The Impact of Living Wall on Building Passive Cooling: A Systematic Review and Initial Test

A M Nugroho

1Department of Architecture, Brawijaya University, Malang

sasimurti@yahoo.co.id

Abstract. In an attempt to provide a passive cooling effect, living walls (LW) gain more attention from architects, engineers, building planners and researchers. Several types of research proved that living walls could contribute to enhance and restore the urban environment and improve thermal buildings performance. This paper aims to provide a literature review for all different LW systems in order to identify and systematize their primary application, method and performance. This review paper organizes and summarizes the literature on LW when it is used as air temperature reduction for passive cooling in buildings. Thermal performance remains the most prevalent theme compared to others, representing almost half of all publications (53 out of 123), with the top three most highly-cited articles all related to air temperature, energy and pollutant reduction of LW. Continuing to evaluate the contribution of current LW systems to improve buildings temperature reduction and comparing the environmental impact of these systems with other passive cooling strategy. This paper reviews existing methodologies for evaluating thermal performance in a tropical climate and makes suggestions of potential LW for optimum temperature reduction. Corresponding to the initial test, it can be concluded that LW provides great potential in increasing building energy saving by passive cooling.

1. Introduction

Energy efficiency is one of many benefits that greenery system can offer to the building. The most common building places that can be used to accommodate vegetation are living wall (LW), roof garden, terrace garden and sky gardens. Several definitions, classifications, and specifications of living wall are described below:

1.1 The Living Wall Definition

1.1.1 The Vertical Garden System-VGS: Definition and Classification. Plants growing on vertical surfaces are called vertical greenery systems [1][2]. In essence, the vertical greenery systems are defined as growing every type of plant on every type of vertical surface [3]. Whereas Plants that are used outdoors as the vegetated cladding of buildings, which are identified as a greening system [4]. According to Besir [5], the vertical greening system is identified as greening vertical layers (facades, walls, blind walls, and partition walls) and with the main function of growing plants on building walls. Vertical greening systems are also referred to as vertical parks, green walls, vertical green, vertical landscaping and bio walls [3,6]. This was also stated by Bustami [7] which stated that VGS refer to
plants grown on a vertical profile and can be called vertical greening systems, vertical greening, vertical gardens, vertical green, green walls, vertical landscaping, and bio shade.

As specified by Wong et al. [8], VGS involve any means to plant in building facades. Traditionally this system consisted of vines that crept into the façade material. In newer approaches, these systems tend to separate plants from the facade surface to avoid problems associated with living organisms. The application of support structures with different designs has been developed in recent years. The classification based on the construction structure system distinguishes the Green Vertical System into two major groups, the Green Façade and the Living Wall [9].

According to Safikhanin [3], there are diverse classifications for vertical greening systems. One of the classification systems is based on growing media, construction methods, and also plant species [10]. In all classifications, the location of the growing media plays an important role in the type of vertical greening system. Accordingly, it can be assumed that the dichotomy of the vertical greening system into green facades and living walls is the main classification which includes other classifications, and it is acknowledged by most researchers. In reference to Safikhanin [3], there are various names for green facades and living walls. The green vertical system [11], the support system and the greening of the facade [12] are commonly used terms for green facades. Whereas vertical gardens, carrier systems and bio-walls [13] are commonly used terms for living walls.

Whereas according to Manson [6], VGS can be further divided into two main systems: green facades and living walls [14][15]. There is a clear difference between the green facade, where usually there are climbing plants that grow along the walls covering it, and the latest concepts of living walls, which include materials and technology to sustain a more extensive variety of plants, creating homogenous growth along the surface [6]. Vertical greening systems are classified based on two main types: green façade and green wall [14][15]. Ground-based greening methods depend on natural soil and lead to the green facades, while the wall-based greening methods involve planting directly on the wall, without connection to natural soil, known as a living wall [16].

This is slightly different from the term used by Besir [5] which explains that VGS consists of two different systems called green facades and living walls. The difference between the green facade and the living wall can be stated that vegetation grows on the building envelope naturally and requires growing media. However, living walls consist of pre-vegetation plants and sheath structures offering many plants to cover the building facades uniformly [3][14][17]. Compared to the green facade, living walls require several important materials such as supporting substrates for growing media and irrigation systems to maintain various plants. Hence, living wall systems require high maintenance costs [18]. However, living walls usually have better performance compared to green facades especially in terms of renewing plants [19]. The classification of green walls according to their construction features is illustrated in Fig. 1. As discussed above it is clear VGS types can be classified into green facades and living walls. The green facade consists of climbing plants or plants that attach directly to the walls of buildings or are installed using cables or trellises [20][21]. Several slight differences in names are due to differences in the construction system [7].

