

Article

Sustainable Design of Vertical Greenery Systems: A Comprehensive Framework

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Abstract: The greening of buildings' facades is not a new practice; it has been used since ancient times for protection and aesthetic purposes. Nowadays, the approach used towards the greening of facades has changed considerably. Vertical greenery systems (VGS) have been proposed as one of the innovative solutions to promote sustainable building functions. Present-day facade greenery not only offers traditional architectural potential but also incorporates advanced materials and technologies to adapt to the requirements of modern urban life. In recent years, the number of buildings that use this technology has increased considerably, and accordingly, the technology involved and the methods of application have changed to be in line with the new necessities. Various types of VGS have been introduced to provide users with a wider range of options that are applicable in different climates and conditions. As a result, different methods of VGS implementation have been adopted; however, there is no established standardization for VGS designs or their variations. Choosing the proper type of VGS is a crucial step in the decision-making process for VGS design. In this research, we provide an overview of the most significant existing classifications of vertical greenery systems and propose a comprehensive classification based on an analysis of their features and classification criteria. Moreover, influential factors in VGS design are investigated. This article presents a comprehensive framework for the sustainable design of vertical greenery systems by outlining the primary parameters that are crucial to identifying and selecting the most suitable type of VGS. The framework also incorporates design aspects, thus stressing the necessity of considering changes to attributes that could affect the overall functionality of a VGS and, as a result, impact the decision-making process. The results of this study provide a valuable resource to systematically study greenery systems, and their parameters, and also to make informed decisions that are aligned with current the sustainability objectives of future research in terms of cost, energy consumption, and maintenance.

Keywords: vertical greenery system; green wall; green facade; living wall; decision making



Citation: Manouchehri, M.; Santiago López, J.; Valiente López, M. Sustainable Design of Vertical Greenery Systems: A Comprehensive Framework. *Sustainability* **2024**, *16*, 3249. <https://doi.org/10.3390/su16083249>

Academic Editor: Olaf Kühne

Received: 20 February 2024

Revised: 5 April 2024

Accepted: 8 April 2024

Published: 12 April 2024



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1. Introduction

The use of vegetation in buildings is a construction technique that has always been in use. The Hanging Gardens of Babylon is one of the first known instances of an attempt to integrate plants with human-made spaces. Moving forward in time, during the Roman Empire, planting trees on the tops and surroundings of buildings was a common practice to create shading [1,2].

The first patented vertical greenery system can be traced back to Stanley Hart White in 1938, and it was called the 'Vegetation-Bearing Architectonic Structure and System'. Several decades later, in 1988, French botanist Patrick Blanc patented a modern living wall technique called 'Mur vegetal'. In this method, the building facade was covered with a felt

layer, allowing the plants to grow without a soil medium using a mechanical irrigation system that delivers the crucial nutrients for plant growth [1].

Since then, research has focused on the various types of VGS with different themes or emphases, such as thermal behaviour, vegetation-related topics, or analytical approaches [1].

By 2007, only a few instances of modern vertical greenery systems existed around the world. The Museum de Qui Branly in Paris and the Caixa Forum building in Madrid are two famous examples. Nowadays, this practice is becoming more popular, and many companies are using it to cover existing walls for aesthetic purposes while benefiting from its many advantages.

Vertical greenery systems can positively impact urban life, in both qualitative and quantitative terms [3]. To mention but a few, the qualitative benefits derived from VGS are the reduction of the urban heat island effect, an improvement in air quality, psychological effects on users, an increase in biodiversity, the creation of natural animal habitats, noise reduction, and positive social and educational benefits [3–5].

The qualitative benefits include improving building energy efficiency, indoor environmental quality, internal air quality, air filtration and oxygenation, health, better envelope protection, and interior noise reduction. The quantitative benefits are often associated with financial returns and increased property value [5].

Despite the proven positive effects of VGS, their implementation is still relatively scarce. There is a common belief that the cost of installation and maintenance is the main reason for this lack of use. However, there are other important reasons, such as the lack of information and opportunities for planners, architects, and decision-makers to efficiently integrate these systems into the decision-making and planning process with less effort [4,6].

On the other hand, the concept of VGS is relatively new from a technological point of view; in fact, most VGS types have emerged post-2006 [1]. Different forms of living wall systems (LWS) have been developed in the last few years, each with specific characteristics. The development of VGS technology has resulted in the use of typologies specific to regions and dependent on the professionals dealing with them. It has also given rise to several different classification systems depending on the market in which the VGS is implemented [2].

Unlike other building systems, such as green roofs which have been classified as extensive and intensive, in the case of vertical greenery systems, there is no established standardization representing their design and variations, which may lead to misunderstandings in assigning systems and methods [4,7]. This confusion is further aggravated by a variety of terms for the same types of VGS structures appearing in the scientific resources and manufacturer's manuals. The problem with the names of all VGS sub-divisions follows the same pattern. This fact prevents comparisons being made between research results, making it necessary to provide information regarding each type of system when discussing the results to avoid data comparisons between different systems [4,8,9].

The sort of VGS used to place plants on the building facades is one of the main factors influencing their function [8]. Hence, it is essential to consider the significant differences between different types of vertical greenery systems, especially between green facades (GF) and living wall systems (LWS) which could influence a building's overall thermal behaviour [8]. Establishing an appropriately organized classification for different VGS types for buildings is crucial when choosing the right type of greenery system both in new and retrofitting projects [4].

In recent years, a considerable number of articles have been published on VGS and various literature reviews have been conducted with the aim of furthering knowledge in this field. Nevertheless, research studies which provide a comprehensive overview of VGS typologies and systematically classify them are scarce. The existing research studies mainly offer a general classification of VGS, which normally follows a more in-depth analysis of the benefits of one category, especially their contribution to the thermal behaviour of building envelopes. Some other studies focus on only one VGS type, overlooking the

others. The main emphasis of such research endeavours lies in exploring recent technical advancements and solutions.

In response to the escalating adoption of VGS technology in recent years, this research recognizes the need for evolving methodologies and standards to keep pace with new requirements. We aim to explore the lack of standardized designs and variations among vertical greenery systems (VGS) despite the introduction of a diverse range of VGS types tailored to different climates and conditions. The proper selection of a VGS becomes a pivotal decision-making step, demanding a nuanced understanding of the available options.

This study will address the gap regarding a VGS classification system through a comparative analysis of the characteristics of VGS researched previously. A comprehensive classification system is proposed based on an analytical approach to results that introduces the most appropriate criteria for VGS classification. A range of important parameters for decision making in VGS design is proposed after the examination of the existing systems and their critical elements. Finally, a case study on vertical greenery systems is presented and their characteristics and properties are analysed based on the classification method offered in this study.

The outcomes of this research offer a valuable resource for the systematic study of greenery systems and their parameters. By providing insights into the decision-making process and aligning it with contemporary sustainability objectives—addressing cost, energy consumption, and maintenance—the study lays the groundwork for future research endeavours in the field of vertical greenery. This research serves as a guide for informed decision-making, facilitating advancements in sustainable urban development.

2. Methodology

In this research, the authors collected data on vertical greenery systems classifications and systematically searched for evidence within primary qualitative studies concerning various VGS types. For clarity purposes, we divided the methodological process into two stages. In the first stage, we aimed to study the most common existing classifications of vertical greenery systems. In the second part, we offered up a framework that considers the most important aspects of VGS for the decision-making process within VGS design. To this end, we carried out the following steps:

1. Initially, data were identified from peer-reviewed scientific papers using keywords to search through online databases. Following the conventions of systematic research, Scopus and Web of Science (WoS) were used to search for relevant articles. Google Scholar was used to include complementary sources on vertical greenery system classifications.

Additionally, a variety of VGS structures are available from commercial catalogues and manufacturers' websites. However, the purpose of this article is to focus on academic and scholarly classifications, thus the keyword search was not extended to other sources such as search engines (Google, Yahoo, etc.).

Since a wide range of terminological approaches are employed for the vertical greenery on buildings in different studies, the commonly applied terms were considered as keywords for this search. The terms included 'Vertical greenery system', 'Vertical greening system', 'Green vertical system', 'Vertical garden', 'Vertical green', 'Green wall', 'Bio-shader', 'Bio-wall', and 'Vertical landscaping' [6,7,9,10]. In this study, we have opted for 'Vertical Greenery System (VGS)' as it is widely recognized and serves as the most comprehensive representation of these structures.

After carefully examining 36 studies centred on VGS classifications, we specifically chose 15 studies that presented original and distinct classification systems. This selection process was key to ensuring that our analysis was based on innovative perspectives and fresh insights. We excluded the remaining articles from our research because they either replicated existing classifications or relied solely on established frameworks. By prioritizing the 15 studies with unique contributions, we aimed to enrich the depth and novelty of

our analysis. In Figure 1, a more detailed depiction of the process is provided; it includes information such as the number of articles examined and the criteria used for their selection.

2. In the second part of the study, a comparative analysis and synthesis of existing vertical greenery system classifications were conducted. As we indicated in the Section 1, the main purpose was to develop a new framework for VGS classification that facilitates the decision-making process within VGS design.

