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Review

Toward Adaptable and Industrialized Vertical Greenery Systems: A Critical Review and Future Developments

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Abstract

Among nature-based solutions, Vertical Greenery Systems (VGS) are widely recognized as effective solutions for improving the environmental performance of buildings and urban areas. Although their benefits have been extensively studied and demonstrated, their large-scale implementation remains limited. This paper explores the hypothesis that the main barriers to the widespread adoption of VGS—and especially Green Facades (GF)—are not related to their environmental performance but rather to their lack of industrialization and to purely technological and construction-related aspects concerning support and anchoring systems. Following an in-depth review of the scientific literature published since 2006, the study found that most publications focus primarily on the environmental performance of green roofs, while the structural and technological aspects, as well as the potential for adaptation to existing buildings, remain largely unexplored areas. This is also reflected in construction practice, highlighting how most existing solutions are based on specific, case-by-case design approaches, limiting replicability and large-scale implementation, especially in existing buildings. The paper identifies the concept of construction adaptability as a potential direction for innovative research aimed at developing industrialized systems that are replicable and adaptable even to existing buildings, thereby promoting the large-scale use of GF.

Keywords: vertical greenery system; green façade; construction adaptability; modular design; building retrofit

1. Introduction

Rapid population growth has played a key role in the rise in urbanization, leading to an increasing concentration of the population in urban areas and a gradual increase in building density. Cities are home to more than half of the world's population, a figure expected to rise to 70% by 2050 [1], placing pressure on natural resources, the urban environment, and quality of life.

The continued expansion of impervious surfaces and the reduction in available green spaces have significantly contributed to the intensification of phenomena associated with urbanization, with negative effects on environmental quality, urban comfort, and the health of residents [2]. In this context, the integration of vegetation into the built environment has been increasingly recognized as an effective strategy for mitigating the urban heat island effect, improving the sustainability of cities, and promoting healthier and more resilient urban environments [3].

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The integration of green systems into buildings can occur on both roofs and façades. Although green roofs have been extensively studied and recognized for their positive effects on the energy and environmental performance of buildings, vegetated vertical surfaces offer particularly interesting application potential, especially in high-density urban contexts where horizontal space is limited.

The use of vegetation in buildings is not a recent development. Since ancient times, various civilizations have experimented with ways to integrate architecture and nature to improve environmental comfort and enhance the aesthetic appeal of built spaces. The Hanging Gardens of Babylon are one of the most famous historical examples of the use of vegetation in building structures, while during the Roman era it was common practice to place trees and plants on terraces, courtyards, and rooftops to provide shade and mitigate the effects of high summer temperatures. However, it was not until the 20th century that these practices began to evolve into technologically advanced systems designed according to scientific criteria.

A major turning point was the patent for the "Vegetation-Bearing Architectonic Structure and System," developed by Stanley Hart White in 1938 and considered the first modern vertical greenery system [4]. Subsequently, research and technological innovation fostered the evolution of increasingly sophisticated solutions, culminating in the 1980s with the development of the "Mur Vegetal" by French botanist Patrick Blanc. This system introduced an innovative approach based on growing plants on vertical surfaces using artificial supports and integrated irrigation systems, paving the way for the contemporary proliferation of green walls and vegetated facades.

Since the 2000s, interest in Vertical Greenery Systems (VGS) has grown significantly, both in the world of research and in professional practice. The ability to use the vertical surfaces of buildings as a support for vegetation has made it possible to overcome one of the main limitations of high-density urban areas: the scarcity of space available for new green infrastructure. In this context, VGS represent a particularly effective solution since they allow for an increase in vegetation without taking up additional space from the established urban fabric [5].

1.1. Features and Performance of VGS

VGS encompasses a diverse range of design solutions that differ in construction characteristics, vegetation growth patterns, irrigation systems, and maintenance requirements. Among the most common types, based on the growth pattern of the vegetation layer and the support system, two categories stand out: Green Facades (GF) and Living Walls (LW).

GF are established using climbing or trailing plants. The plants can grow directly on the building's surface (direct greenery system) or use support elements such as metal grids, nets, modular trellises, cables, or ropes (indirect greenery system).

LW are constructed using prefabricated modular panels—often pre-planted—that are attached directly to the building's masonry or to a vertical support structure. These panels contain the substrate and the technological systems necessary for supporting and fostering the growth of plant species [6].

Table 1 lists the main distinguishing characteristics of GF and LW.

In recent years, new configurations have also emerged, including advanced modular systems, integrated bio façades, and multifunctional solutions capable of combining environmental, energy, and architectural performance, which are described in detail in the following paragraphs.

Table 1. Classification of VGS.

VGS Type	Vegetation Support	Vegetation		Crop Type	Modularity	Industrialization
		Development	Placement			
GF direct system	None	Climbing on the exterior surface of the building	Ground-based	Traditional	No	No
GF indirect system	Grids, nets, trellises, cables, or ropes	Climbing or falling on support elements	On the ground or in containers	Traditional	Almost always	Only for support elements
LW	Frame or cell-based substructure	Primarily on textile substrates	Contained in prefabricated panels, often pre-vegetated	Hydroponics	Yes	Yes

The growing popularity of VGS is closely linked to the many benefits these systems can provide. Scientific literature has extensively documented the role of vegetation as a passive tool for controlling the microclimatic conditions of buildings. Various studies have shown that shading provided by vegetation can reduce the direct exposure of building surfaces to solar radiation, limiting overheating of the building envelope and helping to reduce energy consumption associated with cooling interior spaces [5,7–10], as well as contributing to the mitigation of the urban heat island effect [11,12]. In addition to energy-related benefits, the presence of vegetation in buildings has been linked to improvements in users' health and psychophysical well-being [13,14], the removal of air pollutants [15–17], and improved air quality [18], as well as the conservation of urban biodiversity and the creation of favorable habitats for local flora and fauna [19]. Furthermore, in many urban contexts, green facades are considered tools for urban regeneration, capable of enhancing the appearance of buildings and increasing their economic value [20].

Finally, green facades are generally closer to users and public spaces, contributing significantly to improving the microclimate as perceived at pedestrian level [21].

1.2. Manufacturing Processes and Their Limitations

Despite the large amount of literature demonstrating the environmental benefits of VGS, their widespread adoption remains limited compared to their potential. This suggests that the current barriers are no longer primarily related to environmental performance, but rather to technological integration, constructability, and industrialization.

The main challenges include high initial installation costs, the need for specialized maintenance, water management, the durability of components, and uncertainty regarding long-term performance. Further obstacles stem from the lack of widespread technical knowledge among designers, construction companies, and public administrations, as well as the absence of standardized tools for evaluating the most appropriate solution among the various available options.

One of the most debated aspects in the literature concerns the classification of VGS. Unlike other green infrastructures, such as green roofs, for which there are well-established and widely accepted classification criteria, VGS are described using a variety of terms and definitions that vary depending on the geographical, disciplinary, and commercial context. Terms such as "green facade," "living wall," "vegetated wall," "vertical garden," "green wall," and "bio façade" are frequently used interchangeably, even though they often refer to systems characterized by different construction principles and performances. This

terminological heterogeneity makes it difficult to compare scientific studies and limits the transferability of results to design practice [22].

Although numerous literature reviews on vertical green systems have been published in recent years, most studies focus on specific aspects, such as thermal performance, energy efficiency, plant species selection, water management, or environmental impacts. Less common, however, are analyses that take an integrated approach to the evolution of VGS, the different construction types, and, above all, the technological aspects related to support structures and methods of integration with the building envelope. This fragmentation highlights the need for a critical synthesis of the available knowledge that, in addition to comparing the various configurations of vertical greenery systems, would help identify the main gaps still present in the research.

In particular, a preliminary analysis of the literature reveals that the design of support substructures and anchoring systems is still predominantly based on solutions developed ad hoc for the specific characteristics of individual buildings. While this approach allows for a high degree of customization, it limits the standardization of systems and reduces their replicability, representing one of the main obstacles to the widespread adoption of GF as an intervention strategy for existing buildings.

1.3. Structure of the Study and Research Questions

Based on these considerations, this study proposes a shift in perspective regarding the analysis of VGS in general and GF in particular.

Through a critical review of the scientific literature in the field and a comparative analysis of recently developed commercial systems and research prototypes, this paper aims to identify the barriers to the widespread adoption of GF, shifting the focus beyond performance-related aspects to encompass construction and implementation processes, thereby addressing a potential gap in the literature. More specific criteria, including transferability, reusability, and adaptability to different buildings, are introduced to assess how explicitly constructability and adaptability have been addressed in previous studies. Furthermore, the development of modular and industrializable systems for building renovation is examined.

Specifically, the study addresses the following research questions:

RQ1. What are the main barriers limiting the widespread adoption of GF, despite their well-documented benefits?

RQ2. How many studies have examined the implementation aspects of VGS, rather than focusing exclusively on their performance?

RQ3. To what extent are the vegetation support systems used in VGS designed to be transferable, reusable, and adaptable to different buildings and construction contexts?

RQ4. Have any studies addressed the issue of constructability and adaptability with a view to promoting the wider adoption of VGS?

RQ5. How can scientific research on constructability and adaptability contribute to the development of modular, industrialised systems that are more compatible with the requirements of retrofitting the existing building stock?

