human health in urban areas using green infrastructure: A literature review. Landscape and Urban Planning. 2007;81(3):167-78. https://doi.org/10.1016/j.landurbplan.2007.02.001
18. Lee J, Sim W, editors. Biological absorption of SO_2 by Korean native indoor species. Towards a New Millennium in People-Plant Relationships, Contributions from International People-Plant Symposium, Sydney; 1999. https://doi.org/10.1201/9780203743942-17
19. Ranchana P, Vasudevan V, Vinodh S, Benny E, et al. Green wall: A recuperative strategy for urban life style. 2023 https://doi.org/10.59317/9789390512928
20. Dunnett N, Kingsbury N. Planting green roofs and living walls: Timber press Portland, OR; 2008. https://doi.org/10.2134/jeq2008.0016br
21. Francis RA, Lorimer J. Urban reconciliation ecology: the potential of living roofs and walls. Journal of Environmental Management. 2011;92(6):1429-37. https://doi.org/10.1016/j.jenvman.2011.01.012
22. Kontoleon K, Eumorfopoulou E. The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Building and Environment. 2010;45(5):1287-303. https://doi.org/10.1016/j.buildenv.2009.11.013
23. Patrick B. The vertical garden: from nature to the city: W. W. Norton and Co.; 2008. 192. https://doi.org/10.1093/ww/9780199540884.013.283009
24. Chiang K. Vertical greenery for the tropics: National Parks Board; 2009. https://doi.org/10.1093/ww/9780199540884.013.255870
25. Hopkins G, Goodwin C. Living architecture: green roofs and walls: Csiro Publishing; 2011. https://doi.org/10.1071/9780643103078
26. Devecchi M, Merlo F, Vigetti A, Larcher F, editors. The cultivation of mediterranean aromatic plants on green walls. III International Conference on Landscape and Urban Horticulture 999; 2011. https://doi.org/10.17660/actahortic.2013.999.34
27. Domurath N, Schroeder F-G, editors. Vertical hydroponics for urban areas. International Symposium on Soilless Culture and Hydroponics 843; 2008. https://doi.org/10.17660/actahortic.2009.843.32
28. Dhanda S, Sethi G. Inheritance of excised-leaf water loss and relative water content in bread wheat (*Triticum aestivum*). Euphytica. 1998;104:39-47. https://doi.org/10.1556/crc.35.2007.1.6
29. Kramer PJ, Boyer JS. Water relations of plants and soils: Academic Press; 1995. https://doi.org/10.1016/b978-012425060-4/50003-6 .
30. Dumitras A, Damian A, Mazare G, Singureanu V, Oroian I, et al. Living walls as transitional element in urban growth. Acta Horticulturae. 2010(881):729. https://doi.org/10.17660/actahortic.2010.881.120
31. Sanjuán MdCS. Los cultivos sin suelo y su contribución a la producción en los sistemas hortícolas intensivos. Phytoma España: La Revista Profesional De Sanidad Vegetal. 2008 (199):36-40. https://doi.org/10.4060/cc8064es
32. Salas M. Fertirrigacion y recirculacion de la solucion nutritiva en cultivo sin suelo. Revista Agropecuaria. 2009;79(918):368-71. https://doi.org/10.21930/agrosavia.video.2013.159
33. Van Os E, editor. Closed soilless growing systems in the Netherlands: the finishing touch. International Symposium on Water Quality and Quantity-Greenhouse 458; 1993. https://doi.org/10.17660/actahortic.1998.458.36
34. Teemusk A, Mander Ü. Rainwater runoff quantity and quality performance from a greenroof: The effects of short-term events. Ecological Engineering. 2007;30(3):271-77. https://doi.org/10.1016/j.ecoleng.2007.01.009
35. Clark C, Adriaens P, Talbot FB. Green roof valuation: a probabilistic economic analysis of environmental benefits. Environmental Science and Technology. 2008;42(6):2155-61. https://doi.org/10.1021/es0706652
36. Weinmaster M. Are green walls as "green" as they look? An introduction to the various technologies and ecological benefits of green walls. Journal of Green Building. 2009;4(4):3-18. https://doi.org/10.3992/jgb.4.4.3
37. Schwab A, Al�Assi A, Banks MK. Adsorption of naphthalene onto plant roots. Wiley Online Library. 1998;Report No.:0047-2425. https://doi.org/10.2134/jeq1998.00472425002700010031x
38. Nichols M, Savidov N, Aschim K. Biochar as a hydroponic growing medium. Practical Hydroponics and Greenhouses. 2010 (112):39-42. https://doi.org/10.1201/b18069-26
39. Ottelé M, Perini K, Fraaij A, Haas E, Raiteri R. Comparative life cycle analysis for green façades and living wall systems. Energy and Buildings. 2011;43(12):3419-29. https://doi.org/10.1016/j.enbuild.2011.09.010
40. Cheng C, Cheung KK, Chu L. Thermal performance of a vegetated cladding system on facade walls. Building and Environment. 2010;45(8):1779-87. https://doi.org/10.1016/j.buildenv.2010.02.005
41. Wong NH, Tan AYK, Chen Y, Sekar K, Tan PY, et al. Thermal evaluation of vertical greenery systems for building walls. Building and Environment. 2010;45(3):663-72. https://doi.org/10.1016/j.buildenv.2009.08.005
42. Currie BA, Bass B. Using green roofs to enhance biodiversity in the city of Toronto. City of Toronto Commissioned Report: April. 2010. https://doi.org/10.14796/jwmm.r228-17
43. Berndtsson JC. Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering. 2010;36(4):351-60. https://doi.org/10.1016/j.ecoleng.2009.12.014
44. Getter KL, Rowe DB. The role of extensive green roofs in sustainable development. HortScience. 2006;41(5):1276-85. https://doi.org/10.21273/hortsci.41.5.1276