1.2 The Green Façade-GF: Definition and Classification

According to Perez [9], Green facades are VGS in which climbing plants or hanging shrubs are formed using special support structures, specifically in a directed manner, to cover the desired area. Plants can be planted directly in the ground, at the bottom of the structure, or in pots, at different heights from the façade. Green facades require growing media to grow plants. Growing media is a place where plant roots find nutrients[22]. It is achievable for the growing media to remain on the ground and only the stems of the plant grow vertically and cover the vertical surface [3][23][24]. This system is called the green façade and is mostly found in traditional architecture [25].

This is reinforced by the opinion of Manson [14] which states The green façade is based on the application of climbing plants or hanging along the wall. Plants can grow vertically above the surface, as in the example of a traditional system, or grow vertically below the surface, if the plants are hung at a certain height [16]. The green facades usually use climbing plants to grow vertically on the front of
the building; either directly on the surface of a building or using a secondary support system. Plants for green facades are usually placed on the ground or in strategically placed pots [26]. The green facades are further classified based on the location of the plant, which can be placed directly into the soil, or in a planting pot/soil filled box, accordingly, the third term ‘planting box-based greening method’ is advised to be added [16].

The green facade can be categorized into three different systems [5]. Traditional green facade (Fig.1), where creeping/climbing plant use facade material as a support; double-skin green façade or green curtain, with the purpose of making a double skin or green curtain separated from the wall; and the perimeter of the flowerpot, when hanging shrubs are planted around the building as part of the façade composition to form a green curtain. In the case of double skin green facades, the systems used are modular structures, cables, and mesh structures [5].

Hunter [27] has a sub-classification for green facades according to the location of green plants and wall surfaces as direct green facades and double skin green facades. In direct green facades, climbing plants are attached to vertical surfaces, while on double walls, green facade building structures support plants to grow vertically [3]. This is aligned with the opinion of Manson [6] which classifies [green facade in the form of direct and indirect green facades. A direct green facade is a facade where plants are attached directly to the wall. The green facade indirectly includes a support structure for vegetation. The traditional green facade is considered a direct greening system, consisting of the use of self-sticking climbing plants, which are rooted directly in the ground. Recent solutions for green facades are usually indirect greening systems, which include vertical support structures for the development of climbing plants. In these cases, plants can be rooted straight in the soil or pots and guided to grow along the support structure. Greening systems do not directly include continuous and modular solutions. Sustainable guidance is based on a single support structure that directs plant development along the entire surface. The green facade with modular trellis is the result of mounting several modular elements along the surface. The main differences lie in the modular trellis having vessels for plant rooting and individual support structures for directing plant development [28].

The same is also mentioned in Manso [7] which stated that green facade is composed of climbing plants that cover vertical surfaces and their species is further divided into direct and indirect green facades [7][3][29]. The direct green facade, as referred to in traditional architecture (traditional green facade), does not require structural support because of the attachment of climbing plants that attach to the external wall through the roots [29][30]. The indirect green facade is called a double-wall green facade that includes support systems such as stainless steel cables, modular trellis, or stainless steel nets to aid upward growth thus creating a second skin layer with a certain distance to the wall. [7][28][31].

A slightly different statement was mentioned in Biser [5] which makes three sub-categories of green facade include traditional green facades, double skin green facade (DSGF) and modular trellises. In a traditional green facade, the plants use the envelope as supporting material and the growing media remains on the ground. DSGF is designed by using a double skin/wall frame on all surfaces having an air cavity between the wall and a vertical support structure. Modular trellis has a circular boundary for potted plants [5, 7,32]. This is in accordance with what Zaid [21] states, which categorizes [green facades as traditional green facades, green skin/wall facades, or green curtains and flower pot circles, while living walls can be further categorized into bio-filtration living walls or modular living walls [21][33].

As a conclusion, green facade refers to plants that grow on the surface of a building. The green facade is available either directly or also known as the traditional green façade or indirect green façade which can be planted on a long (continuous/continuous) guide or trellis. Both options can be planted directly in the ground or a soil box/pot [6][12][27] and have a life span of more than 50 years [23]. The climbing/creeping plants in the green façade are proven to be able to grow from 3 m to 10 m in the first 4 years [34]. Installation, design, and maintenance of the green façade is easier than living walls [9]. Based on the above discussion, the green facade can be classified as a direct or traditional
facade, where plants are attached directly to the wall, and skin / indirect wall or double skin/double wall facades, which include modular trellises for vertical support structures for vines [4].