2. Methods

For this study, a comprehensive review of the literature on VGS was conducted, with the aim of critically examining the available evidence, evaluating its methodological and technological contributions, and synthesizing the results in order to provide an up-to-date overview of the state of the art.

The literature search was conducted by consulting major scientific databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar. Search strategies were developed

using combinations of keywords and Boolean operators (AND, OR) to maximize the sensitivity and specificity of the search. To ensure the broadest possible coverage of the relevant literature, synonyms and terminological variants referring to the same concepts were included.

The data collection for systematic classification covered publications from January 2006 to February 2026. The choice of this time frame does not imply that 2006 marks the beginning of studies on VGS, nor does it exclude the relevance of earlier contributions. On the contrary, the definition of the theoretical and epistemological framework also took into account earlier literature, including studies dating back to the 1970s as well as the first documented research and application efforts in Berlin during the 1980s [23–26]. These contributions were considered part of the historical and scientific background necessary to understand the evolution of the systems and their related design and construction approaches. The time frame adopted for the classification was therefore defined to focus the analysis on the most recent developments, while limiting the scope of the bibliographic corpus and enabling a systematic and comparable examination of the contributions. In accordance with the specific objective of the study, attention is therefore directed toward contributions that document the evolution of technical solutions and design and construction processes, including in relation to the prospects for standardization, industrialization, and the development of contemporary building systems. Studies published before 2006 were used to provide context for the historical and conceptual evolution of the field, but were not included in the corpus subjected to systematic classification.

In the first screening phase, the following keywords were used: "Vertical Greenery System," "Living walls," and "Green façades." This initial search identified a total of 4329 records.

The second phase involved applying additional combinations of keywords related to the performance and technological aspects of VGS, including terms such as "Vertical green structures"; "Market classification"; "Green infrastructures"; "Life Cycle Assessment"; "Energy performance"; "Thermal performance"; "Urban heat island"; "Biodiversity"; "Air quality"; "Sustainability"; "Building envelope"; and "Climate adaptation," reducing the number of results to 626 articles.

Subsequently, in the third phase, duplicate records were removed, and articles not written in English, non-peer-reviewed contributions, and opinion pieces were excluded. At the end of this process, 531 articles were selected.

The fourth phase involved screening the article titles to verify their relevance to the objectives of this review. Studies that did not address VGS at the building scale or those dealing exclusively with other types of green infrastructure, such as green roofs, urban parks, landscaping projects, or vegetation systems not integrated with the building envelope, were excluded. This phase resulted in the exclusion of 185 articles, leaving 346 potentially relevant articles.

In the fifth phase, an in-depth evaluation was conducted of the abstracts and full texts of the 346 selected articles. Only studies concerning VGS intended to improve the technology of building envelopes were included, with particular reference to original and distinct classifications of the systems, design and construction characteristics, the development of new prototypes and advanced technological solutions, the improvement of indoor comfort, economic and maintenance aspects, and methods for applying VGS to buildings and the urban context.

The following studies were excluded:

(i) Articles that reiterated established classification systems or adopted previously proposed taxonomies without introducing novel analytical criteria or methodological contributions;

(ii) Studies focusing exclusively on indoor greenery systems, vertical farming, vertical greenhouses, or agricultural applications not integrated into the building envelope;
(iii) Works addressing solely agronomic or botanical aspects without examining the performance of these systems or their integration into the building envelope.

At the end of the selection process, 125 articles were included, as listed in the Appendix A (Table A1). The process of identifying, screening, assessing eligibility, and including studies was summarized in a flowchart (Figure 1).

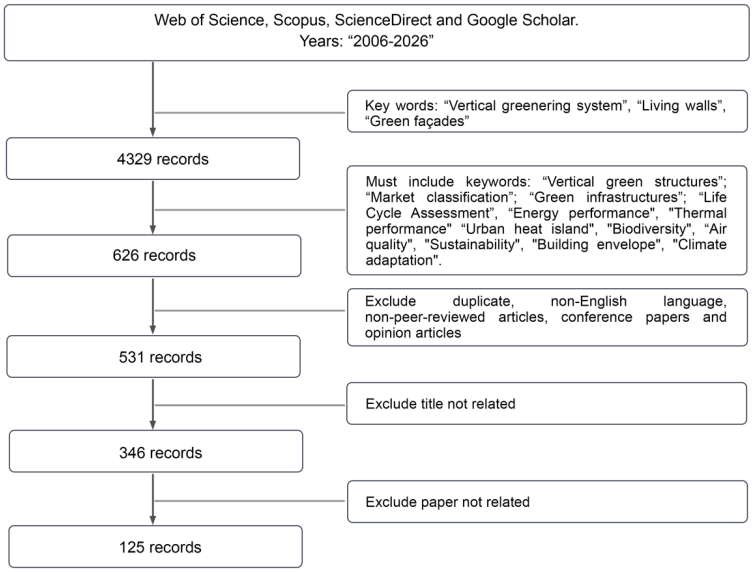


Figure 1. Article selection process for the review.

The selected articles were subjected to thematic analysis and categorized according to the predominant broad areas of investigation (Table 2), including system type, technological configuration, environmental benefits, maintenance aspects, and classification criteria. Since several publications take a multidisciplinary approach by addressing multiple topics simultaneously, individual studies have been assigned to more than one category. The results were subsequently synthesized and discussed to identify emerging trends, knowledge gaps, and prospects for the sector's development, providing useful insights for answering the research questions formulated earlier.

Table 2. Number of papers for each topic.

Topic	Number of Papers	Number of Papers by System Type		
		VGS (GF + LW)	GF	LW
Thermal Benefits	89	39	29	21
Classification Criteria	23	22	0	1
Technological Configuration	35	18	3	14
Vegetation	37	15	10	12
Maintenance	30	23	2	5
LCA	8	4	0	4
Environmental Benefits	34	18	4	12
Modularity and Industrialization	7	3	1	3
Support and Fastening Systems	12	5	3	4

The distribution of articles across various topics reveals limited attention to the construction and industrialization aspects of VGS. In particular, only a very small number of papers address topics related to the study of support substructures, fastening and anchoring devices, modularity, and the industrial production of system components. It should therefore be noted that, to date, research has focused primarily on performance, neglecting the issue of the industrialization of the final product.

To address the research questions listed above, the objective of this paper is to identify the main obstacles to the large-scale adoption of GF, despite the widely recognized benefits associated with their use. The study is based on an analysis of the scientific literature in the field to determine how many studies focus on the construction aspects of green roof systems in general and green roofs in particular, compared to those that evaluate only their performance. Furthermore, again based on the literature review, the study aims to determine to what extent vegetation support systems are designed to be adaptable to different buildings and construction contexts, and how many studies have addressed the issue of construction adaptability.

3. Critical Analysis of VGS

An analysis of the state-of-the-art highlights how the evolution of VGS has been characterized by differing development dynamics depending on the type of system. Although GF and LW are generally grouped together in scientific literature as the two main categories of VGS, they exhibit different technological development dynamics that have distinctly shaped both the evolution of commercial solutions and research activities.

This distinction is a key prerequisite for understanding the current challenges facing the sector. A comparative analysis of the two types allows us to examine not only the differences in technological configurations and performance but also the varying degrees of development of construction solutions and design strategies aimed at their application. In particular, for GF systems, it is essential to assess whether and to what extent technological evolution has facilitated the development of support systems adaptable to different building conditions and whether these aspects have been adequately investigated in scientific literature.

From this perspective, the critical analysis aims to correlate the evolution of the systems, the level of detail in their respective construction solutions, and their potential for large-scale application, highlighting unresolved issues and knowledge gaps that may limit the transition from experimental solutions—or those specifically designed for individual contexts—to systems that are more replicable and adaptable.

In the case of LW, the increased technological complexity of the system favored an integrated design approach. In fact, the construction of a LW requires the coordinated design of the supporting structure, the vegetated modules, the growing medium, the irrigation and drainage systems, and the selection of plant species. These components constitute a single technological system, designed and developed as a unified whole, in which overall performance depends on the mutual integration of all elements. This complexity has led to the emergence of numerous design variations and a much broader commercial offering. Consequently, scientific research and commercial production have followed a largely convergent evolutionary path, focused on the development of complete, high-performance systems.

A different situation characterizes GF, however. In this case, the system can be broken down into relatively independent subsystems -vegetation, plant support elements, load-bearing substructure, anchoring devices, and fastening components- which can be developed, produced, and selected separately. While this configuration ensures greater flexibility in application, it also leads to fragmentation in both commercial production and scientific research.

The manufacturing sector offers a growing number of commercial systems and components but does not provide methodological tools to guide their use and integration into the building envelope.

Research proposes experimental systems that are increasingly advanced in terms of technology and performance; however, these are primarily developed for specific applications and rarely consider the building configurations already on the market or how these can be adapted to different buildings. This misalignment represents an obstacle to the widespread adoption of GF as a systematic solution for the retrofitting of existing buildings.

Since GF are a technologically simpler, more economical solution with lower maintenance requirements, further exploring their performance and application potential represents a possible research direction toward more accessible and sustainable greenery solutions.

In light of these considerations, this section critically analyzes the two main lines of development that have emerged from the literature: on the one hand, the GF systems currently available on the market; on the other, the most recent developments in scientific research, with the aim of highlighting their strengths, limitations, and potential areas of convergence.

3.1. GF on the Market

Although the market currently offers a wide variety of products, studies systematically examine support substructures, fastening systems, anchoring devices, component modularity, and methods of adaptation to different building contexts are rare.