45. Molineux CJ, Fentiman CH, Gange AC. Characterising alternative recycled waste materials for use as green roof growing media in the UK. Ecological Engineering. 2009;35(10):1507-13. https://doi.org/10.1016/j.ecoleng.2009.06.010

46. Santamouris M, Pavlou C, Doukas P, Mihalakakou G, Synnefa A, et al. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. Energy. 2007;32(9):1781-88. https://doi.org/10.1016/j.energy.2006.11.011

47. Wolverton BC, Wolverton JD. Plants and soil microorganisms: removal of formaldehyde, xylene and ammonia from the indoor environment. 1993. https://doi.org/10.1007/bf02858837

48. Yang J, Yu Q, Gong P. Quantifying air pollution removal by green roofs in Chicago. Atmospheric Environment. 2008;42(31):7266-73. https://doi.org/10.1016/j.atmosenv.2008.07.003

49. DL R. Pilot study to assess the impact of green plants on NO_2 levels in homes. Proc Healthy Buildings/IAQ,'97, Wash DC.1997;3:129-34. https://doi.org/10.1093/ww/9780199540884.013.u36806

50. Lohr VI, Pearson-Mims CH. Particulate matter accumulation on horizontal surfaces in interiors: influence of foliage plants. Atmospheric Environment. 1996;30(14):2565-68. https://doi.org/10.1016/1352-2310(95)00465-3

51. Aydogan A, Montoya LD. Formaldehyde removal by common indoor plant species and various growing media. Atmospheric Environment. 2011;45(16):2675-82. https://doi.org/10.1016/j.atmosenv.2011.02.062

52. Castleton HF, Stovin V, Beck SB, Davison JB. Green roofs; building energy savings and the potential for retrofit. Energy and Buildings. 2010;42(10):1582-91. https://doi.org/10.1016/j.enbuild.2010.05.004

53. Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G. Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings. 2001;33(7):719-29. https://doi.org/10.1016/s0378-7788(01)00062-7

54. Perini K, Ottelé M, Fraaij A, Haas E, Raiteri R. Vertical greening systems and the effect on air flow and temperature on the building envelope. Building and Environment. 2011;46(11):2287-94. https://doi.org/10.1016/j.buildenv.2011.05.009

55. Alexandri E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment. 2008;43(4):480-93. https://doi.org/10.1016/j.buildenv.2006.10.055

56. Köhler M, Schmidt M, Laar M, Wachsmann U, Krauter S. Photovoltaic panels on greened roofs. Rio. 2002;2:151-58. https://doi.org/10.1108/09566160210439297

57. Zahran S, Brody SD, Grover H, Vedlitz A. Climate change vulnerability and policy support. Society and Natural Resources. 2006;19(9):771-89. https://doi.org/10.1080/08941920600835528

58. Sailor D, Hutchinson D, Bokovoy L. Thermal property measurements for ecoroof soils common in the western US. Energy and Buildings. 2008;40(7):1246-51. https://doi.org/10.1016/j.enbuild.2007.11.004

59. Perini K, Ottelé M, Haas E, Raiteri R. Vertical greening systems, a process tree for green façades and living walls. Urban Ecosystems. 2013;16:265-77. https://doi.org/10.1007/s11252-012-0262-3

60. R CP, W JR, editors. Air conditioning and noise control using vegetation. 8th International Conference on Indoor Air Quality and Climate. 1999;Bangalore. https://doi.org/10.1109/iccad49821.2020.9260514

61. Van Renterghem T, Botteldooren D. *In-situ* measurements of sound propagating over extensive green roofs. Building and Environment. 2011;46(3):729-38. https://doi.org/10.1016/j.buildenv.2010.10.006

62. Wong NH, Tan AYK, Tan PY, Chiang K, Wong NC. Acoustics evaluation of vertical greenery systems for building walls. Building and Environment. 2010;45(2):411-20. https://doi.org/10.1016/j.buildenv.2009.06.017

63. Kellert SR, Heerwagen J, Mador M. Biophilic design: the theory, science and practice of bringing buildings to life. John Wiley and Sons; 2011. https://doi.org/10.1353/cye.2008.0027

64. Ulrich R. editor communicating with the healthcare community about plant benefits. Proceedings of the Sixth International People Plant Symposium Chicago: Chicago Botanic Garden; 2002. https://doi.org/10.31353/cs0501

65. SB. The benefits of biodiversity from green roofs. First North American Green Roof Infrastructure Conference; Chicago. 2003. https://doi.org/10.4324/9780203121993-11

66. Jain R, Janakiram T. Vertical gardening: A new concept of modern era. Commercial Horticulture. 2016;1:527-36. https://doi.org/10.5958/2582-2527.2022.00008.2