In this respect, we assessed various criteria such as system features, installation methods, maintenance needs, environmental benefits, and performance indicators. We analysed these factors to understand the strengths and weaknesses of each classification. Additionally, we compared their applicability, comprehensiveness, clarity, and ease of implementation. Beyond these criteria, we also considered factors such as plant compatibility, structural support requirements, maintenance needs, aesthetic considerations, and environmental performance so as to provide an inclusive assessment.

3. Finally, based on the findings from the analysis, we synthesized information to propose an ultimate classification for vertical greenery systems. The strengths and best practices from the existing classifications were incorporated and the selection criteria were refined to create a comprehensive and effective classification framework.
4. As a case study, a group of different VGS were selected and their characteristics have been analysed based on the ultimate classification to validate the effectiveness of the framework proposed here. By applying the classification to real-world examples, we can assess how well it captures the variations within VGS and whether it adequately categorizes them according to relevant criteria. This case study implementation will also ensure that the framework is robust, practical, and aligned with current industry trends and scientific understanding. See Figure 1 for a clearer illustration of the process.

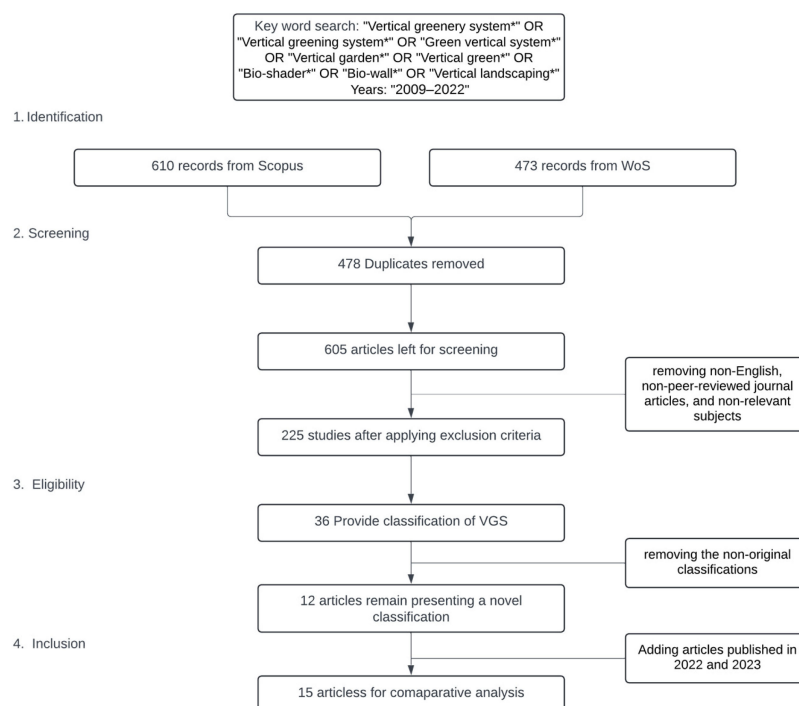


Figure 1. Selection method.

3. Existing VGS Classifications

The 15 articles selected have been analysed according to the year of their publication so that the changes that have occurred in VGS classification throughout the evolution of the vertical greenery systems can be identified.

The study reveals that the authors applied different general definitions and terms for VGS classifications in their studies. Thus, for further comparison, it was necessary to introduce the terms used by the authors into the classification along with their descriptions to explain the reasons behind the authors' choices.

The studies by Dunnet and Kingsbury [11] and later Kohler et al. [12] in 2008 were the first to classify vertical greenery into two categories of green facades and living walls based on the type of vegetation used. However, by that date, there were few examples of LWS worldwide.

1. In a study published in 2009, Yu and Hien [13] divided VGS, or their so-called vertical landscaping (VL), according to species of plants, types of growing media, and construction methods, into four main groups: (1) tree-against-wall type, (2) wall-climbing type, (3) hanging-down type, and (4) module type.

In this classification, the tree-against-wall type is not exactly a vertical greenery system. However, due to the strategic method of placing trees around the building surface and the thermal effects that they directly have on the walls of buildings, the authors considered it as a vertical greenery method. They describe wall-climbing systems as climbing plants that cover the walls of buildings naturally or with the help of a trellis or other supporting system.

Furthermore, the hanging-down type is another vertical landscaping method in which vegetation can be planted at every level from the floor to cover the partial or entire facade by hanging down the wall surfaces. Finally, there is module type which is introduced as the most recent greening concept consisting of lightweight panels that contain growing media. It is noted that module VGS have a more complicated design and require set-up and maintenance. This classification does not provide additional detailed descriptions of the elements and functions of each classification.

2. In 2011, Perez et al. [8] suggested the term 'green vertical systems of building' to generally encompass all the systems available on the market. They proposed another classification for VGS. In this classification, the authors classified VGS into 'extensive' and 'intensive' systems according to implementation cost and further maintenance requirements. On the other hand, this classification also organised the VGS into two groups, green facades and living walls. It seems that Perez et al. decided to develop the same method used for green roof classification to categorise VGS; however, this classification falls short of covering all VGS types and lacks the development of subdivisions for living wall systems.

Perez et al. subsequently divided extensive VGS into two different groups: (1) Traditional green facades, which use climber plants as the facade material and as support, and (2) double-skin green facades or green curtains, which create a double-skin or green curtain which is separated from the wall. In the case of double-skin green facades, the systems used are modular trellises and wired or mesh structures [8].

In the classification by Perez, intensive LWs are divided into three groups: (1) Perimeter flowerpots, where hanging shrubs are planted around the building, creating a green curtain, (2) geotextile felt, and (3) panels. The panels and geotextile felt are fixed to vertical supports or the wall structure and support the vegetation that can be pre-cultivated [8].

3. In 2011, Ottel  [14] also provided a classification for VGS according to which VGS had been initially classified as green facades and living walls. He further classified green facades into two groups: climbing and hanging. Climbing green facades consist of direct and indirect greening systems [9,14]. The hanging green facades were previously mentioned by Perez et al. [8] and Yu et al. [13] under the names of 'perimeter flowerpots' and 'hanging-down'.

Living walls were divided into two groups in the classification by Ottel  according to their growing method: hydroponics and substrate-based. Substrate-based living walls were then divided into three groups: (1) vertical, (2) angled, and (3) horizontal, which indicates the method of plants' arrangement [9,14]. Considering the variety of existing

LWS hitherto this method, allocating all existing types to one of these categories can produce limitations and misunderstandings among users.

4. In 2011, Sheweka et al. [15] presented a classification of VGS that replicates the classification by Yu et al. [13]. The only difference is the omission of the tree-against-wall group. Ottelé et al. [14] also mentioned this type of greenery and referred to it as near-wall planting in their research.
5. As in previous approaches, another classification by Perini et al. [16] divided vertical greenery systems into two groups according to the growing method: facade greening and living wall systems (LWS). They further classified green facades into direct and indirect facades. According to their research, direct facades use climbers attached directly to the building surface, as in traditional architecture, or supported by cables or a trellis. In indirect facades, the greenery is supported by cables or meshes, which could be made of different materials (coated steel, stainless steel, galvanized steel, different types of wood, plastic, or aluminium).

Further, they classified LWS into four groups according to the different principles of growth and planning: (1) LWS based on plastic planter boxes (HDPE) filled with potting soil, (2) LWS based on a foam substrate with steel baskets as a support, (3) LWS based on several felt layers that act as substrate and waterproofing, supported by a PVC sheet, and (4) LWS based on mineral wool covered by fleece supported by a metal frame.

Perini et al. (2011) [16,17] used this classification to demonstrate that green facades and living wall systems (LWS) have different characteristics which help to reduce temperatures and positively affect buildings' insulating properties due to the thickness of the foliage which forms a stagnant air layer and shades the facade and due to water content, material properties, and possible air cavities being created between the different layers of leaves.

Perez et al. [18] associated green facades with damage to the facade materials, animal attraction, and high maintenance costs, while the research by Perini et al. [16] focuses on the positive aspects of these systems such as cost-efficiency and sustainability.

After an analysis of the VGS types presented by Perini et al. [16,17], Čekić et al. [2] and Trkulja et al. [19] presented a similar VGS classification that considered the vegetation growth mechanism and the method of application of the appropriate types of substructures, as well as the plant substrate and irrigation systems. Neither the comparison nor selection criteria were fully clarified. However, they used the classification to further study other criteria such as the environmental impact of VGS using simulation on the facades of a residential building in urban areas.

6. Susorova et al. [20] also used the conventional classification of green facades and living walls for VGS. They further classified green facades into two classes: (1) two-dimensional, formed by cables, ropes, and meshes, and (2) three-dimensional, formed by rigid frames and cages. Moreover, they went beyond the conventions of living walls and introduced different classifications of living walls, including (1) vegetated mats, (2) hanging pockets, and (3) modular systems.