One of the few studies addressing this topic is the work by Ogut et al. (2022) [27], which presents a systematic review of the VGS market with the goal of developing a taxonomy of available products and identifying their main evolutionary trends. The authors highlight how the rapid expansion of the market necessitates comparative analyses capable of evaluating not only the technological characteristics of the systems but also economic, maintenance, and environmental aspects, in order to support designers and operators in selecting the most appropriate solutions.

The study is based on an analysis of 142 products marketed by 58 international manufacturers and shows that the market is currently heavily skewed toward LW, which accounts for approximately 83% of the systems surveyed, compared to 17% for GF.

The taxonomy proposed by the authors classifies VGS according to their main components—support structure, vegetation, substrate, drainage, and irrigation—highlighting that, in the case of green façades (GF), the configuration of the load-bearing substructure is the defining element of the entire system. Specifically, the choice of constituent material—coated stainless steel, galvanized steel, aluminum, or plastic—determines the system's weight, profile thickness, durability, and cost, thereby influencing both the aesthetic and functional properties of GF [28].

An analysis of commercial products shows that indirect GF can be broadly categorized into two main construction configurations: systems based on modular trusses and systems consisting of tensioned cables or ropes. The former involves lightweight lattice structures, generally made of aluminum or steel, combined with modular nets or panels designed to support the vegetation. The latter, on the other hand, use systems of metal cables, wires, or nets anchored to the building' r façade using specific fastening and spacing devices. Although these configurations have different geometric and material characteristics, they share the same construction principle, based on the use of a substructure anchored to the building that supports the vegetation and transfers loads to the building envelope.

The examples analyzed by Ogut et al. are divided into:

1. Modular trellis systems, such as Gsky Basic Wall, are characterized using fiberglass containers to which a standard-sized mesh is attached. The planters can be mounted on the structure or on a built-out sub-structure using light brackets.
2. Cable/rope systems, which include:
    - Two-dimensional solutions consisting of vertical cables, horizontal cables, rods, and grids, and three-dimensional solutions consisting of panels with fixed length, width, and depth, known as the Greenscreen trellis system produced by Greenscreen;
    - Products such as Green Trellis and Webnet by Jakob Rope Systems, which use stainless steel cables suitable for use on building facades up to 150 m high and applicable both on the exterior and interior of buildings.

In addition to systems developed specifically for GF, design practice frequently relies on components derived from other industries and subsequently adapted to the needs of vertical greening.

Among the most widely used solutions are:

- The GRIPPLE® system, which uses polymer strands tensioned by self-adjusting clamps originally developed for agricultural applications and subsequently adapted to support vegetation on building facades;
- Seilsysteme systems employ orthogonal grids of stainless-steel cables secured using tensioning devices and metal spacers;
- The TENAX® system consists of prefabricated plastic grids anchored to the facade using anchors and brackets.

Despite differences in technology and materials, these solutions share similar construction principles, based on the use of simple, lightweight, and easily assembled components.

A comprehensive analysis of the systems currently on the market leads to a particularly interesting observation. The variety of available solutions might suggest a high level of standardization in GF systems; however, a more in-depth analysis reveals a different reality. In fact, it is not the standardization of components that represents the main challenge, but rather that of the system as a whole. Cables, nets, grids, tensioning devices, brackets, and anchoring systems are now widely industrialized components available in numerous technological configurations. What continues to require specific design, however, is their integration into a structural configuration consistent with the geometric, dimensional, and technological characteristics of the individual building. Design therefore retains a significant element of artisanal customization that limits the replicability of solutions and represents one of the main factors hindering the wider adoption of GF in the redevelopment of existing building stock.

3.2. Evolution of Research

In parallel with the development of the commercial systems market, scientific research has followed a different evolutionary path, focusing primarily on improving the environmental performance associated with the integration of vegetation into buildings, with particular attention to the effects on the urban microclimate, the thermal performance of the building envelope, air quality, and occupant comfort. As knowledge regarding these benefits has gradually solidified, scientific attention has progressively shifted toward the development of more technologically advanced solutions capable of integrating functions beyond the simple greening of surfaces.

This evolution has led to the emergence of increasingly complex systems, characterized by the use of new materials, prefabricated components, control devices, and integrated management strategies [29]. In Nanjing, China, a new method was proposed to assess

the direct cooling benefits of green facades based on infrared thermal data and three-dimensional point clouds [30]. Another study presented a prototype of a solar-powered fertigation system designed to automate the recirculation of drainage water within the system using recycled materials [31]. As part of another research project, a modular LW system was designed that utilizes recycled materials known as Geogreen—derived from mining waste (geopolymers)—and locally available materials, such as expanded cork panels, along with climate-appropriate plants [32].

However, a review of the literature shows that this development has primarily occurred through the evolution of systems designed on a case-by-case basis for individual buildings, rather than through a review of the technological solutions available on the market and their adaptation to different building contexts [29]. Most of the prototypes identified fall into the LW category.

The modular cork panel system developed by Cortês et al. (2021) is a significant example of this trend, as it proposes a rethinking of the construction process through the introduction of materials with reduced environmental impact and the optimization of the system's life cycle [33]. The authors described the design process of a new modular LW system made of insulation cork boards (ICBs) (Figure 2). This process was carried out by considering the main environmental critical issues identified in a comparative life cycle assessment (LCA) conducted for the production phase of five different modular wall systems. To reduce these impacts, the new system replaces commonly used plastic components with ICB modules, a natural material derived from cork byproducts, characterized by good water retention and drainage capabilities. Additionally, ICB modular blocks were developed so that they could be fastened directly to the bearing wall by means of a waterproofing adhesive mortar, replacing the most used metal fasteners while also ensuring a continuous layer with thermal and acoustic insulation properties, as well as a protective function.

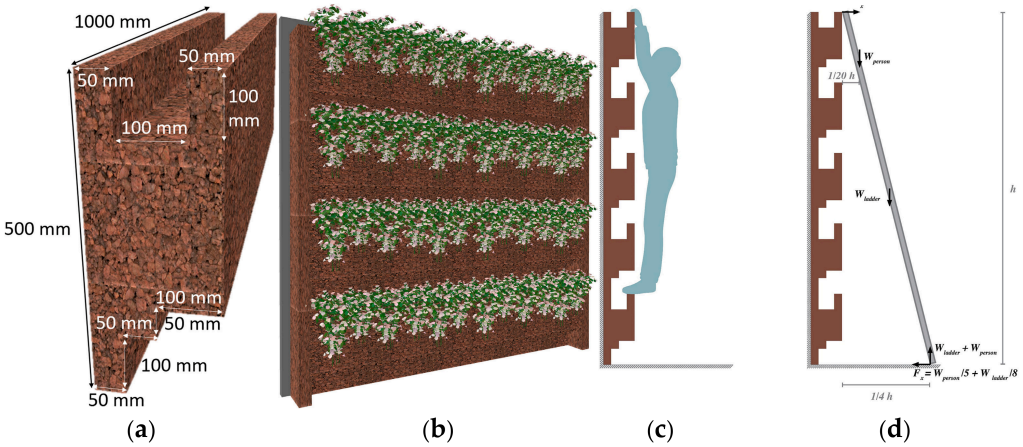


Figure 2. (**a**) Schematic representation of the new ICB module for LW. (**b**) Illustration of a modular LW built with the new ICB modules. (**c**) Illustration of a person climbing the LW, simulating the loads generated by doing so. (**d**) Illustration of a ladder propped against the LW, representing a maintenance operation [33].

The prevalence of studies on LW in the literature can be attributed to their technological configuration itself; as previously noted, they require the development of vegetated modules, artificial substrates, irrigation systems, and dedicated structural components. GF, on the other hand, are generally based on simpler and relatively well-established construction principles, such as mesh, cables, and metal support structures, and for this reason have been less frequently the subject of technological experimentation. This situation appears paradoxical when one considers that GF are precisely the most widespread systems and potentially the most suitable for extensive applications in the existing building stock.

Among the most recent developments in the field of GF, the Adaptive Photovoltaic Green Facade (APVGF), proposed by Li et al. (2025), represents a significant contribution [34].

The system consists of an innovative multifunctional vegetated envelope that combines an adjustable photovoltaic awning system with a green facade. The goal of the proposal is to combine the environmental benefits associated with vertical greenery with renewable energy production, through movable photovoltaic components capable of adapting their orientation to operating conditions. As shown in Figure 3, plants grow between the photovoltaic shades and the exterior wall, providing dual solar shading to prevent excessive solar radiation from entering the interior and to reduce heat buildup in the rooms during the cooling season. Furthermore, plant transpiration cools both the photovoltaic shades and the adjacent wall. The layer of vegetation gives the building a pleasant and aesthetically pleasing landscape effect, while the plants' leaves provide favorable diffused light and a beautiful view for the interior spaces. The photovoltaic awnings not only allow climbing plants to grow but also effectively protect both the building and the plants from extreme temperatures, cold winds, hail, and other adverse weather conditions. Furthermore, the self-adjusting photovoltaic shades can adjust their angle based on the angle of incidence of solar radiation, maximizing the use of solar energy while always maintaining a perpendicular position relative to the incident radiation beam. This system is also capable of flexibly adjusting the angle to meet the needs of natural lighting and views.