1.3 The Living Wall-LW: Definition and Classification

Basically living walls are made of geotextile containers and/or panels, sometimes pre-cultured, mounted on vertical supports or wall structures [9]. Geotextile panels and containers provide support to vegetation formed by, among others, upholstery plants, ferns, small shrubs, and other climbing plants. In addition, it is achievable for the growing media to stand vertically in front of the vertical surface [35][36][37][12][38]. On the living wall can accommodate a vaster variety of plants. Conventional systems for living walls are panel and container systems [39, 40]. The panel systems are pre-plant panels mounted on a structure. The container systems consist of pockets that are filled by plants and attached to a waterproof wall that is connected to the structure. In container systems, plants are planted in containers and spread on trellises.

The superiority of living walls is also revealed by Manso [6]. [Living walls are a fairly new area of innovation in the field of wall cladding. They appeared to allow the integration of green walls in tall buildings. Living walls enable the rapid reach of large surfaces and a more uniform growth along vertical surfaces, seizing higher areas and adjusting to all types of buildings. They also enable the integration of broader plant species [3]. Manso [6] as well as plants that are spread all over the walls of Riley [26]. Because it is designed with vertical panels and modules allowing plant growth without relying on root space on the ground surface [16][34][41]. This is as referred by Bustami [7] which mentions wall refers to vegetation planted in planter boxes that can be advanced into a modular system that attaches to the wall without depending on the root space on the ground and has mechanised watering. Living walls also allow hydroponic planting [6] although the installation is more complicated but is suitable for new buildings with a plant life span of fewer than 10 years [7].

In essence living wall systems (LWS) can be categorized as continuous and modular systems, based on their application method. Continuous LWS are based on light and permeable gauze applications where plants are inserted individually [42][43]. Modular LWS is an element with particular dimensions, which includes growing media where plants can grow. Every element is supported by a corresponding structure or fixed structure directly on a vertical surface. The continuous LWS is also recognized as Vertical Gardens, a name given by the French botanist Patrick Blanc who made his first "Vertical Garden", also referred to as "Vegetal Mur" in 1994 [6]. The modular LWS have variations in composition, weight, and assembly. They can be in the form of trays, vessels or flexible bags. Trays are usually shaped rigid, stick together, which can hold plants and the weight of the growing media. Vessels are adaptations of the most common support for plants with the distinction that they can be tied to vertical structures or connected vertically to one another. Flexible bags include growing media with lightweight materials that allow the application of vegetation on surfaces with different shapes, such as curved or tilted surfaces [6].

A slightly different classification is carried out by Riley [26] which divides the two main types of living walls are the hydroponic system and the soil-cell system. Hydroponic systems usually use felt as a growing media for plants. The growing media is doubled and continues to be moistened with nutrient-rich water. Plant roots grow on and between the two layers of the growing media. Whereas the soil cell system grows plants in compartmentalized soil into individual cells, which are grouped in panels attached to a frame (however, some hydroponic systems use cell-based modular typologies, which usually replace the soil with inorganic materials such as rock wool [26]. Medll[16] classifies living walls [in accordance to their application method, as modular green walls and continuous green walls [7][44][45] whereas, Scharf et al. [46] added a third type, namely linear green walls. Continuous green walls are based on a single supporting structure, while modular green walls come from the installation of several modular elements, together creating the whole greenery [7]. Linear green walls come from flowing elements, which are appended to the wall linearly [16][47].

This is aligned with the distribution done by Besir [5] where the main types of living walls are described as continuous and modular systems with the main distinction being the growing media. In
continuous systems, growing media is not a necessity because of the presence of geotextile membranes. This material can be used as a substitute for soil. Plants in a continuous system are grown through irrigation using hydroponic techniques. As stated by Charoenkit and Yiemwattana [45], modular walls can be designed as including planter, pocket-shaped grower containers, and panels. There are two types of panels used in applications, namely single panels and grid panels. Each component is usually used to supply nutrients that are tailored to the supporting material. As mentioned earlier, living walls offer a vast variety of plants and it is easy to replace damaged plants with fresh ones [5][7][45]. Conclusions related to living walls are of two main types: continuous green walls using continuous layer or geotextile membrane/felt, and modular green walls using trays, vessels. Seyam [4] provides more choices for plant choices and is more suitable for high-rise buildings because it can be applied up to the top floor, unlike green walls [21][45], however, is equipped with growth media and an adequate irrigation system [20].

![Classification of the vertical greenery system](image)

**Figure 1.** Classification of the vertical greenery system

Green Facade, ground-based greenery methods: direct (a) and indirect (b)) and Living Walls, greenery-based methods: walls: continuous (c), modular (d), and linear (e)

*based on Safikhani et al. [3] and Hunter et al. [27], modified and developed*

2. Methodology
2.1 A Systematic Review

A systematic review is an increasingly popular form of literature review in a range of research fields and is characterised by the fact that it follows a method that is reproducible by other researchers [41]. The systematic review has to be inclusive yet specific. This study adopts a strict protocol with a four-phase process following [42]. This study applies and adopts Moher's 2010 protocol to focus on outdoor VGS. The four phases for conducting the review are: identification of relevant articles, screening according to established criteria, classification according to themes of articles and their methods, and finalising number of articles for the inclusion for the review [4] as presented in figure 2.