In this classification, vegetated mat living walls consist of fabric layers attached to a fixed backup layer. Pre-grown plants are inserted into holes cut in the fabric, where they base their root system. Hanging pocket living walls consist of pocket-shaped containers attached to a rigid backup layer. Plants are rooted in these felt or plastic containers filled with planting medium. Modular living walls are made of rigid rectangular containers filled with a growing medium that can be attached to an exterior wall or be free standing. They can be in different forms: troughs, boxes with cells, framed boxes, perforated boxes, or wire cages.

This classification is the most inclusive one to date; however, as far as the green facade classification is concerned, there is no clear distinction between the two-dimensional and the three-dimensional systems and the climbers attached to or hanging from the building surfaces.

7. In the research by Manso and Castro-Gomes [10] in 2015, a classification of the different existing green wall systems that were available on the market was proposed according to their structure and application method. Manso and Castro-Gomes [10] used the term green wall to address VGS in general and subdivided green walls into two main groups: green facades and living walls. The authors later classified green facades as either direct or indirect. In direct green facades, plants are attached directly to the wall. Indirect green facades are more modern green facade solutions, including a vertical support structure for the growth of climbing plants. In indirect systems, plants can be rooted directly in the ground or planters. Indirect green facades include (1) continuous and (2) modular solutions.
Continuous indirect green facades are based on a single support structure that guides the development of plants along the entire surface. Green facades with modular trellises are similar solutions but result from installing several modular components along the surface. The main difference that Manso and Castro-Gomes [10] reported was that the modular trellises require vessels for plant rooting and an individual support structure for guiding plant development.
According to the application method, Manso and Castro-Gomes classified living walls as continuous or modular. Continuous LWs are based on lightweight permeable screens into which plants are inserted individually. Modular LWS, which is a relatively new solution, consists of elements with a specific dimension, including the growing media where plants can grow. Modular LWS offer differences in arrangement, weight, and assembly [10].
Manso and Castro-Gomes [10] further classified Modular LWSs into four groups: (1) Trays, (2) Vessels, (3) Planter tiles, and (4) Flexible bags. Trays consist of rigid containers attached together to hold the weight of the plants and the substrate. Vessels are a transformation of the most common support used for plants, but they can be attached to a vertical structure or be connected vertically to each other. Planter tiles highlight the modular elements of the design of greenery layer cladding. Flexible bags include growing media and lightweight materials that facilitate the application of plants on surfaces with different shapes, such as curved or inclined surfaces.
The classification offered by Manso and Castro-Gomes is one of the classifications that cover the majority of the existing VGS types. The criteria used in the classification are based on methods of application and thus might need modifications in the future due to the expansion and development of application methods.
8. In 2015, C.Y. Jim [21] conducted a study to address the significant variation in the meaning and use of terms related to VGS up to 2014 and to develop an alternative classification scheme and the terms associated with it. He proposed a triple-criteria classification scheme that initially divided green walls (GWs) into climber (CGWs) and herb–shrub (HGWs) types using the overarching plant growth form. Each type was further extended based on the following factors:
(A) For climbers, two main factors were considered: (1) The training system (how the plants are supported) and (2) the wall-toe substrate (the substrate at the base of the wall). As a result, four options for each factor, leading to 16 possible combinations of types of climber green walls, became available.
The author introduced four training system states crossed with four wall-toe substrate states, resulting in 16 possible combinations of types of climber green walls being available.
(B) The factors for herb–shrub green walls were (1) the type of substrate system (how the vegetation is planted) and (2) whether the substrate is elevated or not, which in turn yielded eight different types of herb–shrub green walls.
According to C.Y. Jim’s classification, each type and subtype has its own characteristics and requirements. For example, CGW systems are relatively lightweight and can be installed above ground with minimal technical constraints in hanging mode, and

HGW variants may require specific considerations of their load-bearing capacity, especially for containerised types with heavy substrates [21].

9. Allan and Kim. [22] introduced the VGS categorisation performed by the Singapore government and adopted it as the main classification in their approach. This classification organised VGS into four categories: (1) Support systems, (2) Cassette systems, (3) Planter systems, and (4) Pocket systems.

Support systems like the traditional VGS consist of planters climbing on wire trellises of a distance, generally 3 m apart. Cassette systems consist of modular units containing growing media built for manageable mounting onto metal frame structures as stand-alone systems or attached to existing wall surfaces. Planter systems are made of individual pots placed on a frame at regular intervals. Pocket systems are panels consisting of a minimum of two layers of moisture retention mats attached to a rigid backing for support. Pockets of openings are made at the outer layer for plant placement [22].

10. Medl et al. [23] presented a new classification for vertical greenery systems developed inspired by the ideas previously introduced by Ottel   et al. [14] and Perez et al. [18] and replicated by Hunter et al. [24] and Safikhani et al. [7], according to which two general forms of green facades exist: Direct green facades and double-skin green facades. Direct green facades feature self-clinging climbers, which adhere to the building exterior using adventitious roots or self-adhesive pads. Double-skin green facades rely on engineered support structures (modular trellises, stainless steel cables, or stainless steel/HDPE mesh) to assist the upward growth of a wider variety of climbing plants.

Safikhani et al. [7] replicated the same classification which was previously offered by Yu et al. [13]. In many of the studies this classification is assigned to Safikhani et al.; however, this idea was first proposed by Yu et al., while Safikhani et al. did not make any substantial contribution to the earlier classification.

Medl et al. [23] suggested the terms ‘ground-based greening method’ and ‘wall-based greening method’, respectively, to describe green facades and living walls to emphasise the importance of the planting method.

Ground-based greening methods rely on natural ground, while wall-based greening methods include direct planting on the wall without a connection to the natural ground. Green facades are further classified according to the location of the plants, which can either be placed directly into the soil or into soil-filled planter boxes, for which they suggest the term ‘planter box-based greening method’ [23].

In their classification, indirect green facades use supporting systems such as stainless-steel cables, modular trellises, or stainless-steel mesh to assist the upward growth of climbing plants by creating a second-skin layer at a distance from the wall [23].

Furthermore, Medl et al. classified LWS according to their application method as (1) continuous, (2) modular, or (3) linear systems. In this classification, continuous green walls are based on a single support structure, while modular green walls result from installing several modular elements together to form the whole system. Linear green walls result from cascading components linearly attached to the wall [23].

11. Bustami et al. [1] also classified VGS as green facades or living walls. According to them, a green facade refers to vegetation grown on or adjoining to a building’s surface. They further classify green facades into the two categories of direct and indirect. The direct green facade is the traditional style, and indirect green facades can be grown on continuous guides or trellises. Both can be planted in the ground or planter boxes. The authors use the term ‘living wall’ to refer to LWS and claim that living walls could be developed into modular systems. They classify LWS into three categories: (1) Tray, (2) Vertical felt, and (3) Horizontal felt systems. However, they do not clearly explain their selection criteria [1], and their classification is not inclusive.
12. Arengghi et al. [25] by elaborating the classification provided by Bi [26], proposed a classification to divide VGS systems into specific categories based on the differ-

ences among the main technological solutions by considering both geometrical and mathematical properties that have a different effect on the building envelope. They considered the differences in each group's interaction with the building envelope to emphasise the substantial differences in the approach to simulation.

This study classifies VGS into three main categories: Green Barrier Systems (GBS), Green Coating Systems (GCS), and Green Walls (GW). GBS, including Green Tree Barrier (GTB) and Green Climbing Barrier (GCB), have minimal wall contact, while GCS, subdivided into Green Climbing Coating (GCC) and Green Modular Coating (GMC), involve plants growing with or without climbing mechanisms. GW, encompassing Mur Vegetal (MV), Light Systems (LS), and Heavy Systems (HS), exhibit varying technical complexities and substrate compositions, forming a gap with walls resembling ventilated facades. This classification aids in understanding the differences in each group's interaction with the building envelope to emphasise the substantial differences in their approach to energy simulation [25].

13. In their study, Karimi et al. [27] proposed a classification system for vertical greenery systems, defining three categories: wall vegetation, green facades, and living walls. They introduced a novel classification termed 'wall vegetation', representing a type of VGS where plant growth occurs organically within wall crevices and joints, devoid of human intervention and lacking structured support systems.

Expanding upon the framework established by Medl et al. [23], Karimi et al.'s classifications (in the year 2022) of green facades and living walls demonstrate some variance in the terminology, although the underlying principles remain similar. However, the study lacks explicit criteria for this classification scheme, leaving some ambiguity as to why naturally occurring wall vegetation is classified as a form of green wall.

14. Ogut et al. [28] performed a market review of VGS. According to them, 'vertical green' refers to all forms of vegetated wall surfaces and is mainly divided into two groups according to the absence or presence of the following components: supporting elements, growing media, vegetation, drainage, and irrigation. GFs require fewer components when compared to LWs and can be classified based on where the plants are rooted. LWs are further categorized based on characteristics such as supporting system type, cultivation method, growing media, and integration potential. The key components of VGS are the vegetation, structural support system, and growing media. The selection of vegetation for GFs depends on climate conditions and available light, typically consisting of climbing and self-clinging species. Various plant options are utilised, including main-stem twiners, vine types with wiry tendril structures, and plants using attachment mechanisms like leaf hooking and thorns. In this classification, both GFs and LWs can be classified into minor categories based on several characteristics.