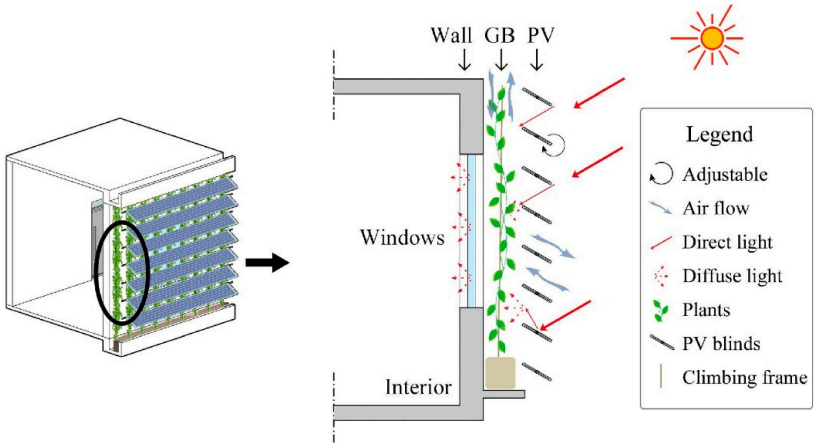


Figure 3. Structure and solar energy utilization of the APVGF [34].

The examples provided summarize a recurring trend that emerged in numerous studies analyzed as part of this research. Despite the technological and construction differences that characterize the identified prototypes, the vertical greenery systems examined share the same design approach: they are generally developed for specific building configurations, often involving new construction or unique application cases. In this context, the issue of standardizing construction solutions and adapting substructures to the different characteristics of buildings -geometric, dimensional, morphological, and technological- remains largely marginal. Consequently, the recently developed prototypes can be interpreted as examples of performance-based innovation rather than examples of construction-based innovation: they improve the system's performance but do not substantially alter the design paradigm, which continues to be based on defining specific solutions for individual application contexts.

The "artisanal" approach adopted thus far for the design of facade greening projects represents a critical issue that appears particularly relevant in the case of retrofitting projects for existing buildings, as the structural configurations of GF systems are defined based on the specific characteristics of the building, through design processes that involve adapting

grids, cables, or frames to the geometric conditions of the facade. Although this approach allows for an effective response to the needs of each individual project, maintaining a significant artisanal component in the design process limits the replicability of the solutions, hindering the large-scale adoption of GF.

It is noteworthy that this tendency to develop tailor-made solutions for individual projects is also evident in high-profile projects and design significance, such as those carried out by architect Stefano Boeri on the ALER public housing units in Monza or in a public housing neighborhood in Prato [35]. In the first case, a climbing greenery system was integrated into the building facades, supported by metal cables anchored to the ground, with vegetation planted directly in the areas adjacent to the building to promote growth and reduce maintenance. In the second case, the redevelopment of an office building and a public housing complex involves introducing trees and plants onto the facades and roofs of the existing buildings, selecting native plant species with a high capacity for CO_2 sequestration and absorption of atmospheric pollutants [36]. Although implemented on existing buildings, these projects are highly context-specific and developed on a case-by-case basis, rather than as systems that are easily transferable and adaptable to other similar situations. In view of these considerations, there is a need to direct research toward the concept of structural adaptability. This can be defined as a system's ability to adapt to different structural, volumetric, and morphological characteristics of buildings through the reconfiguration of standardized components, without requiring a complete redesign of the substructures.

The concept of design adaptability presupposes the simultaneous presence of specific requirements such as:

- System modularity;
- Standardized components;
- Dimensional flexibility;
- Configurable joints;
- Dry assembly;
- Retrofit compatibility.

Among the few studies that explicitly address the issue of structural adaptability is the "Vertical Greening Frame for Existing Buildings" (VGF4EB). This is a modular, versatile VGS support system adaptable to existing buildings, developed by the authors as part of research on the integration of vertical greenery into the building envelope [37].

It was designed to facilitate the application of green facades to existing buildings and consists of a modular, configurable construction system—classified as an indirect continuous-cable system—made of tubular steel profiles assembled using dry-assembly threaded joints (Figure 4). The innovative aspect of the project does not lie in technological innovation, but rather in the construction logic adopted, which is based on the combination of a limited number of standardized components capable of generating different configurations through flexible assembly processes.

By combining the various components, it is possible to cover surfaces of various sizes, vary the distance of the green wall from the existing facade, and adapt the vegetated screen to the presence of balconies or overhangs. This approach moves beyond the traditional logic of ad hoc design for individual buildings and introduces a development method more consistent with the principles of industrialization.

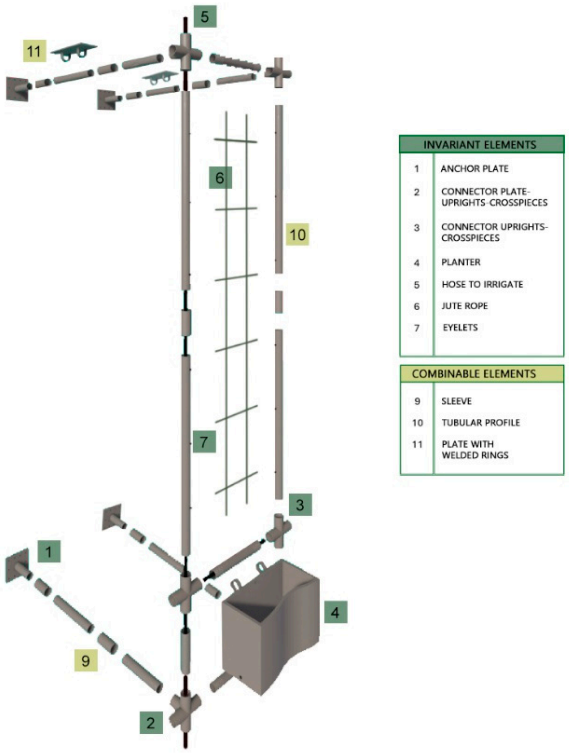


Figure 4. VGF4EB elementary module. All system components are shown divided into invariant and combinable elements [37].

The design of building systems based on the concept of construction adaptability does not necessarily entail the standardization of the final result.

Traditionally, standardization has been associated with the repetition of identical solutions, while customization required the design of specific components.

Building systems designed according to the concept of construction adaptability could effectively help demonstrate that design flexibility—and thus also the uniqueness of the final product—can be achieved through different combinations of standardized components.

From this perspective, adaptability is not an alternative to industrialization, but rather one of its key prerequisites.

The ability to generate different configurations from a limited number of prefabricated elements makes it possible to combine:

- Industrial production;
- Application flexibility;
- Design simplification;
- Cost reduction;
- Greater replicability of solutions.

The concept of construction adaptability should therefore not be interpreted exclusively as a technical characteristic of the system, but as a design principle capable of overcoming the misconception that standardization and originality must necessarily be mutually exclusive. Research and development of industrialized construction systems characterized by high versatility and adaptability could represent a valuable contribution to promoting the widespread adoption and replicability of GF, even in existing buildings.

4. Conclusions

The analysis of the literature and case studies examined in this review highlights how the growing adoption of VGS has been accompanied by significant advances in the assess-

ment of the environmental, energy, and functional performance of these systems. However, there also appears to be limited attention paid to the technological and construction aspects aimed at integrating GF into the building envelope, particularly with regard to support substructures and strategies for adapting to different application contexts. Design practice has focused primarily on refining individual systems and defining specific, case-by-case solutions. This approach constitutes a limitation that hinders the large-scale adoption of these solutions, especially at a time when the energy and environmental retrofitting of the existing building stock is one of the main tools for ecological transition and adaptation to climate change.

This paper proposes a conceptual shift from performance-oriented research to feasibility-oriented research.

In this context, construction adaptability emerges as one of the keys, yet still largely unexplored, areas of development for the future evolution of GF. The ability to design systems based on industrialized, modular, and reconfigurable components would make, in fact, possible to overcome the traditional dichotomy between production standardization and design customization, thereby promoting greater applicability of these solutions to retrofit processes, the renovation of existing buildings, and environmental mitigation. From this perspective, adaptability is not merely a technical characteristic of the system, but a design principle capable of supporting its replicability, flexibility of application, and potential for industrialization.

Future research should therefore focus on the development of support systems and anchoring devices characterized by high versatility and design flexibility, capable of accommodating the volumetric, morphological, and structural variability that characterizes the existing building stock. At the same time, it seems appropriate to expand the investigation to include the materials used in the construction of support structures, promoting the adoption of solutions with a reduced environmental footprint.

In this context, particular attention could be given to the use of natural, recyclable, and environmentally friendly materials, both for elements designed to support vegetation and for load-bearing substructures. Possible future research directions include the use of natural fibers, such as jute, as a substitute for traditional metal or plastic cables or trellises to support vegetation, as well as the use of materials such as wood, bamboo, or recyclable bioplastics for the load-bearing substructure. It represents possible avenues for development aimed at increasing the environmental sustainability of GF without compromising their technical and structural performance.

The integration of construction adaptability, modularity, and material sustainability therefore appears to be a particularly promising prospect for the future evolution of GF, contributing to the development of systems that are more compatible with the needs of building stock revitalization and with sustainable development goals in the construction sector.