2.2.1 Identification. In the first selection stage, only peer-reviewed scientific papers, found by means of keyword search through online databases (ScienceDirect) were selected using the keywords “vertical greening system”. The identification phase establishes reproducible search parameters according to eligibility criteria, as well as specifying the database(s) searched. Following the convention of other systematic review papers, Scopus was chosen as the popular indexed electronic
databases for their systematic reviews[41]. The search terms were constructed to identify all available papers on VGS, including both outdoor and indoor VGS, and papers within the search criteria which highlighted VGS in their studies. The searching process was also specified publication year range from 2010 to early 2019.

2.2.2 Screening. The screening process considers scanning the collected articles to exclude not related to the living wall and the eligibility criteria for this review.

2.2.3 Classification. In this phase, many disciplines have been conducted with living wall method. These disciplines can be classified as interview, content analysis, experimental measurements, simulation analysis, mathematical modeling, and field measurements.

2.2.4 Inclusion. This selected paper focuses on the review articles by using systematic review method for three living wall performance: climate influence; temperature reduction and plants influence. To follow this review scheme, the captured studies have been organized and analyzed based on the following: first, General information mentioned in the studies: such as types of greenery systems, location and environment, type of study, and season, excluding the plant species. Second, providing a comparison to bare building envelopes. Third, the microclimate parameters can be divided into outside and inside parameters. The outside parameters are ambient temperature (To), ambient relative humidity (RHo), external wall surface temperature (Tse), the solar radiation (SR), and the wind speed (WR. The inside parameters are the inside wall surface temperature (Tsi), the indoor air temperature (Ti), and the indoor air relative humidity (RHi) [4] as seen in figure 3.

![Figure 2: The process of article selection in the review](image)
2.3 Initial Test

The research material as the focus and main variable in this study is the green wall for natural cooling of dense residential dwellings. The green walls that were studied were related to the types of family medicinal plants to decrease the temperature. The city of Malang, which is indicated to have experienced an increase in temperature in the last ten years due to the reduction in the city's green land, especially in areas that have experienced land use change. The research location is in a residential environment of a sub-urban area adjacent to the industrial area of the city of Malang. The building object used as the object of research is residential housing in densely populated urban settlements with limited land, which also has constraints on decreasing air quality. Experiments were conducted to measure the temperature reduction on the green walls with different distances of the planting air gap (0.5 m and 1 m).

3. Results and Discussion

The results of this paper are the effect of living wall on temperature reduction based on a review of previous research and initial tests on the application of living wall in minimalist homes in Indonesia.
3.1 The Impact of Climate and Plants Species for Living Wall Performance

There are three climate factors that need to be considered when designing a living wall, namely: air temperature; humidity; wind; and orientation [50]. Temperature and humidity data will be collected and analyzed based on monthly data and, if available, daily data to reveal the extreme range of climate conditions. Using more detailed data will be useful compared to the average data in the long run [26].

The Living Wall (LW) concept has been adjusted and developed in multiple countries, including tropical regions such as North, South and Central America, the Caribbean, India and Southeast Asia. The demand to integrate LW in urban areas has increased because it is one of the best approaches for sustainable development as ground spaces become limited. The Santalaia building in Bogota, Colombia is noted to have the largest vertical park and is capable of supplying oxygen to 3100 people each year, filtering out 2000 tons of hazardous gas and trapping 881 lb of dust [21]. The other aspect that needs to be considered in VGS as passive energy saving systems is the type of plant. Green facades usually use climbing plants while the living wall uses herbal plants or shrubs. Types of plants with deciduous leaves will affect the thermal behavior of the building facade. Building facades exposed to sunlight throughout the year need to be selected for plants that are leafy throughout the season [9].

According to Safikhanin [3], determining suitable plants for specific purposes influences the performance of vertical greenery systems and increases system efficiency. Several studies have conducted experiments on the growth process and plant density on the green façade and its effect on the cooling performance of buildings. Experiments carried out in the tropical climate of Thailand studied plant species of *thunbergia grandiflora*, *coccinia grandis* and *antigonon leptopus*. The results revealed the growth of the *thunbergia grandiflora* tree grows very fast and provides consistent density through minimum pruning. Therefore it can be said that the Thunbergia grandiflora tree is a suitable plant to cover the green façade in a tropical climate [50].