15. J. Irga et al. [29] built upon the established classification framework for VGS initially outlined by Manso and Castro Gomez. However, they introduced a novel intermediate typology termed the Tessellated Double Green Perforated Facade system. This approach combines features of both green facades and living walls, addressing the inherent limitations of current systems.

The system diverges from conventional methods by fragmenting modular substrate panels of living walls into facade elements. These elements are strategically rotated to be perpendicular to the host building's facade, thereby forming a porous structure with apertures. These apertures serve multiple functions, facilitating maintenance access and creating habitat corridors for various fauna, including birds, insects, and small animals, providing the maximum diversity and depth to the ecosystem.

4. Analysis of Results

As seen in Section 3, most of the studies agree on the general division of VGS into two main categories: green facades and living walls [1,9,10,14,16,20]. However, a key challenge arises from variations in terminology, where certain VGS types are labelled differently across studies, while some terms are used interchangeably for the same VGS type [10].

There is also disagreement regarding the living wall classification, including subcategories and the criteria for classification.

To consider the diverse influences of the vertical greenery systems, various criteria must be considered. Thus, different greening variants are possible for certain circumstances. Knowledge of the different existing VGS types, their parameters, and their strengths and limitations makes it possible to minimize the effort required in the planning process, explore numerous variables, and thus facilitate decision making for the improvement of sustainable cities [30].

4.1. Comparison and Analysis

It seems that since there is less variety in the types of green facades, the majority of the authors consent to the classification of green facades into two classes: direct and indirect. Regarding LWS, there are various discrepancies, and each researcher employs distinct criteria and methods for classification.

Table 1 shows the 15 studies finally selected for the analysis that employed principles to classify VGS. We indicate the year of publication and the classification criteria.

Table 1. Results from the analysis.

Author	Year	Classification Criteria	General Classification	Sub-Classifications
Yu et al. [13]	2009	Plant species, type of growing media, and construction methods	Tree-against-wall, wall-climbing, hanging-down, and module type	-
Perez et al. [8]	2011	Requirements of implementation cost and further maintenance	Intensive and extensive	Extensive: 1. traditional green facades, 2. double skin (or green curtain); Intensive: 1. perimeter flowerpots, 2. panels, 3. geotextile felt
Ottelé et al. [9,14]	2011	Growing method	Green facades and living walls	GF: 1. climbing (direct, indirect), 2. hanging; LW: 1. Hydroponics, 2. substrate-based (vertical, angled, horizontal)
Sheweka et al. [15]	2011	Species of the plants, types of growing media, and construction method	Wall-climbing, hanging-down, and module green wall	-
Perini et al. [16]	2013	Growing method	Facade greening and living walls	GF: 1. direct, 2. indirect; LWS: 1. based on plastic planter boxes (HDPE), 2. based on foam substrate, 3. based on felt layers, 4. based on a foam substrate, 5. based on mineral wood
Susorova et al. [20]	2013	Application method	Green facades and living walls	GF: 1. two-dimensional, 2. three-dimensional; LW: 1. vegetated mats, 2. hanging pockets, 3. modular systems
Manso and Castro-Gomes [10]	2015	Structure and application method	Green facades and living walls	GF: 1. direct, 2. indirect (continuous and modular); LWS: 1. (trays, vessels, planter tiles, and flexible bags)
C.Y. Jim [21]	2015	Plant growth form	Climber green wall; herb-shrub green wall	Climber GW: training-system, wall-toe-substrate; Herb-shrub GW: substrate-system, elevated-substrate
Allan et al. [22]	2016	Application method	Support system, cassette system, planter system, pocket system	-
Medl et al. [23]	2017	Location of plants and application method	Ground-based greening method and wall-based greening method	Ground-based: 1. Direct, 2. double skin; Wall-based: 1. continuous, 2. modular, 3. linear.
Bustami et al. [1]	2018	Not explained clearly	Green facades and living walls	GF: 1. direct, 2. indirect; LW: 1. tray, 2. vertical felt, 3. horizontal felt
Arengi et al. [25]	2021	Interaction with building envelope	Green barrier systems (GBS), green coating systems (GCS), and green walls (GW)	GBS: 1. green tree barrier (GTB), 2. Green climbing barrier (GCB); GCS: 1. green climbing coating (GCC), 2. green modular coating (GMC); GW: 1. mur vegetal (MV), 2. light systems (LS), 3. heavy systems (HS)
Karimi et al. [27]	2022	Growing method	Wall vegetation, green facades, living walls	GF: 1. direct 2. indirect; LW: 1. continuous, 2. modular, 3. linear
Ogut et al. [28]	2022	Characteristics	Green facades and living walls	Differing based on supporter system, cultivation, integrity, growing media
J. Irga et al. [29]	2023	Application method	Green facades, living walls, tessellated double green perforated facade system	GF: 1. direct, 2. indirect; LW: 1. continuous, 2. modular, 3. linear

4.2. Classification Proposed

In this study, we present a refined and more advanced approach to VGS classification. The proposed classification is developed after a comprehensive examination of existing VGS types available up to 2024, alongside an evaluation of the classification systems proposed by the experts in this scientific field. After an extensive analysis of the previous VGS classifications, we decided that the most comprehensive approach for the classification of VGS involves the application of a multi-criteria method.

Consequently, for the initial classification stage, we adopted the widely utilised categorisation which divides VGS into two primary groups: green facades and living wall systems. This classification, approved and used by the majority of VGS experts, effectively divides VGS considering the application of primitive or more advanced methods of plant growth on the building surface.

We further classified green facades into two categories considering the direction of the plants' growth:

(1) ascending and (2) hanging green facades.

Unlike the majority of the existing classifications, which divide green facades into only two groups, direct and indirect [1,9,10,16,18,23], we believe that a separate classification should be considered for hanging green facades. Hanging greenery systems differ from ascending systems in terms of attachment and growth mechanisms. They are characterized by the suspension of plants in containers or planters, which are often attached to (or designed to be inside) the building's facade through various means, such as hooks, cables, or brackets. The plants in hanging systems generally grow downwards, allowing for a distinctive visual appearance and unique aesthetic qualities.

Both the ascending and hanging groups can be subdivided into two categories: direct and indirect, depending on whether they rely on a support structure. In the direct method, plants are affixed directly to the building surface without additional assistance, whereas in the indirect method, they utilize a support system. The type of support employed may vary depending on the plants' requirements and the design objectives, leading to further classification within the indirect group based on support structure (trellis/mesh or cable/rope). Another distinguishing factor for green facade systems is whether plants are grown in planter boxes or directly in the soil. Hanging green facades typically utilize planter boxes due to their intrinsic nature. However, for ascending green facades, the planting methods may vary based on design considerations and the facilities available. All of these types of system could be located at different heights on the facade.

On the other hand, more advanced vertical greenery systems greatly depend on the material used as the growing medium. Therefore, in this study, the living wall systems were classified according to their planting methods into two main categories:

(1) soil-based and (2) sheet-based.

Since the growing method directly influences the technical aspects of the VGS, such as substrate choice, irrigation systems, nutrient delivery, and plant selection, classifying VGS based on the growing method makes it possible to capture these technical distinctions and understand the specific requirements and considerations associated with each type of VGS.

In addition, each growing method has its own installation, maintenance, and management requirements. By considering the growing method in the classification, it is possible to provide practical guidance for implementing and maintaining VGS. This information is crucial for architects, designers, and practitioners who need to understand the practical aspects of each method when integrating greenery into their projects.

Furthermore, classifying LWS according to the growing media used enables comparative analysis and benchmarking among systems that employ similar techniques. It allows researchers to evaluate the strengths, limitations, performance metrics, and the most appropriate practices associated with each growing method. This comparative analysis can lead to the development of more efficient and effective VGS designs.

The use of different types of soil as breeding grounds is the main factor in the distinction of LWS types. Soil-based living wall systems use soil as the growing media that provides support to the vegetation roots, and the plants can grow in it. The soil used can come in different forms. Depending on the LWS' functions, sand, mineral wool, perlite, or a mixture of them can be used as the substrate in these systems.

Soil-based systems are further classified into three sub-categories based on the planting method:

(1) Hollow systems, (2) pocket systems, and (3) planter systems.

Hollow systems could be used to fix plants into the small mounds of soil in hole-shaped pockets perforated inside the living wall surface. The wall surface could be made of different materials such as fibreglass, foam, or recycled materials that permit the partial absorption of water.

In pocket systems, the plants are fixed into the soil and set into bags or pockets. The pockets are normally made of a flexible material that permits the easy transit of water.

Planter-based systems typically use planter boxes, troughs, or containers built on or attached to existing walls or support structures. Planting is supported by soil-based substrates like those used in the pocket and hollow installations, utilising a lightweight combination of recycled materials containing the right balance of nutrients with a free-draining medium. The planter-based systems can be made of different materials such as HDPE, metal, wood, etc.