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

Abbreviations

The following abbreviations are used in this manuscript:

VGS	Vertical Greenery Systems
GF	Green Facades
LW	Living Walls
LCA	Life Cycle Assessment
ICB	Insulation Cork Boards
APVGF	Adaptive Photovoltaic Green Facade
VGF4EB	Vertical Greening Frame for Existing Buildings

Appendix A

Table A1. List of articles included at the end of the selection process, arranged in chronological order. For each article, the following information is provided: Title, Authors, Yars, DOI, Keywords, Subject of the Study, Output of the Study, Analysis Type—Theoretical and/or Software simulation, Experimental assessment in real-world conditions, Design/conceptualization/creation of Vertical Greenery System (VGS)—Results, System Type—Vertical Greenery System (VGS), Green Façade (GF), Living Wall (LW), Topics—Thermal benefits, Classification criteria, Technological configuration, Vegetation, Maintenance aspects, Life Cycle Assessment (LCA), Environmental benefits, Modularity and industrialization of the greening system, Support and Anchoring systems for the greening system.

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type			Topics								
								Theo-reti-cal/Soft-ware Simu-la-tion	Exp. in Real-World Con-di-tions	De-sign/Con-ceptual-iza-tion/Cre-ation of VGS		VGS	GF	LW	Ther-mal Bene-fits	Clas-sifica-tion	Tech. Con-figu-ra-tion	Vege-ta-tion	Main-te-nance	LCA	Env. Bene-fits	Mod-ular-ity & Ind.	Sup-port/An-choring
1	Green facades—a view back and some visions	Manfred Köhler	2008	https://doi.org/10.1007/s11252-008-0063-x	Living walls; Green facades; Extensive roofs; Nature in cities; Environmental benefits	Historical and technical review of green façades, focusing on German research, climbing vegetation, ecological benefits, maintenance and urban implementation, including long-term projects in Berlin, Germany.	A synthesis of historical research, ecological and thermal findings, species growth observations, maintenance challenges and recommendations for wider adoption of green façades.	X			German studies documented façade temperature buffering of approximately 3 °C under specific winter conditions, particulate capture and biodiversity benefits. Plant suitability, maintenance and support requirements influence successful long-term implementation.		X		X		X	X	X		X		X
2	Tempera-ture decreases in an urban canyon due to green walls and green roofs in diverse climates	Eleftheria Alexandri, Phil Jones	2008	https://doi.org/10.1016/j.buildenv.2006.10.055	Green roofs; Green walls; Urban canyon; Plants; Built environment	Numerical investigation of vegetation effects on urban canyon temperatures, outdoor comfort and cooling demand across nine international cities, considering different canyon geometries, orientations and wind conditions.	A two-dimensional microclimatic simulation model comparing bare, green-wall, green-roof and combined greening scenarios across nine climates and three urban canyon configurations.	X			Simulations predicted substantial cooling in urban canyons, with maximum air temperature reductions of 8.4 °C in Hong Kong for combined greening and 3.9 °C for green walls alone.		X		X						X		
3	Experimen-tal approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes	E.A. Eumor-fopoulou, K.J. Kontoleon	2009	https://doi.org/10.1016/j.buildenv.2008.07.004	Plant-covered wall; Thermal performance; Temperature field; Thermal inertia	Experimental comparison of vegetated and uncovered insulated wall sections on two floors of a residential building in Thessaloniki, Central Macedonia, Greece, during the summer cooling period.	Field temperature measurements and thermal calculations comparing exterior and interior wall surfaces, daily temperature variations, heat transfer and thermal inertia with and without climbing vegetation.		X		In Thessaloniki, Greece, vegetated wall sections showed lower peak surface temperatures and reduced daily thermal fluctuations compared with bare walls, improving envelope thermal stability during hot summer conditions.		X		X								
4	Energy simulation of vertical greenery systems	Nyuk Hien Wong, Alex Yong Kwang Tan, Puay Yok Tan, Ngian Chung Wong	2009	https://doi.org/10.1016/j.enbuild.2009.08.010	Vertical greenery systems; Simulations; Urban heat island effect; Thermal comfort; Mean radiant temperature; Energy cooling load; Envelope thermal transfer value; Estate air temperature	Simulation-based assessment of vertical greenery effects on building cooling loads, mean radiant temperature, envelope thermal transfer and urban microclimate, using Singapore climatic conditions and an industrial estate case.	An integrated assessment using TAS building simulations, ETTV calculations and the STEVE urban temperature model, supported by measured leaf area index and shading coefficients from HortPark vegetation.	X			Singapore simulations predicted a 40.68% ETTV reduction with 50% glazing greenery coverage and low shading coefficients. Fully vegetated opaque-wall scenarios reduced cooling loads by 74.29% under idealized assumptions.	X			X			X			X		

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type			Topics								
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
5	Shading performance of a vertical deciduous climbing plant canopy	Kenneth Ip, Marta Lam, Andrew Miller	2010	https://doi.org/10.1016/j.buildenv.2009.05.003	External shading device; Deciduous climbing plant canopy; Shading coefficient; Bioshading Coefficient, Bioshader	Two-year field monitoring of Virginia Creeper shading devices installed outside office windows at the University of Brighton, East Sussex, United Kingdom, assessing seasonal solar transmission and foliage development.	An experimentally derived dynamic Bioshading Coefficient Function describing seasonal shading performance from measured solar radiation, leaf-layer transmissivity and vegetation coverage.		X		The two-year monitoring demonstrated that deciduous climbing canopies provide seasonally responsive solar shading, allowing the calculation of daily bioshading coefficients from changing foliage density and solar transmission.		X		X		X	X					X
6	Thermal evaluation of vertical greenery systems for building walls	Nyuk Hien Wong, Alex Yong Kwang Tan, Yu Chen, Kannagi Sekar, Puay Yok Tan, Derek Chan, Kelly Chiang, Ngian Chung Wong	2010	https://doi.org/10.1016/j.buildenv.2009.08.005	Vertical greenery systems; Thermal environments; Surface temperature; Ambient temperature	Experimental comparison of eight green façade and living wall configurations installed at HortPark in Singapore, examining their effects on wall temperatures, substrate temperatures and surrounding ambient conditions.	Comparative field measurements from eight vegetated wall systems and a control wall, documenting construction typologies, substrate thicknesses, surface temperature fluctuations and cooling effects at different distances.		X		In Singapore, modular living walls generally achieved stronger surface cooling. System 4 reduced wall temperature by approximately 10.94 °C, with detectable ambient cooling extending 0.60 m from the façade.	X			X		X						
7	Quantifying the deposition of particulate matter on climber vegetation on living walls	Marc Ottelé, Hein D. van Bohemen, Alex L.A. Fraaij	2010	https://doi.org/10.1016/j.ecoleng.2009.02.007	Particulate matter (PMx); Living walls; Façades; Common ivy; Hedera helix; Vertical greening; Building surfaces; Noise barrier; Ecological engineering	Experimental investigation of particulate matter accumulation on Hedera helix leaves collected from a vegetated roadside noise barrier and woodland near Bergen op Zoom, North Brabant, Netherlands.	A preliminary study on the classification of total particle mass through particle counting in ESEM photographs and factorial statistics comparing deposition by leaf surface, sampling height, season and surrounding environment.		X		Near Bergen op Zoom, Netherlands, roadside ivy leaves accumulated approximately 7000 particles on upper surfaces versus 3200 underneath; woodland samples showed about 3300, demonstrating environmental and leaf-surface differences.		X					X			X		
8	The Living walls as an Approach for a Healthy Urban Environment	Samar Sheweka, Nourhan Magdy	2011	https://doi.org/10.1016/j.egypro.2011.05.068	Bio walls; climatic change; vertical vegetations	Review of living wall applications and their potential thermal, environmental, social and economic benefits, examining construction typologies and international building examples with recommendations for arid climates.	A comparative overview of climbing, hanging and modular green wall systems, supported by international architectural case studies and recommendations for sustainable urban greenery.	X			The review highlights the potential of vertical vegetation to mitigate urban heat, improve air quality and support sustainable development, identifying design considerations for applications in arid climates.	X			X	X	X				X		