As living organisms, plants on the living wall are selected to have survival ability on the extreme climatic conditions they will inhabit. There are plants that cannot absorb water because the temperature is too hot or has an inappropriate pH. Various climate data reveal the characteristics of plants and growing media needed for survival [26]. In accordance with wit Bustami [7], type of plant will affect the type of LW, for example, LW with shrubs species requires high gravity support because it contains components such as heavy irrigation systems, structural frames, containers, planting media and the plant itself. In contrast, LW which is composed of climbing plants that have a lightweight system carries less weight. However, LW with shrubs produces higher density compared to LW with climbing plants [52].

3.2 The Impact of Living Wall for Air Temperature Reduction in Tropical Climate

Thermal performance can be described as the temperature difference between the layers of the building envelope. Comparing building envelopes with vegetation and without vegetation is needed to calculate the difference in heat flux through the building envelope in the same environment. The vegetation systems have several advantages, such as insulation effects, cooling effects, reducing urban heat islands, sun absorption, and wind barrier [18][53][54]. Based on the results of research on the green wall system in Singapore [8][55] and Indonesia [56] in the rainy season. Exterior wall temperatures decrease by an average of 9°C, while interior wall temperatures decrease by 0.5-10°C [4].

Vertical greenery system is able to reduce temperature through shading in the building facades, thermal insulation and transpiration cooling [9]. Temperature reduction is one of the important performances of vertical green systems. Besides the shading effect, the cooling effect of the plant is effective in reducing the temperature. This helps to reduce cooling energy demand and energy consumption. Wong et al. [8] experimented with thermal behavior on seven green wall models in Singapore (tropical climate). The parameters measured are the wall surface temperature and the air temperature in front of the green wall. The results revealed that, in terms of the average temperature
reduction in the wall surface, cooling efficiency was performed the best during the day, achieving more than 10°C temperature reduction at maximum. The maximum average temperature reduction in the wall surface range between 8°C and 10°C. In particular, it was found that all vertical green systems reduce ambient temperature, wall surfaces and growing media during the daytime [3]. The maximum temperature reduction is 11.5°C and the maximum ambient temperature reduction is 3.3°C with the distance between the plant panel and the building facade 15 cm wide [8].

Chen et al. [57] conducted an experimental evaluation of the LW system in the hot and humid climate of Wuhan, China. The experiment used six different types of plants with the main parameters were interior, interior wall surface, exterior wall surface, air gap, interior back panel surface and inside / outside air temperature, relative humidity, wind speed and solar radiation. The results showed a decrease in surface temperature by 20.8°C, a reduction in interior wall surface temperature by 7.7°C, and a reduction in indoor temperature by 1.1°C. In the air gap between the building's facade there was a decrease in temperature of 9.7°C during the day and 1.6°C at night. The smaller the distance of the air gap, the better the performance [9][16].

Vertical Greenery system is able to enhance and regulate the effects of decreasing building temperatures and the surrounding environment by the mechanism of VGS plants absorbing solar energy for their growth needs and converting it into latent heat through evapotranspiration [33]. The evapotranspiration mechanism reduces air temperature and increases air humidity by releasing water vapor from plants into the atmosphere through stomata leaves [32]. Radiation heat is absorbed by humidity and provides cooling effects to the surrounding environment [45]. VGS also exerts a shadowing effect on the facade. The further effect of applying VGS is to provide significant cooling performance and reduce building energy consumption and greenhouse gas emissions [58].

Thermal was the most studied research theme in VGS studies [9]. Passive cooling performance was usually demonstrated by comparing the surface temperature of walls with and without VGS [59-64] or calculating heat transfer into buildings [59, 60, 61]. LW's contribution to energy savings in buildings is influenced by aspects of climate and plant species. Weather conditions directly affect the thermal performance of buildings and LW while specific aspects of plant types have an impact on growth and transpiration rates [1]. LW application in buildings depends on the selection of suitable plants and leaf index properties to achieve high shade levels. The nature of plants must be tested in different climates and different weather conditions. Vertical greenery systems on building walls must be tested in different climates separately to find the appropriate orientation in order to achieve maximum efficiency. LW as a temperature reducer can be improved by providing a ventilation system as an addition [16].