The natural water retention of most soil types allows for the simple design and construction of irrigation systems, thus reducing installation and maintenance costs. However, a disadvantage associated with soil-based systems is their weight compared to other solutions. New lightweight materials are increasingly becoming available to address this issue. Another drawback is that the soil needs to be replaced regularly depending on the plants and the location of the wall.

In sheet-based living wall systems, plants take root in mats made of felt, fibre mats, or similar substances instead of soil. So, in this case, the mat is the substrate/growing medium. Sheet-based systems are thin, and they will not be able to retain much water or hold very large plants with long, thick roots, so this is an essential factor to be considered by the designers at the decision-making stage.

In recent years, technologies have been developed to help adjust sheet-based LWS to have better water retention and root-bearing capacities by using different materials, which also tend to last much longer. Sheet-based systems generally use hydroponic or aeroponic irrigation methods that employ nutrient-rich water or mist solutions to nourish the plants. In these systems the vegetation is mostly grown on pre-constructed panels before vertical installation [31].

Aeroponic and hydroponic techniques employ nutrient-rich water or mist solutions to nourish the plants

Various authors have proposed categorising living wall systems into “modular” and “continuous” forms. However, it becomes apparent that relying solely on these criteria is insufficient for a comprehensive classification of VGS.

While the modular and continuous forms are crucial aspects of VGS design, they primarily address the physical arrangement and structure of the greenery. Thus, each sub-category of living wall systems can be further divided into modular and continuous groups based on their potential for structural assemblage and integrity.

Effective decision-making in VGS design requires the consideration of various technical factors, such as growing methods, substrate types, irrigation systems, and maintenance requirements. Focusing solely on one aspect limits the understanding and evaluation of the diverse design options available, potentially leading to suboptimal design choices and the inadequate implementation of VGS.

Given the above, a more comprehensive classification that considers multiple criteria, including growing method and technical considerations, is necessary for effective decision making in VGS design (see Section 4.3).

It is very important that the VGS classification is assigned and selected carefully because it can influence the entire decision-making process. Choosing the method of VGS application as the main criteria for VGS classification would make the workflow more manageable and cause less confusion in the selection of the parameters of the design in the next steps. The result of our classification of VGS is shown in Figure 2.

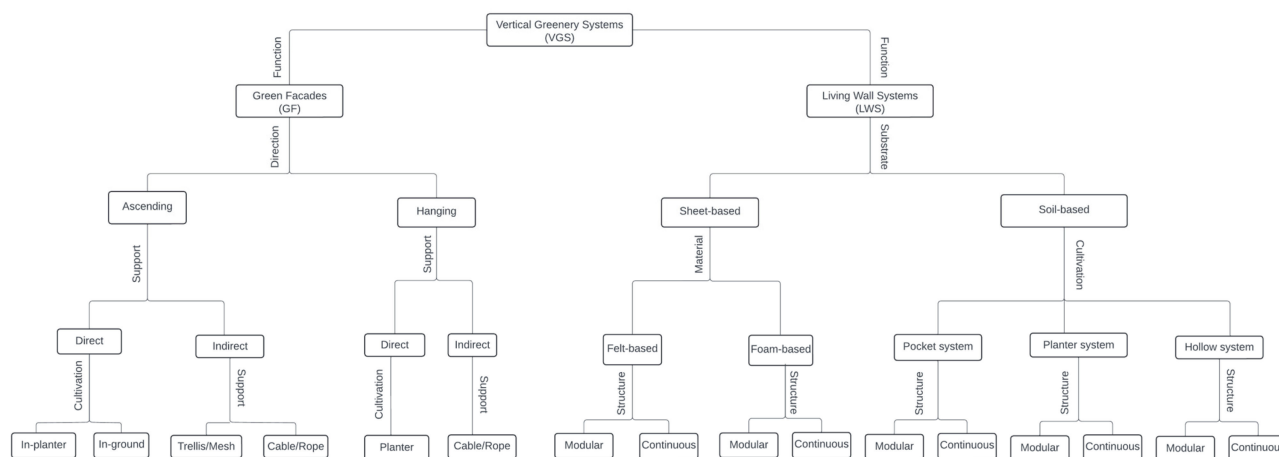


Figure 2. Classification for VGS (Resource: Manouchehri. M.).

4.3. Parameters for VGS Design

In the previous section, a classification method for VGS was proposed that highlights the distinctions that can be made between different types of VGS considering the most influential factors within their design process. Each VGS type consists of multiple individual elements made of different materials and with corresponding different life spans. For example, the aluminium troughs used in the aluminium planter system have a potential useful life of 40 years, whereas the drip hoses used in the irrigation system would merely last for 10 years according to the product's datasheet. Therefore, these properties have an impact on the maintenance and technical servicing of the VGS [32,33].

Once the decision to design a VGS has been made, the process of determining the VGS type and selecting the plants begins. To design a vertical greenery system successfully a wide range of criteria must be considered. The primary parameters that should be considered are type and classification, which identify the general characteristics of a VGS (Section 4.2). To incorporate a wider range of systems and applications, parameters related to design aspects should also be considered, as any changes introduced to their attributes could affect the whole VGS' function.

Since plants are subject to considerable changes during their life cycle due to their inherent characteristics, the consideration of factors such as the height of the plant and the duration of greening in their different phases is important during the decision-making stages.

Other relevant plant specifications like leaf area index and reflectivity should equally be considered. The result of the studies also shows the importance of including external environmental factors like solar exposure, shadow, and wind [34]. Furthermore, other parameters such as irrigation and care and maintenance intervals were proven to play an important role in the decision-making process at an early stage. Additionally, including details about biodiversity, effects on the microclimate, construction criteria, and details on the substructure, etc., seem to play a positive role in the decision-making process.

Research projects, as well as the findings from practical applications, show that an early integration of greenery into the planning process is necessary to ensure that vertical greening systems remain healthy in the long term and to be able to include all of the aspects of the building into the design for sufficient plant care and maintenance [35,36].

Through an analysis of the existing greenery system elements, their features, and challenges from the pre-design to the maintenance phase, we determined the parameters that played a significant role in the process of decision-making to achieve an optimum

VGS design. Eventually, the selected parameters were classified into eight main groups according to their functions and impact [6]:

1. Type and classification parameters. This includes parameters that contain information about the type of greenery system, its components, and their dimensions and materials [37–40]. We break these factors down into five principal groups:

- **Greenery System Type:** This is the most influential part for the designers. One or a combination of the classifications among the types previously mentioned in Section 4.2 must be selected based on the project's characteristics and needs.
- **Total Dimension of Greenery System:** This parameter refers to the overall size and scale of the greenery system, including its height, width, and depth. It considers the extent of coverage and spatial requirements for installation.
- **Element Dimensions:** Element dimensions pertain to the individual components or modules comprising the VGS, including panels, planters, or modules, and their respective sizes.
- **Climbing Aids:** Climbing aids are structures incorporated into the system to support climbing plants in green facades. These could include trellises, wire meshes, or other climbing frameworks [37].
- **Vegetation Support Structure:** This parameter describes the primary framework or support structure that holds the greenery system in place, providing stability and anchorage for plant growth. It can vary from simple trellises to more complex modular systems.
- **Substrate:** Substrate refers to the material in which the plants are rooted. It includes considerations such as composition, depth, and drainage properties to support plant growth effectively.
- **Planting:** Planting details encompass the selection of plant species, planting density, and arrangement within the greenery system. It also includes considerations of the irrigation, fertilization, and maintenance requirements to ensure plant health and vitality.

2. Facade Design Aspects. This includes the influential parameters that need to be considered within the planning and design. By carefully considering these aspects, architects and designers can plan and design VGS that not only enhance the visual appeal of buildings but also contribute to environmental sustainability and human well-being [37–40]:

- **Placement:** Placement involves determining the specific location on the building's facade where the greenery system will be installed. Factors to consider include structural integrity, architectural aesthetics, number of building openings and their location, sunlight exposure, and accessibility for maintenance.
- **Orientation:** It refers to the direction in which the facade faces relative to the sun. It influences factors such as sunlight exposure, shading effects, and microclimate conditions, which in turn affect plant growth and the overall performance of the greenery system.
- **Coverage Pattern Selection:** The coverage pattern selection involves deciding how extensively the greenery will cover the facade's surface. Options range from partial coverage to full coverage, each offering different aesthetic and environmental benefits. Factors to consider include visual impact, building aesthetics, and maintenance requirements.
- **Plant Choice:** Selecting suitable plant species is crucial for the success of the greenery system. Considerations include climate suitability, water requirements, growth habits, and aesthetic characteristics. Plants should be chosen based on their ability to thrive in the specific environmental conditions of the site.
- **Selection of Greening Combinations:** Greening combinations involve selecting a mix of plant species, as well as incorporating other elements such as vines, shrubs, or flowering plants to create visual interest and biodiversity. The combination should be harmonious, considering factors such as colour, texture, and seasonal variation.
- **Selection of Greening Area Ratio (Percentage):** The greenery area ratio refers to the proportion of the facade's surface that will be covered by vegetation relative to other

materials. This ratio affects the visual impact, thermal performance, and environmental benefits of the greenery system. Balancing aesthetics with functional considerations is important when determining the appropriate ratio.