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type					Topics						
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
9	Evaluating the Impact of Vertical Greenery System on Cooling Effect on High Rise Buildings and Surroundings: A Review	Badrulzaman Jaafar, Ismail Said, Mohd Hisyam Rasidi	2011	https://doi.org/10.21776/ub.ruas.2011.009.02.1	Vertical greenery system; cooling effect; temperature reduction; humidity	Literature review of vertical greenery technologies and their influence on building cooling, urban microclimate, thermal performance and design considerations, examining studies published between 1999 and 2011.	A structured review of 21 studies, comparing vertical greenery typologies, support and carrier technologies, thermal benefits, cooling mechanisms, climatic influences and design parameters.	X			An analysis of 21 studies identifies the influence of design, structural, and thermal parameters on the performance of green roof systems, highlighting the role of shading and evapotranspiration in reducing surface temperatures, heat fluxes, and the urban heat island effect.	X			X	X				X			
10	Comparative life cycle analysis for green façades and living wall systems	Marc Ottelé, Katia Perini, A.L.A. Fraaij, E.M. Haas, R. Raiteri	2011	https://doi.org/10.1016/j.enbuild.2011.09.010	Façade greening; Living wall systems; LCA (life cycle analysis); Sustainability; Environmental burden; Environmental benefits	Comparative environmental life cycle assessment of direct and indirect green façades, planter-box and felt-based living walls, and a conventional brick façade, using a Delft, Netherlands reference context.	A 50-year LCA model comparing five façade scenarios through material inventories, transport, replacements, maintenance, disposal and estimated energy-saving benefits, identifying environmental burdens across greening technologies.	X			Direct green façades showed comparatively low additional environmental burdens, while material-intensive living wall systems, especially felt-based configurations, required greater environmental benefits to offset construction and maintenance impacts.	X			X		X		X	X	X		
11	A sustainability evaluation of vertical greenery systems based on emergy	R. M. Pulselli, N. Patrizi, F. M. Pulselli, S. Bastianoni	2012	https://doi.org/10.2495/ARC120211	Building facade; emergy evaluation; life cycle; living wall; vertical greenery system	Assessment of environmental resource consumption associated with manufacturing and maintaining a hypothetical 90 m^2 felt-based living wall through emergy accounting over an assumed 20-year lifespan within the Italian GREENED research project.	An emergy-based environmental accounting framework quantifying material, plant production, transport, assembly, water and energy inputs across manufacturing and maintenance phases, identifying dominant resource demands and potential eco-design improvements.	X			For the hypothetical Italian living wall, total emergy investment reached 1.25×10^{16} sej over 20 years. Manufacturing accounted for 80%, maintenance for 20%, with structural materials, plant production and irrigation water dominating resource consumption.			X			X		X			X	X
12	Sustainable green walls in architecture	M. Urrestarazu, S. Burés	2012		Green roof; green walls; urban canopy; plant built environment; urban vegetation; green chemistry; Rosmarinus officinalis	Design and construction of a self-sufficient modular green wall prototype using Mediterranean native vegetation, renewable energy and isolated closed-loop fertigation at the University of Almería, Andalusia, Spain.	A 5 m by 2.5 m living wall prototype comprising recycled plastic cultivation modules, coconut-fiber substrate, photovoltaic-powered irrigation, independent drainage circuits and mechanical wall anchoring.			X	The Almería prototype demonstrated a feasible modular configuration with independently irrigated units, reduced water losses and separated drainage circuits intended to limit root disease transmission between planting modules.			X			X	X	X		X	X	X

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type			Topics								
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
13	An Experimental Study on a Microclimatic Layer of a Bionic Façade Inspired by Vertical Greenery	Tomaž Šuklje, Sašo Medved, Ciril Arkar	2013	https://doi.org/10.1016/S1672-6529(13)60213-9	Green façade; adaptive façade; bionic leaf; PV cooling; evaporative cooling; PV cell temperature	Experimental comparison of an artificial bionic façade incorporating photovoltaic cells and evaporative matrices with a natural green façade under outdoor summer conditions.	A full-scale bionic façade prototype combining photovoltaic cells and capillary evaporative materials, evaluated through microclimatic temperature, humidity, wind and photovoltaic cooling measurements.		X		Outdoor measurements showed comparable microclimatic performance between bionic and green façades. Evaporative cooling lowered photovoltaic cell temperatures by up to 20.8 °C, increasing estimated daily electricity generation by 6.6%.		X		X		X				X		
14	Impact of Vertical Greenery System on Internal Building Corridors in the Tropic	Badrulzaman Jaafar, Ismail Said, Mohd Nadzri Md Reba, Mohd Hisyam Rasidi	2013	https://doi.org/10.1016/j.sbspro.2013.11.059	Vertical greenery system; cooling effect; temperature; air velocity	Experimental assessment of green façade and living wall effects on temperature, humidity and airflow across five-storey building corridors in Petaling Jaya, Selangor, Malaysia.	One-month field monitoring dataset comparing cable-supported green façades and modular living walls across different floor levels, measuring temperature, relative humidity and air velocity.		X		In Petaling Jaya, Malaysia, vegetated corridors recorded average temperatures around 29.3–30.0 °C, versus 30.8 °C for the control. Modular systems generally improved cooling, while façade configurations influenced humidity and airflow.	X			X								
15	Vertical Greenery Systems (VGS) for energy saving in buildings: A review	Gabriel Pérez, Julià Coma, Ingrid Martorell, Luisa F. Cabeza	2014	https://doi.org/10.1016/j.rser.2014.07.055	Vertical Greenery System; Green wall; Green Façade; Passive system; Energy savings; Building	Literature review comparing thermal mechanisms, energy-saving performance and climatic influences of green façades and living walls, considering vegetation, orientation, foliage density and construction systems.	A comparative synthesis of experimental and simulation findings organized by VGS typology and climatic conditions, highlighting energy performance, methodological limitations and future research requirements.	X			The review identifies substantial summer cooling potential for VGS but insufficient evidence on winter and annual performance. It highlights the importance of climate, plant species, orientation and substrate properties.	X			X	X	X	X					
16	A comprehensive lifecycle evaluation of vertical greenery systems based on systemic indicators	R. M. Pulselli, F. Saladini, E. Neri, S. Bastianoni	2014	https://doi.org/10.2495/SC140862	Carbon Footprint; EMergy Evaluation; global warming; Living Walls; sustainability	Life cycle environmental assessment of a hypothetical 98 m^2 living wall on a south-facing building façade under Mediterranean climatic conditions, evaluating energy savings, carbon footprint and emergy.	An environmental accounting model combining life cycle carbon footprint, emergy evaluation and cost–benefit balance to assess the long-term sustainability of a proposed living wall configuration.	X			For the simulated Mediterranean case, expected cooling savings were approximately 282 kWh/year, or 15%. Environmental costs could be compensated by benefits within approximately 25 years under favourable assumptions.			X	X		X			X	X		

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type				Topics							
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
17	Quantifying the thermal performance of green façades: A critical review	Annie M. Hunter, Nicholas S.G. Williams, John P. Rayner, Lu Aye, Dominique Hes, Stephen J. Livesley	2014	https://doi.org/10.1016/j.ecoleng.2013.12.021	Green wall; Vertical greening; Climbing plant; Climate change adaptation; Green infrastructure	Critical review of green façade thermal performance research, examining experimental and modelling limitations, climbing plant physiology, microclimatic measurements and design factors influencing building cooling.	A methodological framework defining essential microclimatic measurements, experimental requirements and future research priorities for assessing green façade performance and vegetation–building energy interactions.	X			The review identified inadequate experimental replication, inconsistent measurements and poorly justified modelling assumptions. Plant physiology and façade design effects were insufficiently investigated, preventing reliable generalization of thermal performance.		X		X		X	X					
18	Green Walls in High-Rise Buildings: An output of the CTBUH Sustainability Working Group	Antony Wood, Payam Bahrami, Daniel Safarik	2014	ISBN: 9781864705935		Technical guidance on vertical greenery integration in high-rise buildings, combining international building case studies with considerations of design, structural support, vegetation, maintenance, climatic conditions and energy performance.	A CTBUH technical guide documenting 18 international projects and providing design considerations, technological typologies, practical recommendations and a synthesis of research on green wall energy efficiency.	X			The guide documents diverse built applications of vertical greenery and identifies design opportunities and constraints involving façade integration, structural loads, irrigation, plant survival, maintenance and energy efficiency.	X			X	X	X	X	X		X		X
19	Green wall systems: A review of their characteristics	Maria Manso, João Castro-Gomes	2015	https://doi.org/10.1016/j.rser.2014.07.203	Green wall systems; Green facades; Living walls; Classification; Composition	Review and classification of green wall construction systems, comparing technological composition, supporting elements, growing media, vegetation, irrigation, maintenance and environmental considerations.	A construction-based taxonomy of direct and indirect green façades and continuous or modular living walls, with comparative descriptions of technological systems and implementation requirements.	X			The review identifies major technological differences in construction, assembly, material selection and maintenance, providing a structured basis for comparing green wall systems and their sustainability characteristics.	X				X	X	X	X		X		
20	An Experimental Study on Bioclimatic Design of Vertical Greenery Systems in the Tropical Climate	Badrulzaman Jaafar, Ismail Said, Mohd Nadzri Md Reba, Mohd Hisham Rasidi	2015	https://doi.org/10.1007/978-4-431-54439-5_37		Experimental comparison of the temperature and relative humidity effects of two vertical greenery configurations installed along an office corridor in Petaling Jaya, Selangor, Malaysia, under tropical climatic conditions.	A five-day field monitoring dataset comparing modular green façade and cable-supported vegetation configurations with an unvegetated control, evaluating corridor microclimate through temperature and relative humidity measurements.		X		In Petaling Jaya, Malaysia, the modular green façade recorded an average temperature of 29.8 °C, compared with 30.0 °C for cable-supported vegetation and 30.6 °C for the control, demonstrating modest cooling benefits.	X			X								