3.3 The Initial Test of Living Wall Application in Indonesian House

Based on the results of 12 hours measurements with 2 modifications of the green wall growing media distance (figure 5), the lowest air temperature occurred on green walls with a growing media distance of 1 m. There is a variation on the indoor air temperature reduction in the green wall experiments of red spinach plants with a green wall growing media distance of 1 m, respectively: 1°C and 0.9°C. At a green wall growing media distance of 0.5 m, the decrease in air temperature that occurred in amaranthus hybridus is 1°C and 1.2°C. The cooling effect can be observed by comparing the decrease in air temperature in the area between the green wall and outdoor air temperature. The experiments results on the green wall showed that within 12 hours, the biggest decrease in air temperature occurred on the green wall with a growing media distance of 1 m. Thus, it can be said that the modification of green wall growing media has a great potential for cooling. The findings showed that the distance of the growing media on the green wall is one of the most important factors that is significant in decreasing air temperature in Indonesian tropical houses. A decrease in air temperature inside and outside the building is beneficial for passive cooling of buildings as well as energy savings in tropical climates. In addition, the greater the distance of the growing media and the higher the green wall, with dark leafy plants, will result in a greater decrease of air temperature in the room and in the space between the vertical landscapes.
After the conducted experiments of temperature reduction on the green walls of amaranthus hybridus plant, the temperature reduction measurements were carried out on several types of herbal plants: gynura segetum, brassica juncea, apium graveolens linn and orthosiphon spicatus. The choice of herbal plant types is based on the types of small sized plants adapted to the limitations of residential land. In addition, the type of herbal plants that are not propagating were also chosen to make it easier to regulate and measure the height of the use of plants as a green wall, and use polybags as a plant container to facilitate the mobility of the medicinal plants transfer. After doing the five types of herbal plants, the result of temperature reduction can be seen in figure 6 below.
The table shows that the green wall does provide a cooling effect, similar with the experiments which have been done. All types of plants were observed to provide the effect of the greatest temperature decrease occurred at 12.00. Based on the five types of herbal plants measured, by looking at the average decrease in temperature that occurred (see figure 5.8), the gynura segetum showed the greatest decrease (16.1°C). Furthermore, the decreasing in reduction occurred consecutively starting from amaranthus hybridus plant (14.7°C), brassica juncea (14.5°C); apium graveolens linn (13.4°C) and orthosiphon picatus (13°C).

4. Conclusion

The study concludes that the benefits of the LW systems in current literature often refer to the general benefits of vegetation. The latest developments in LW mainly focus on system design to achieve more energy efficient solutions and better thermal environment performance. Continue evaluating the contribution of the current LW system to increase building temperature reduction and comparing the environmental impact of these systems with other passive cooling strategies.

It can be concluded that when studying the contribution of VGS to the passive energy savings in buildings, four main aspects that can affect its operations must be considered: the influence of climate and plant species. Climatic conditions affect VGS operations because climate directly affects the thermal performance of buildings, and the specific aspects of plants such as the species to be used, growth rate, transparency, etc. Most of the studies found were located in the quadrant corresponding to the intersection of the Northern and Eastern hemisphere (figures 6a and b), specifically in Europe (Green façade) and Asia (Green Wall). Effect of plant species: Different VGS typologies use different plant species, and this fact must be taken into consideration when studying their thermal behavior. In Green Wall, herbaceous and shrubs species (occasionally climbing plants) are the most common, typically adapt well to local climatic conditions, and are always green throughout the year. The number of species used in the studies analyzed on the Green Wall was quite high. However, this implies different thermal behaviors in the same Green Wall. Further studies are needed on the characteristics of each plant species in each climate.

To implement vertical greenery systems for various purposes, special attention to select appropriate plants and the properties of the leaf area index is needed as well as attention to maintenance and growth in order to achieve high shade rate. The properties of plants should be tested in different climates and different weather conditions. Furthermore, the orientation of the vertical greenery system on the walls of buildings should be tested in different climates separately to find an appropriate orientation for installing a vertical greenery system in order to achieve maximum efficiency. In implementing a vertical greenery system due to its ability to reduce the temperature and add ventilation to the system can improve the efficiency of the system, but there are limited researches and studies on integrating the performance of ventilation and vertical greenery systems simultaneously. For future experiments, the discovery of an innovative method that applies ventilation and the performance of a vertical greenery system is highly recommended. Along with ventilation, combinations of vertical greenery systems and different architectural features are recommended to find new techniques and methods to improve the ability to reduce temperature and the efficiency of vertical greenery systems.

Nevertheless, according to the initial test, the living walls must continue to evolve into more sustainable solutions, through the use of materials with less incorporated energy and CO₂ emissions and the application of climate-adapted plant species with less irrigation needs. Some examples have shown the concerns of sustainability by using natural or recycled materials and native plants, the integration of water recovery systems and sensors to minimize water and nutrition.
References

[1] Shah K, Kim JW and Oldridge S 2011 An investigation into the application of vertical garden at the New SUB Atrium Vancouver, Canada: The University of British Columbia

[2] Loh S and Stav Y 2008 Green a city grow a wall. Proceedings of the subtropical cities 2008 conference: from fault-lines to sight-lines: subtropical urbanism in 20–20. Centre for Subtropical Design, Australia: Queensland University of Technology 1–9

[3] Safikhanin T Abdullah AM Ossen DR and Baharvand M 2014 A review of energy characteristic of vertical greening systems Renewable and Sustainable Energy Reviews 40: 450–46