- **Material Choice:** Material choice involves selecting appropriate materials for the support structure, substrate, and irrigation system within the greenery system. Considerations include durability, weather resistance, sustainability, and compatibility with plant growth requirements.
- **Slope Angle:** The slope angle of the facade influences water runoff, sunlight exposure, and planting arrangements. It affects factors such as drainage, soil erosion, and plant growth orientation. Choosing an appropriate slope angle ensures the optimal performance and longevity of the greenery system.
- **Structural aspects of the building walls (edging profiles on building Corners):** Edging profiles on building corners refer to the design and construction details used to integrate greenery systems seamlessly with architectural elements. Edging profiles provide structural support, aesthetic cohesion, and weatherproofing for green facades or living walls. Paying attention to the edging profiles of a building ensures proper installation, durability, and the visual integration of greenery systems into the built environment.

3. Irrigation Parameters. The effective design of these parameters ensures that the greenery system receives sufficient water to support plant growth and vitality while minimizing water waste and the environmental impact of the system [37–39]:

- **Moisture Percentage:** Moisture percentage refers to the level of soil moisture maintained within the greenery system. It is crucial for the health and vitality of plants, as insufficient or excessive moisture can lead to stress, root rot, or dehydration. Monitoring moisture levels helps to ensure optimal growing conditions and water efficiency.
- **Irrigation Systems:** Depending on the system's needs, various irrigation systems can be employed to deliver water to the greenery system efficiently [37].
- **Irrigation Intervals:** The frequency at which the greenery system is watered is an important factor to consider in the design of VGS. This parameter depends on factors such as the plants' water requirements, soil type, weather conditions, and seasonality. Balancing water conservation with plant health is essential, avoiding both under-watering and over-watering.

4. Care and maintenance. Effective care and maintenance practices are essential for preserving the functionality and aesthetics of greenery systems over time. A consideration of the necessary actions in this regard can contribute to the long-term success and sustainability of greenery installations:

- **Accessibility:** Accessibility refers to the ease with which maintenance personnel can access and perform tasks within the greenery system. Design considerations should ensure that access points are strategically located to allow personnel reach all areas of the system safely and efficiently. This includes provisions for ladders, scaffolding, or access platforms where necessary.
- **Construction:** Construction considerations encompass the installation process and building techniques used to create the greenery system. Quality craftsmanship, proper waterproofing, and adherence to structural integrity are essential for long-term durability and performance. The construction methods should also facilitate future maintenance activities, such as irrigation system repairs or plant replacements.
- **Maintenance Intervals:** Maintenance intervals dictate the frequency at which routine upkeep tasks are performed to ensure the health and aesthetics of the greenery system. This includes activities such as pruning, fertilizing, pest control, and irrigation system checks. Maintenance schedules may vary depending on factors such as plant growth rates, seasonal changes, and weather conditions.
- **Planting Intervals:** Planting intervals refer to the timing and frequency of planting new vegetation within the greenery system. This could involve replacing dead or declining

plants, refreshing planting beds, or introducing seasonal varieties for visual interest. Planting intervals should be coordinated with maintenance schedules to minimize disruption and optimize plant health.

5. Plant Parameters. Careful consideration of these parameters is essential for creating resilient and visually appealing sustainable VGS [37–40]:

- **Plant Type:** The species or variety of plants selected for inclusion in the greenery system play a crucial role in system's functionality. This includes considerations such as deciduous or evergreen, flowering or non-flowering, annuals or perennials, and native or non-native species. Plant selection should align with the project's goals, the site conditions, and design aesthetics.
- **Leaf Area Index (LAI):** The Leaf Area Index (LAI) is a measure of the total leaf surface area per unit of ground area. It quantifies the density of foliage within the greenery system and influences factors such as photosynthetic capacity, shading effects, and transpiration rates. Higher LAI values indicate denser vegetation cover and potentially greater environmental benefits.
- **Plant Height:** Plant height refers to the vertical dimension of the vegetation within the greenery system. It impacts visual aesthetics, spatial planning, and shading effects. Selecting plants with varying heights can create visual interest and texture within the greenery system, while also considering any height restrictions based on architectural or functional requirements.
- **Reflectivity:** Reflectivity, or albedo, refers to the ability of plant surfaces to reflect sunlight. Light-coloured or glossy foliage tends to have higher reflectivity, which can reduce heat absorption and mitigate urban heat island effects. Reflectivity influences microclimate conditions, energy usage, and thermal comfort within the surrounding environment.
- **Duration of Greening:** Duration of greening refers to the length of time that the vegetation remains green and actively growing within the greenery system. This can vary depending on factors such as plant lifespan, seasonal changes, maintenance practices, and environmental conditions. Selecting a diverse mix of plant species with staggered growth patterns can help maintain greenery throughout the year.

6. Stress Factors. The external environmental factors that affect the greenery system's functions should be considered in the decision-making process when planning out VGS, as they can greatly affect the following factors:

- **Solar Exposure:** The intensity and duration of sunlight received by the greenery system throughout the day should be taken into account in the design calculations. Excessive solar exposure can lead to stress on plants due to heat stress, dehydration, and photoinhibition. It can also cause leaf scorching, wilting, and sunburn. Proper plant selection, shading strategies, and irrigation management are essential for mitigating the negative effects of solar exposure.
- **Shadow-Stressed Area:** Shadow-stressed areas are regions within the VGS that receive limited or fluctuating sunlight due to shading from nearby structures, vegetation, or topography. Plants in these areas may experience reduced photosynthetic activity, slower growth rates, and an increased susceptibility to fungal diseases. Strategic plant placement, pruning, and supplemental lighting can help address shadow-stressed areas and maintain plant health.
- **Wind Factor:** The wind factor refers to the strength, direction, and frequency of wind affecting the greenery system. Strong winds can cause mechanical stress on plants, leading to physical damage, desiccation, and uprooting. Wind can also exacerbate transpiration rates, drying out plant tissues and soil moisture. Windbreaks, wind-resistant plant species, and structural reinforcements can help to mitigate the negative effects of wind stress on greenery systems.

7. Cost information. This refers to the cost of the installation and maintenance of the greenery system in different phases of its life cycle.

- **Planning:** Planning involves the systematic process of envisioning, organizing, and coordinating the development of greenery systems. It encompasses site analysis, goal setting, stakeholder engagement, and feasibility assessments. Effective planning ensures that greenery installations align with project objectives, regulatory requirements, and environmental considerations, while maximizing its aesthetic, social, and ecological benefits.
- **Design:** Design encompasses the creative and technical process of conceptualizing and specifying the physical and aesthetic attributes of greenery systems. It involves site layout, plant selection, irrigation design, structural engineering, and integration with architectural elements. Design considerations prioritize functionality, sustainability, accessibility, and visual harmony to create cohesive and resilient greenery installations.
- **Construction:** Construction involves the physical implementation of greenery systems according to the approved design plans and specifications. It includes site preparation, the installation of support structures, planting, irrigation system assembly, and quality control. Skilled labour, proper equipment, and adherence to safety protocols are essential for ensuring the successful execution of construction activities within budget and schedule constraints.
- **Substructures:** Substructures are the underlying support systems that provide structural stability and anchorage to greenery installations. These may include foundations, retaining walls, drainage systems, and irrigation infrastructure. Substructures are designed to withstand environmental loads, accommodate plant growth, and ensure the longevity of greenery systems in diverse urban environments.
- **Care and Maintenance:** Care and maintenance encompass the ongoing activities required to preserve the health, functionality, and aesthetic appeal of greenery systems over time. This includes watering, fertilizing, pruning, pest control, and irrigation system maintenance. Regular monitoring, timely interventions, and proactive management practices are essential for sustaining plant vitality, preventing damage, and maximizing the longevity of greenery installations.
- **Demolition and Disposal:** Demolition and disposal involve the removal and disposal of greenery systems at the end of their life cycle or when redevelopment is necessary. This process includes dismantling support structures, extracting plants, and disposing of materials in accordance with environmental regulations. Proper disposal methods prioritize recycling, composting, or repurposing materials to minimize waste and environmental impact.

8. Other Influential Factors. There are other influential parameters that could not be classified into any of the previous groups but were equally important for the designers:

- **Light Condition:** Light condition refers to the availability, intensity, and duration of sunlight received by the greenery system. Factors such as the location of the site, orientation of the facade, and shading from surrounding buildings influence light conditions. Understanding these factors helps determine suitable plant species, planting locations, and irrigation requirements to optimize photosynthesis and plant growth.
- **Effects on Microclimate:** Greenery systems can significantly impact the microclimate of their surroundings by modifying temperature, humidity, wind patterns, and air quality. Vegetation provides shading, evaporative cooling, and air purification, which influence thermal comfort and environmental quality in adjacent spaces. Considering the effects on the surrounding microclimate helps to mitigate heat island effects, reduce energy consumption, and enhance human well-being, and thus is a crucial factor in the decision-making processes within designing a VGS.
- **Biodiversity:** Biodiversity refers to the variety and abundance of plant and animal species within the greenery system and its surrounding environment. Greenery installations contribute to urban biodiversity by providing habitats, food sources, and refuge for wildlife species. Incorporating diverse plant species, vegetation layers, and habitat features promotes ecological resilience, pollinator health, and ecosystem services.