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type				Topics							
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
21	A novel vertical greenery module system for building envelopes: The results and outcomes of a multidisciplinary research project	V. Serra, L. Bianco, E. Candelari, R. Giordano, E. Montacchini, S. Tedesco, F. Larcher, A. Schiavi	2017	https://doi.org/10.1016/j.enbuild.2017.04.046	Vertical greenery modular system; Green wall; Green façade; Living wall system; Energy performance; Environmental performance; LCA; Acoustic performance; LAI; Vegetation species; Building envelope	Development and multidisciplinary assessment of a new modular living wall using recycled and natural materials, examining thermal, acoustic, mechanical, botanical and environmental performance in Turin, Piedmont, Italy.	The GRE EN S modular living wall prototype, incorporating engineered planting boxes, recycled materials, root-support layers and façade connections, validated through laboratory tests and long-term outdoor monitoring.			X	Research in Turin, Italy, developed and tested an integrated modular living wall, demonstrating the feasibility of combining thermal, acoustic, botanical and mechanical performance considerations with environmentally informed material selection.			X	X		X	X	X	X	X	X	X
22	Towards a comprehensive green infrastructure typology: A systematic review of classification approaches, methods and typologies	Carlos Bartesaghi Koc, Paul Osmond, Alan Peters	2017	https://doi.org/10.1007/s11252-016-0578-5	Urban greening; classification schemes; typologies; systematic review; ecosystem services; spatial scales	Systematic review of green infrastructure classification approaches, analysing 85 studies from 15 countries and examining functional, structural and spatial attributes, including vertical greenery as one infrastructure category.	A conceptual classification framework organizing urban green infrastructure into tree canopy, green open spaces, green roofs and vertical greenery systems using functional, morphological and configurational criteria.	X			The review identifies four major green infrastructure categories and recommends integrating functional, structural and spatial criteria, concluding that no universal classification can satisfy every planning and research context.	X					X							
23	Energy performance analysis of a dormitory building based on different orientations and seasonal variations of leaf area index	Sinchita Poddar, Dongyoon Park, Seongju Chang	2017	https://doi.org/10.1007/s12053-016-9487-y	Energy efficiency; Vertical vegetation; Green wall; Leaf area index; Seasonal variations; Heating and cooling energy consumption	Assessment of green wall energy performance across building orientations and seasonal leaf area index variations through simulations of a university dormitory in Daejeon, South Korea, evaluating annual heating and cooling energy consumption.	A calibrated DesignBuilder energy model comparing bare and ivy-covered façades across four orientations and seasonal leaf area index values, identifying configurations that optimize heating and cooling energy savings.	X			In Daejeon, South Korea, complete green wall coverage reduced heating energy consumption by approximately 60% and cooling demand by 17%. North-facing vegetation maximized heating savings, while east-facing vegetation optimized cooling performance.			X	X		X	X					
24	Simulation of Vertical Greenery System in Reducing Energy Cooling Loads for High Rise Residential Building	Hazril Sherney Basher, Sabarinah Sh. Ahmad, Abdul Malek Abdul Rahman	2017		Vertical Greenery System; Multi-storey Building; Temperature Reduction; Energy Cooling Load	Simulation-based evaluation of edible climbing-plant vertical greenery for reducing indoor temperatures and cooling energy demand in low-rise and high-rise residential units under Penang, Malaysia, climatic conditions.	IESVE simulations comparing vegetated and unshaded residential units, including short-term temperature predictions, annual cooling energy calculations and estimated electricity cost savings for different building heights.	X			In Penang, Malaysia, simulations predicted indoor temperature reductions of 0.47 °C for low-rise and 1.53 °C for high-rise units, with annual cooling energy savings of 7.6% and 18.27%, respectively.		X		X								

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type			Topics								
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
25	Thermal behaviour assessment of a novel vertical greenery module system: first results of a long-term monitoring campaign in an outdoor test cell	Lorenza Bianco, Valentina Serra, Federica Larcher, Marco Perino	2017	https://doi.org/10.1007/s12053-016-9473-4	Vertical greenery modular system; Green wall; Green façade; Living wall; Energy performance; LAI; Vegetation species	Experimental assessment of a newly developed modular living wall using different substrates and two plant species, monitoring seasonal thermal performance in an outdoor test cell in Turin, Piedmont, Italy.	A prefabricated 40 cm × 50 cm vegetated panel system with recycled-felt substrates, monitored for plant growth, leaf area index, surface temperatures, heat fluxes and thermal transmittance.		X		In Turin, Italy, the modular system reduced winter equivalent thermal transmittance by approximately 40% and summer exterior surface temperatures by up to 23 °C, but did not significantly reduce inward summer heat gains.			X	X		X	X				X	
26	Studying the potential of energy saving through vertical greenery systems: Using EnergyPlus simulation program	K.W.D. Kalani C. Dahanayake, Cheuk Lun Chow	2017	https://doi.org/10.1016/j.enbuild.2016.12.002	Vertical Greenery Systems (VGS); EnergyPlus; Integrated model; Thermal performance; Building energy simulation; Energy savings	Development and validation of a mathematical model integrating foliage and substrate heat balances into EnergyPlus to assess vertical greenery effects on building thermal behavior and energy consumption.	An EnergyPlus-integrated VGS simulation model validated against experimental studies from Wuhan and Hong Kong, enabling predictions of façade temperatures, indoor conditions and annual heating and cooling demand.	X			Simulations predicted maximum exterior façade temperature reductions of 26 °C and approximately 3% annual cooling energy savings in warm climates. Winter insulation effects increased heating demand, reducing seasonal benefits.			X	X								
27	Selection of suitable plant species for energy efficient Vertical Greenery Systems (VGS)	Kalani C. Dahanayake, Cheuk Lun Chow, Guo Long Hou	2017	https://doi.org/10.1016/j.egypro.2017.12.185	Vertical greenery systems; plant species; plant characterisics; energy saving	Theoretical and simulation-based investigation of plant selection criteria and vegetation traits influencing vertical greenery energy performance, using a hypothetical high-rise office building in Hong Kong, China.	EnergyPlus simulations testing leaf area index and plant height variations, combined with botanical selection guidelines addressing leaf morphology, climate suitability and maintenance requirements.	X			Hong Kong simulations showed annual cooling savings increasing from 0.4% to 1.8% as leaf area index increased from 1 to 5. Plant height had substantially less influence on energy performance.	X			X			X					
28	Cooling effect of direct green façades during hot summer days: An observational study in Nanjing, China using TIR and 3DPC data	Haiwei Yin, Fanhua Kong, Ariane Middel, Iryna Dronova, Hailong Xu, Philip James	2017	https://doi.org/10.1016/j.buildenv.2017.02.020	Cooling effect; Direct green façade; Plant characteristics; Thermal infrared images; Three-dimensional point cloud	Field investigation of the relationship between climbing vegetation structure and façade cooling during hot summer days at Nanjing University in Nanjing, Jiangsu Province, China, using infrared thermography and 3D point clouds.	An integrated thermal infrared and terrestrial laser scanning methodology generating pixel-scale vegetation indicators and surface temperature maps, supported by statistical correlations with weather variables and canopy characteristics.		X		In Nanjing, China, vegetated façade surfaces were 2.56 °C cooler on average, with a maximum mean reduction of 4.67 °C. Vegetation coverage strongly influenced cooling, particularly during midday.		X		X			X					

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type				Topics							
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
29	Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect	Gabriel Pérez, Julià Coma, Salvador Sol, Luisa F. Cabeza	2017	https://doi.org/10.1016/j.apenergy.2016.11.055	Vertical greenery systems (VGS); Green facades; Energy savings; Buildings; Leaf area index (LAI); Shadow effect	Experimental assessment of leaf area index, solar shading and cooling-energy savings in vertical greenery systems, focusing on façade orientation under Mediterranean continental conditions near Lleida, Catalonia, Spain.	A field-tested methodology for indirect LAI measurement, combined with comparative monitoring of vegetated and reference test cells to quantify shading effectiveness and energy consumption.		X		Near Lleida, Spain, Boston ivy with LAI values of 3.5–4 achieved up to 34% summer energy savings. East- and west-facing greenery contributed substantially to overall performance.	X			X			X					
30	Building community-driven vertical greening systems for people living on less than £1 a day: A case study in Nigeria	Oluwafeyikemi H. Akinwolemiwa, Clarice Bleil de Souza, Luigi M. De Luca, Julie Gwilliam	2018	https://doi.org/10.1016/j.buildenv.2018.01.022	Vertical greening systems prototypes; Community driven design in Nigeria; Thermal comfort in low income houses	Participatory design and development of affordable vertical greening prototypes to improve indoor thermal comfort and provide edible and medicinal plants in Agege, Lagos State, Nigeria.	Four community-developed prototypes using HDPE, bamboo and prefabricated timber, accompanied by thermal monitoring, plant growth observations, economic assessment and a product development roadmap.			X	In Lagos, Nigeria, prototypes reduced indoor air temperature by an average of 2.3 °C, achieved thermal comfort for 90–100% of monitored time and supported approximately 16 annual crop harvests.		X		X		X	X	X				X
31	Vertical greenery systems: A systematic review of research trends	Rosmina A. Bustami, Martin Belusko, James Ward, Simon Beecham	2018	https://doi.org/10.1016/j.buildenv.2018.09.045	Green façade; Living wall; Passive cooling; Systematic review; Vertical greenery system	Systematic review of research trends in outdoor vertical greenery systems, classifying 166 publications by research methods and 13 thematic areas to identify disciplinary developments and knowledge gaps.	A bibliometric and thematic research classification documenting VGS study types, dominant research subjects, methodological approaches and emerging multidisciplinary trends.	X			Of 166 reviewed studies, 76 examined thermal performance. Multidisciplinary publications increased from 25% in 2011 to over 60% in 2017, while cost and maintenance emerged as major implementation barriers.	X			X				X				
32	Vertical Greenery System as the Passive Design Strategy for Mitigating Urban Heat Island in Tropical Area: A Comparative Field Measurement Between Green Facade and Green Wall	Ratih Widiastuti, Chely N. Bramiana, Bangun I.R.H, Bintang N. Prabowo, Mirza Ramandhika	2018	https://doi.org/10.1088/1755-1315/213/1/012037	Building envelope; green facade; green wall; vertical greenery system	Experimental comparison of green façade and living wall thermal performance through field measurements of surface temperatures, surrounding air temperature and humidity, using separate building configurations in Semarang, Indonesia.	Comparative field measurements of vegetated and bare walls, documenting hourly surface temperature and nearby microclimatic conditions for a climbing-plant façade prototype and an existing geotextile living wall.		X		In Semarang, Indonesia, living walls reduced average exterior and interior surface temperatures by 3.17 °C and 5.38 °C, respectively. Green façades achieved reductions of 4.4 °C and 2.9 °C.	X			X							