[4] Seyam S 2019 The impact of greeneries systems on building energy: Systematic review Journal of Building Engineering 26: 100887

[5] Besir AB and Cuce E 2018 Green roofs and facades: A comprehensive review Renewable and Sustainable Energy Reviews 82: 915–939

[6] Manso M and Castro-Gomes J 2015 Green wall systems: a review of their characteristics Renew Sustain Energy Rev 41: 863–871

[7] Bustami BA, Belusko M, Ward and, Beecham S 2018 Vertical greening systems: A systematic review of research trends Building and Environment 146: 226–237

[8] Wong NH, Kwang Tan AY, Chen Y, Sekar K, Tan PY, Chan D, Chiang K and Wong NC 2010 Thermal evaluation of vertical greening systems for building walls Build Environ 45: 663–672, https://doi.org/10.1016/j.buildenv.2009.08.005

[9] Pérez G, Coma J, Martorell I and Cabeza LF 2014 Vertical Greener Systems (VGS) for energy saving in buildings: A review Renewable and Sustainable Energy Reviews 39: 139–165

[10] Yu C and Hien W 2009 Thermal impact of strategic landscaping in cities: a review Adv Build Energy Res 3: 237

[11] Perez G, Rincon L, Vila A, Gonzalez JM, Cabeza LF 2011 Behaviour of green facades in Mediterranean Continental Climate Energy Convers Manag 52: 1861–18617

[12] Perini K, Ottelé M, Haas E, Raiteri R 2011 Greening the building envelope, façade greening and living wall systems. Open J Ecol 1:1–8

[13] Binabid J 2010 Vertical garden: the study of vertical gardens and their benefits for low-rise buildings in moderate and hot climates [1476132]. United States – California: University of Southern California

[14] Kohler M 2008 Green facades – a view back and some visions. Urb Ecosyst 11: 423–436

[15] Dunnett N, Kingsbury N 2008 Planting green roofs and living walls. Portland/ London: Timber Press

[16] Medl A, Stangl R and Florineth F 2017 Vertical greening systems e A review on recent technologies and research advancement Building and Environment 125:227-239

[17] Mazzali U, Peron F, Romagnoni P, Pulseli RM and Bastianoni S 2013 Experimental investigation on the energy performance of living walls in a temperate climate. Build Environ 64:57–66

[18] Perini K and Rosasco P 2013 Cost–benefit analysis for green façades and living wall systems Build Environ 70:110–121

[19] Raji B, Tenpierik MJ and van den Dobbelsteen A 2015 The impact of greening systems on building energy performance: a literature review Rene Sustain Energy Rev 45:610–623

[20] Timur OB and Karaca, E 2013 Vertical gardens. In: Ozyavuz, M. (Ed.), Advances in Landscape Architecture. Intech, European Union, pp. 587–622

[21] Zaid SM, Perisamy E, Hussein H, Myeda NE and Zainon N 2018 Vertical Greener System in urban tropical climate and its carbon sequestration potential: A review Ecological Indicators 91:57–70

[22] Binabid J 2010 Vertical garden: the study of vertical gardens and their benefits for low-rise buildings in moderate and hot climates [1476132]. United States – California: University of
Southern California

[23] Perini K, Ottelé M, Haas E, Raiteri R 2011 Greening the building envelope, façade greening and living wall systems. *Open J Ecol* 1:1–8

[24] Kontoleon KJ, Eumorfopoulou EA 2010 The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Build Environ* 45:1287–303

[25] Mir MA. 2011 Green façades and building structures. Delft: Delft University of Technology.

[26] Riley B 2017 The state of the art of living walls: Lessons learned *Building and Environment* 114: 219-232

[27] Hunter AM, Williams NSG, Rayner JP, Aye L, Hes D and Livesley SJ 2014 Quantifying the thermal performance of green façades: a critical review *Ecol Eng* 63:102–13

[28] Laurenz J, Paricio I, Alvarez J, Ruiz F. Natural envelope. The green element as a boundary limit. SB05 Tokyo. The 2005 World Sustainable Building Conference, Tokyo; 2005

[29] Cuce E 2016 Thermal regulation impact of green walls: an experimental and numerical investigation, *Appl. Energy* 194 247-254

[30] Isnard S, W.K. Silk WK 2009 Moving with climbing plants from Charles Darwin’s time into the 21st century, *Am. J. Bot.* 96:1205-1221

[31] Coma J, Perez G, de Gracia A, Bure S, Urrestarazu M and Cabeza LF 2016 Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green façades *Build. Environ.* 111:228-237

[32] Wong I and Baldwin AN 2016 Investigating the potential of applying vertical green walls to high-rise residential buildings for energy-saving in sub-tropical region. *Build Environ* 97:34–39

[33] Wang C, Er SS, Rahman AH 2016 Indoor vertical greenery system in urban tropics. Indoor *Built Environ.* 25:340–356

[34] Köhler M, 2008 Green façades—a view back and some visions *Urban Ecosyst.* 11:423–436.