- **Growing Medium Thickness:** The depth or thickness of the substrate layer within the greenery system can affect root development, water retention, and nutrient availability for plant growth. An adequate growing medium thickness ensures sufficient root space and support for vegetation, while also allowing for proper drainage and soil aeration.
- **Life Cycle Assessment Parameters:** Life cycle assessment parameters evaluate the environmental impacts associated with the production, installation, use, and disposal of greenery systems. This includes considerations such as resource consumption, energy usage, greenhouse gas emissions, and waste generation. Conducting life cycle assessments helps to identify opportunities for improving sustainability, reducing environmental footprints, and informing decision making throughout the project's life cycle.

Table 2 proposes a systematic classification of the above-mentioned parameters.

Table 2. Properties and parameter classification, (Resource: Manouchehri. M.).

Type and Classification Parameters	Facade Design Aspects	Irrigation Parameters	Care and Maintenance	Plant Parameters	Stress Factors	Cost Information	Other Influential Factors
Greenery system type	Placement	Moisture percentage	Accessibility	Plant type	Solar exposure	Planning	Light condition (location, direction and shading from surrounding buildings)
Total dimension of greenery system	Orientation	Irrigation systems (water pipes and irrigation hoses)	Construction	Leaf Area Index	Shadow Stressed Area	Design	Life cycle assessment parameters
Element dimensions	Coverage pattern selection	Irrigation intervals	Maintenance intervals	Plant Height	Wind factor	Construction	Effects on microclimate
Climbing aids	Plant choice		Planting intervals	Reflectivity		Care and maintenance	Biodiversity
Vegetation support structure	Selection of greening combinations			Duration of greening		Demolition and disposal	Growing medium thickness
Substrate	Selection of greening area ratio					Substructures	
Planting	Material choice						
	Slope angle						
	Structural aspects of the building walls						

Research shows that a pure consideration of private costs and benefits is not sufficient to reflect the actual functionality of VGS, since the effects of greening are complex and impact different groups of people and areas at different levels. Therefore, other criteria need to be considered in future assessments to make statements about the actual profitability of these systems in a more comprehensive way [41–43].

4.4. Case Study

As we mentioned in Section 1, the existence of a unified classification system offers the possibility to further analyse the different VGS types under the same climatic circumstances. In the following section a case study of Madrid Metropolitan is presented, which can be considered as an example of a Mediterranean climate. The different types of VGS constructed in recent years are studied, and their structure and characteristics are analysed according to the classification method proposed in this study to provide a clearer idea of the classification presented.

Given the research objectives and context, purposeful sampling was employed to select vertical greening systems (VGS) for this case study. This method allows for the selection of cases that are most informative and illustrative of the phenomenon under study, which, in this case, is the classification and analysis of VGS in urban environments, specifically in Madrid, Spain.

Despite the relatively small number of cases (seven), the selection of cases is based on their relevance to the research objectives and the variability they offer in terms of the type of VGS. This approach is particularly suitable for this study as it allows use to focus on cases that provide the most valuable insights into the proposed classification system, thereby enhancing the validity and reliability of the research findings. However, further investigation is required to solidify the uniqueness and functionality of the classification system.

The selection of cases in Madrid is advantageous due to several factors. Firstly, the utilization of VGS in Madrid has been evolving in recent years, ensuring a diverse pool of examples with variability in the design, installation methods, and maintenance practices used within Madrid's urban environment. Furthermore, Madrid's Mediterranean climate presents a unique environment in which the performance and characteristics of VGS can be examined. Additionally, by focusing on real-world examples in Madrid, the research can provide practical insights into the implementation and effectiveness of VGS in addressing the challenges of urban settings. Therefore, purposeful sampling in Madrid enables the research to capture the complexity and variability of VGS while ensuring that the selected cases are the most representative of and informative for the proposed classification framework.

An analysis of the structure and characteristics of each VGS type can be found in Table 3. These data are crucial for assessing the diversity of green facade solutions employed in urban environments. By examining the characteristics of each system, one can discern the suitability and effectiveness of different approaches to green facade implementation. The classifications are justified based on the features described for each system, such as the method of attachment, the substrate used, irrigation systems, and architectural considerations. Understanding these classifications aids specialists in making informed decisions regarding the selection and design of VGS to address specific needs and challenges in urban environments.

Table 3. Specifications of the vertical greenery systems under analysis, (Resource: Manouchehri. M.).

Name	Location	Year of Establishment	Type of Greenery System	Area	Architect	Characteristics
Hispanoamerica VGS (Figure 3)	Jiloca St., Madrid, Spain	Unknown	Direct green facade	Unknown	-	Ivy climbers attached directly to the building surface
Santander Bank (Figure 4)	Castellana, Madrid, Spain	Unknown	Hanging green facade	Unknown	Fernando Higuera	Ivy hanging from building surface
Ciudad Universitaria VGS (Figure 5)	Francisco de Diego St., Madrid, Spain	Unknown	Indirect green facade	Unknown	-	Hedge plants supported by a wire mesh
Canal Isabel II (Figure 6)	Bravo Murillo, 42, Madrid, Spain	2020	Hollow-soil based	240 m ² divided into 3 parts	Singular Green	Use aluminium profiles dimensioned according to support requirements, special inert substrate of 40 mm thickness, planting of 30 units per square meter
Caixa Forum (Figure 7)	Paseo del Prado 36, Madrid, Spain	2008	Sheet-based living wall system	460 m ² , more than 15,000 plants, 24 m height	Patrick Blanc	Polyurethane sheet is anchored to the wall of building leaving a gap that allows passage through its interior for monitoring, automated irrigation, and fertilisation system
Hotel Santo Domingo (Figure 8)	Calle de San Bernardo 1, Madrid, Spain	2011	Planter-soil based	25 m height, 1026 m ² , more than 110 species of plants	Félix González-Pasquín Agero	Uses modular planter box and soil. The irrigation system utilises the water used by the 50 rooms, and utilises an advanced illumination system during the night
El Escarpin (Figure 9)	Hileras 17, Madrid, Spain	2016	Pocket soil based	9 m ²	Paisaje Sostenido	Uses prefabricated frame; consists of pockets made of lightweight and flexible materials; irrigation system powered by battery

Figures 3–9 present photos of each type of VGS providing a more detailed view of the systems and their components. In Figure 3, a four-storey residential building with a green facade is shown. In this case, a direct green facade is applied, using ivy climbers that directly attach to the building facade to provide a green coating over the building exterior excluding the building openings, adding natural beauty and visual appeal to the building.

This direct green facade provides natural insulation, helping to regulate indoor temperatures by reducing heat gain during the summer. This can lead to energy savings and improved comfort for the building's occupants. The ivy-covered surface acts as a natural air filter, removing pollutants and particulate matter from the air and contributing to a better overall air quality in the neighbourhood while providing habitats and food sources for birds, insects, and other wildlife, supporting urban biodiversity, and contributing to the ecological balance in cities. The foliage can help dampen noise pollution from traffic and other urban sources, creating a quieter and more peaceful environment for building occupants. However, this VGS requires regular maintenance, including watering, pruning, and pest control, which can be labour-intensive and costly.

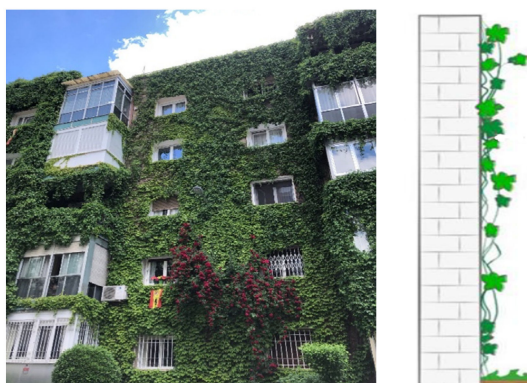


Figure 3. Direct green facade—Hispanoamerica, Madrid, Spain (Resource: Manouchehri. M).

In Figure 4, a hanging green facade can be seen, with vegetation planted in soil on different levels of the Santander Bank building. Some of the plants are hanging from the facade, producing a green effect on the wall surface. The amount of plant coverage is small compared to the building surface, which indicates the aesthetic focus of the designers rather than the environmental concerns.

While the primary focus may be on visual enhancement, the presence of vegetation planted at various levels provides several advantages. Firstly, the greenery contributes to improved air quality by filtering pollutants, creating a healthier environment for both occupants and the surrounding community. Additionally, the plants aid in temperature regulation, reducing the building's energy consumption by providing natural shade and lowering the need for excessive cooling. Moreover, the green facade supports urban biodiversity by offering a habitat for birds, insects, and other wildlife, thereby promoting ecological balance within the urban landscape. Furthermore, the vegetation acts as a natural sound barrier, mitigating noise pollution from nearby traffic or urban activities.



Figure 4. Hanging green facade—Castellana, Madrid, Madrid, Spain (Resource: Manouchehri. M).

Figure 5 shows an indirect green facade applied to the exterior part of a building complex. Hedge plants are used which are supported by a wire mesh to hold the plants at a distance from the wall. This design offers specific benefits that go beyond mere aesthetics. Firstly, the space created between the plants and the building wall serves as an effective insulating layer, contributing to energy efficiency by regulating internal temperatures. This not only reduces energy consumption but also leads to cost savings for building occupants. Moreover, the hedge plants play a crucial role in improving air quality by filtering pollutants and capturing particulate matter, thereby creating a healthier environment for residents and visitors alike. Additionally, the dense foliage provides a habitat for wildlife, promoting biodiversity within the urban landscape. Visually, the greenery softens the appearance of the building complex, adding visual interest and enhancing the overall aesthetic appeal of the surroundings. Furthermore, the hedge plants act as a natural sound barrier, reducing noise pollution from external sources and creating a more tranquil environment within the complex. Offering privacy and screening, they enhance comfort and security for occupants. Finally, through carbon sequestration, the plants contribute to mitigating climate change by absorbing carbon dioxide from the atmosphere.

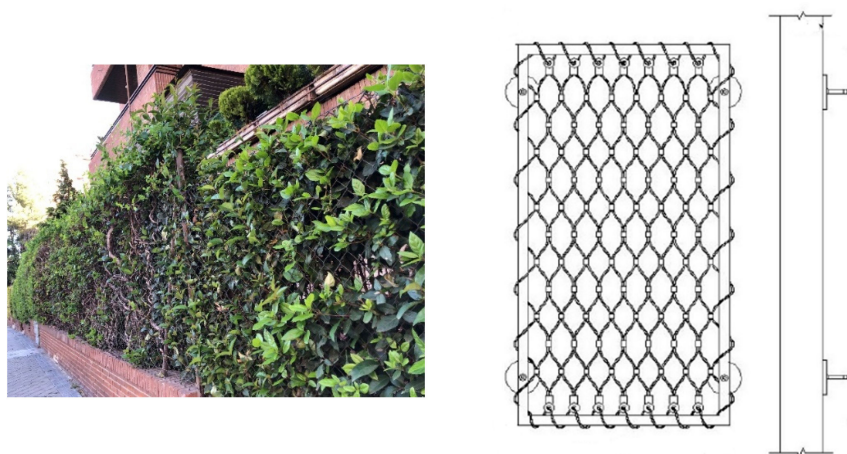


Figure 5. Indirect green facade—Ciudad Universitaria, Madrid, Spain (Resource: Manouchehri. M).

Regarding living wall systems, there has been a fast growth in the number these systems in recent years, and thus several LWS can be found in Madrid. However, to avoid redundancy, only one example of each type was selected for further analysis.

Figure 6 is a hollow-soil-based living wall system with hole-shaped pockets composed of a fibre substrate. The fibre substrate used in the hole-shaped pockets retains moisture for extended periods, reducing the frequency of irrigation needed to sustain the vertical garden. This not only conserves water but also minimizes maintenance requirements, making the system more sustainable and cost-effective in the long run. Additionally, the modular form of the panels simplifies the assembly process, allowing for easy installation and customization to fit the specific needs and dimensions of the site. The incorporation of a remote-controlled irrigation system further enhances efficiency by enabling precise management of watering schedules and nutrient delivery, ensuring optimal growth conditions for the diverse array of plant species selected for the vertical garden. Moreover, by utilizing a variety of plants suitable for the climate of Madrid, the living wall system contributes to local biodiversity and ecosystem resilience, providing habitats and food sources for pollinators and other beneficial wildlife.



Figure 6. Pocket-soil-based living wall system—Canal Isabel II, Spain (Resource: Manouchehri. M).

The famous vertical greenery system of the Caixa Forum designed by Patrick Blanc is an example of a sheet-based green wall (Figure 7). According to the classification proposed in this study, this VGS can be classified as a sheet-based living wall system. A non-biodegradable felt substrate with very small openings on the surface for inserting greenery is used for potting plants.

A polyurethane sheet is anchored to the wall of the building, leaving a gap that allows passage through its interior for monitoring of the irrigation and fertilization system, which is located at different heights. It includes a network of pipes placed in layers with emitters, fed by a pump. Irrigation is vertical and layered, using gravity, wetting the felt layer and being spread by the plants; all of this is automated. Nearly 300 different species were chosen to sustain the façade throughout the demanding hot summers and cold winters of Madrid.



Figure 7. Sheet based living wall system—Caixa Forum, Madrid, Spain. (Resource: Manouchehri. M).

The hanging garden of the Hotel Santo Domingo, with a 1000 m² surface, and more than 260 plant species, is an example of a planter-based living wall system (Figure 8). The planters are positioned at an elevated level, where certain spaces were adapted for the soil and placed towards the edges of the planters in a way that allows the vegetation to overhang, and some of the branches of the the larger plants could drop to the lower levels. An air chamber is then generated between the building wall and the planters, which is used for work and maintenance purposes so that work can be carried out in complete safety and is perfectly accessible at any time. Irrigation was carried out with localized drip irrigation, self-compensating to each planter and with independent phases depending on the location of the plants. To make the best use of the available water resources and

reduce water consumption, the water from 50 hotel rooms (toilets and showers) is collected, filtered, and purified for reuse in the irrigation system.



Figure 8. Planter-soil-based living wall system—Hotel Santo Domingo, Madrid, Spain (Resource: Manouchehri. M).

In Figure 9, a relatively small pocket-soil-based living wall system can be seen. The VGS is used to decorate a bare wall that belongs to a restaurant. A prefabricated frame is installed on the wall surface covered with a felt fabric layer which consists of pockets filled with soil. Pockets are made of lightweight and flexible materials and have space for root insertion and the growth of plants. The irrigation system is powered by a battery that lasts for approximately 2 years.



Figure 9. Pocket-Soil-based living wall system—El Escarpin, Madrid, Spain (Resource: Manouchehri. M).

This study proposes the creation of a central online platform that provides precise naming for VGS and detailed descriptions of their functions and components. This platform allows researchers and manufacturers to contribute to the data synchronisation by adding their results and commenting on the content, making it possible to compare different greenery systems.

Further study on the design and use of this online platform requires the multidisciplinary collaboration of architects, manufacturers, urban planners, landscape designers, and other relevant experts. The form of access to data revision and the details of the application can be developed in future studies.

5. Conclusions

This study introduces a novel framework for the classification of vertical greenery systems (VGS) and addresses the critical need for consistency and clarity in this burgeoning field. By meticulously analysing existing classifications and synthesizing their strengths and limitations, our approach presents a multi-criteria-based classification system for VGS, providing a comprehensive framework that can be adapted to diverse urban contexts.

One of the key contributions of this work is the introduction of hanging green facades as a distinct category, recognizing their unique characteristics and requirements compared to traditional direct and indirect green facades. Moreover, our classification system emphasises the importance of classifying LWS according to their substrate type, resulting in the two sub-categories of sheet-based and soil-based living wall systems, which can affect the technical considerations, implementation requirements, and maintenance protocols for these systems. The proposed multi-criteria approach enables decision-makers, architects, and urban planners to make informed choices aligned with contemporary sustainability objectives, considering environmental impact, cost effectiveness, and maintenance efficiency.

Furthermore, our study identifies eight crucial parameters that are essential for optimizing VGS design decisions, which range from facade design aspects to plant parameters and cost information. Understanding these influential factors enables the development of innovative, site-specific designs that can be tailored to meet the evolving needs of urban environments, which in turn ensures that VGS installations are not only effective but also sustainable, resilient, and capable of bringing multifaceted benefits.

The field of vertical greenery systems continues to evolve and is fuelled by advancements in technology and design approaches. So, ongoing research and collaboration among experts are imperative. This collaborative effort will facilitate the continuous refinement and updating of our classification framework, ensuring its relevance and applicability to a constantly changing urban landscape.

An online platform for the precise naming and description of VGS is proposed to facilitate collaboration among researchers and manufacturers. The aim is to ensure easy access to the latest information concerning critical factors pertinent to decision making and the design of VGS. However, further research is necessary to enable multidisciplinary development and application. By embracing innovation and cooperation, we can harness the full potential of vertical greenery systems to create healthier, more sustainable cities for generations to come.

Author Contributions: Conceptualization, M.M.; investigation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, J.S.L. and M.V.L.; supervision, J.S.L. and M.V.L.; funding acquisition, J.S.L. and M.V.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CGW	Climber Green Wall
GBS	Green Barrier System
GCB	Green Climbing Barrier
GCC	Green Climbing Coating
GCS	Green Coating System
GF	Green Facade
GMC	Green Modular Coating
GTB	Green Tree Barrier
HGW	Herb-shrub Green Wall
LS	Light System
LW	Living Wall
LWS	Living Wall System
MV	Mur Vegetal
VGS	Vertical Greenery System
WoS	Web of Science

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