[35] Domurath N and Schroeder FG 2009 Vertical hydroponics for urban areas *Acta Hortic* 843

[36] Francis RA and Lorimer J 2011 Urban reconciliation ecology: the potential of living roofs and walls *J Environ Manag* 92:1429–37

[37] Ottelé M 2011 Comparative life cycle analysis for green façades and living wall systems *Energy Build* 43:3419–3429.

[38] Horoshenkov K 2013 Acoustics properties of lowgrowing plants. *J Acoust Soc Am* 133(5):2554–2565

[39] Franco A 2012 Wind tunnel analysis of artificial substrates used in active living walls for indoor environment conditioning in Mediterranean buildings *Building Environ* 51:370–378

[40] Asdrubali F 2012 A review of sustainable materials for acoustic applications *Build Acoust* 19(4):283–312

[41] Feng H and Hewage K 2014 Lifecycle assessment of living walls: air purification and energy performance, J. *Clean. Prod.* 69:91-99.

[42] Corradi L 2009 Hydroponic growing system. US 2009/007486 A1

[43] Bribach C 2011 Vertical garden panel. US 2011/0059518 A1

[44] Dover JW 2015 *Green Infrastructure: Incorporating Plants and Enhancing Biodiversity in Buildings and Urban Environments*, Routledge, Great Britain

[45] Charoenkit S and Yiemwattana S 2016 Living walls and their contribution to improved thermal comfort and carbon emission reduction: a review, *Build. Environ.* 105:82-94.

[46] Scharf B, Pitha U and Oberarzbacher S 2012 Living walls e more than scenic *beauties* 49th IFLA word congress landscapes in transition cape town South Africa

[47] Pitha U, Scharf B, Enzi V, Oberarzbcher S, Hancvencl G, Wenk D, Steinbauer G, Oberbichler C, Lichtblau A, Erker G, Fricke J, Haas S and Preiss J 2011 *Recommendations on Façade Greening Methods* Magistrat der Stadt Wien, Wien

[48] Malys L, Musy M and Inard C 2013 A hydrothermal model to assess the impact of green walls
on urban microclimate and building energy consumption *Build Environ.* 73:187–197, https://doi.org/10.1016/j.buildenv.2013.12.012

[49] Pulselli RM, Pulselli FM, Mazzali U, Peron F and Bastianoni S 2014 Energy based evaluation of environmental performances of Living Wall and Grass Wall systems *Energy Build.* 73:200–211

[50] Hopkins G and Goodwin C 2011 Living Architecture: Green Roofs and Walls CSIRO Pub., Collingwood, Vic.

[51] Sunakorn P, Yimprayoon C 2011 Thermal performance of biofacade with natural ventilation in the tropical climate *Procedia Eng.* 21:34–41

[52] Jim CY 2015 Thermal performance of climber greenwalls: effects of solar irradiance and orientation *Appl. Energy* 154:631–643

[53] Castleton HF, Stovin V, Beck SBM and Davison JB 2010 Green roofs: building energy savings and the potential for retrofit *Energy Build.* 421582–1591.

[54] Fernandez-Canero R, Urrestarazu LP and Franco Salas A 2012 Assessment of the cooling potential of an indoor living wall using different sub-strates in a warm climate, *Indoor Built Environ.* 21:642–650

[55] Tan CL, Wong NH and Jusuf SK 2014 Effects of vertical greeneries on mean radiant temperature in the tropical urban environment Landsc. *Urban Plan.* 127:52–64

[56] Widiastuti R, Caesarendra W, Prianto E and Budi W 2018 Study on the leaves densities as parameter for effectiveness of energy transfer on the green facade *Buildings.* 8:138

[57] Chen Q 2013 An experimental evaluation of the living wall system in hot humid climate *Energy Build.* 61:298–307

[58] Gratani L, Varone L, Bonito A 2016 Carbon sequestration of four urban parks in Rome Urban For. *Urban Gree.* 19:184–193

[59] He Y, Yu H, Ozaki A, Dong N and Zheng S 2017 An investigation on the thermal and energy performance of living wall system in Shanghai area *Energy Build.* 140:324–335

[60] Cheng CY, Cheung KKS, Chu LM 2010 Thermal performance of a vegetated cladding system on facade walls *Build. Environ.* 45:1779–1787, https://doi.org/10.1016/j.buildenv.2010.02.005

[61] Tudiwer D and Korjenic A 2017 The effect of living wall systems on the thermal resistance of the façade *Energy Build.* 135:10–19