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
33	Percentage Coverage of Tropical Climbing Plants of Green Facade	Mohd Khairul Azhar Mat Sulaiman, Mohd Fairuz Shahidan, Maslina Jamil, Mohd Fauzi Mohd Zain	2018	https://doi.org/10.1088/1757-899X/401/1/012025		Experimental comparison of foliage coverage, growth patterns and botanical characteristics of three tropical climbing species on small-scale indirect green façade prototypes in Serdang, Selangor, Malaysia.	A 30-day field experiment using three trellis-supported green façade mock-ups and digital image segmentation to quantify foliage coverage and assess plant species suitability.		X		In Serdang, Malaysia, Anemopaegma chamberlaynii achieved 86.5% average foliage coverage, outperforming Antigonon leptopus (79.6%) and Quisqualis indica (69.4%). Growth rate and climbing patterns proved more influential than leaf size.		X					X					
34	Shading Effect and Heat Reflection Performance of Green Façade in Hot Humid Climate Area: Measurements of a Residential Project in Guangzhou, China	H. Lin, Y. Xiao, F. Musso	2018	https://doi.org/10.1088/1755-1315/146/1/012006		Experimental investigation of green façade shading and surface temperature reductions on east- and south-facing elevations of a high-rise residential building in Guangzhou, Guangdong Province, China.	Six-day onsite temperature and humidity monitoring combined with thermal imaging and foliage coverage analysis of three existing climbing-plant green façades.		X		In Guangzhou, China, green façades reduced average shaded air temperatures by 0.6–0.7 °C on sunny days, with maximum reductions of 3.2–3.8 °C, and lowered façade surface temperatures by approximately 3–4 °C.		X		X								
35	Orientation effect on thermal and energy performance of vertical greenery systems	Lan Pan, Shen Wei, L.M. Chu	2018	https://doi.org/10.1016/j.enbuild.2018.07.024	Vertical greenery systems; Wall orientation; Thermal performance; Indoor and outdoor cooling; Cooling load	Experimental assessment of façade orientation and weather effects on surface temperatures, ambient cooling, indoor temperatures and energy performance of modular living walls in Hong Kong, China.	One-year monitored comparison of vegetated and bare test rooms across four orientations, supplemented by steady-state calculations estimating building-envelope cooling load reductions.		X		In Hong Kong, China, north-facing greenery reduced ambient temperatures by up to 10.1 °C, while west-facing systems achieved 6.1 °C wall cooling. Estimated cooling load reductions ranged from 12% to 42%.			X	X								
36	Green façades to control wall surface temperature in buildings	Giuliano Vox, Ileana Blanco, Evelia Schettini	2018	https://doi.org/10.1016/j.buildenv.2017.12.002	Urban agriculture; Green walls; Air-conditioning; Energy savings; Microclimate; Urban heat island	Two-year experimental comparison of two evergreen climbing plant façades and an uncovered masonry wall, examining seasonal surface temperatures and weather effects in Valenzano, Bari, Apulia, Italy.	Field monitoring of three south-facing experimental walls, measuring surface temperatures, radiation, wind and humidity, with statistical evaluation of seasonal thermal performance for two climbing species.		X		In Bari, Italy, vegetated walls were up to 9.0 °C cooler during warm daytime conditions and up to 3.5 °C warmer on cold nights, confirming seasonal thermal benefits of both climbing species.		X		X			X					

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
37	Potential of Particle Matter Dry Deposition on Green Roofs and Living Walls Vegetation for Mitigating Urban Atmospheric Pollution in Semiarid Climates	Margareth Viecco, Sergio Vera, Héctor Jorquera, Waldo Bustamante, Jorge Gironás, Cynnamon Dobbs, Eduardo Leiva	2018	https://doi.org/10.3390/su10072431	particulate matter (PM); air pollutants; green roofs; living walls; air quality; sustainable urban development; vegetation species; PM2.5; PM10; wax; dry deposition; PM capture	Controlled experimental comparison of nine plant species used in green roofs and living walls, assessing particulate matter deposition and leaf-wax retention for semiarid conditions in Santiago, Chile.	Species-specific particulate deposition measurements obtained through controlled pollutant exposure, leaf washing, filtration and gravimetric analysis, identifying vegetation suitable for PM10 and PM2.5 capture.		X		In Santiago, Chile, deposition ranged from 0.09 to 1.32 $\mu g/cm^2/h$ for PM2.5 and 0.48 to 4.7 $\mu g/cm^2/h$ for PM10; Sedum species showed high capture potential.			X				X			X		
38	Effects of a Vertical Green Façade on the Thermal Performance and Cooling Demand: A Case Study of a Tube House in Vietnam	Phan Anh Nguyen, Regina Bokel, Andy van den Dobbelsteen	2019	https://doi.org/10.7480/jfde.2019.2.3819	Green façade; thermal performance; cooling demand	Experimental evaluation of the thermal performance and cooling energy demand of a Bougainvillea-covered green façade compared with an aluminium shading device and an unshaded façade in a residential tube house in Hanoi, Vietnam.	Field measurements comparing indoor and outdoor temperatures, solar radiation and air-conditioning electricity consumption across different façade configurations in two rooms of an existing residential building during summer.		X		In Hanoi, Vietnam, the green façade reduced indoor temperatures by approximately 1 °C and air-conditioning energy consumption by up to 35% compared with an unshaded façade, demonstrating slightly better cooling performance than aluminium shading.		X		X								
39	Experimental comparison of green facades with outdoor test cells during a hot humid season	Georgios Kokogiannakis, Jo Darkwa, Sofia Badeka, Yilin Li	2019	https://doi.org/10.1016/j.enbuild.2018.12.038		Experimental comparison of thermal performance among direct and indirect green façades, felt-layer and planter-box living walls, and an unvegetated reference wall using outdoor test cells under hot, humid summer conditions in Ningbo, China.	Comparative field measurements and statistical correlations quantifying external wall surface temperature reductions, diurnal fluctuations, and relationships with meteorological conditions for four vertical greenery systems.		X		In Ningbo, China, felt-layer living walls achieved the greatest cooling, reducing daily average surface temperatures by 1.9–4.8 °C and peak temperatures by 7.1–13.4 °C, followed by planter-box systems and climbing vegetation.	X			X		X					
40	Convective heat transfer in green façade system	Fabiana Convertino, Giuliano Vox, Evelia Schettini	2019	https://doi.org/10.1016/j.biosystemseng.2019.10.006	Green infrastructure; Energy balance; Modelling; Convective coefficient; Green layer; Passive system	Evaluation of mathematical models describing convective heat transfer between vegetation and external air in green façades, using energy balance calculations and experimental data collected in Valenzano, Italy.	A comparative validation of six convective heat transfer equations against experimental measurements, identifying the most suitable mathematical approaches for modelling heat exchanges in green façade systems.	X			In Valenzano, Italy, forced convection dominated heat exchanges between vegetation and air. The Morrison-Barfield equation and adapted Deardorff model provided the closest agreement with measurements, supporting more accurate green façade energy modelling.		X		X								

Table A1. *Cont.*

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41	A Statistically Rigorous Approach to Experimental Design of Vertical Living Walls for Green Buildings	Rosmina A. Bustami, Chris Brien, James Ward, Simon Beecham, Robyn Rawlings	2019	https://doi.org/10.3390/urbansci3030071	Living wall; vertical greenery system; carry-over effect; native plants	Experimental investigation of native plant growth, survival, substrate composition, irrigation regimes, and cascading interactions between vertically arranged plants in a modular living wall over nine months in Adelaide, South Australia.	A statistically designed field experiment using 144 modular planting trays and 36 treatment combinations, evaluating plant growth, survival, irrigation, substrates, and carry-over effects through mixed-model statistical analysis.		X		In Adelaide, South Australia, 76% of plants remained healthy, with Goodenia varia achieving 100% survival. Plant species, substrate and vertical positioning affected growth, while irrigation frequency showed limited influence on survival.			X			X	X	X				
42	Design for maintainability of high-rise vertical green facades	Michael Y. L. Chew, Sheila Conejos, Fikril Hakim Bin Azril	2019	https://doi.org/10.1080/09613218.2018.1440716	Design quality; green facade; high-rise; living wall; maintainability; quality control; vertical greenery systems; Singapore	Investigation of design and maintenance defects affecting high-rise vertical greenery systems through site inspections, stakeholder interviews, and expert assessments across 12 building case studies in Singapore.	Case-study-based Design for Maintainability (DfM) guidelines addressing maintenance accessibility, structural safety, vegetation selection, irrigation, drainage, material durability, and design requirements for high-rise vertical greenery systems in tropical climates.		X		In Singapore, 12 case studies identified seven critical VGS defects, particularly maintenance inaccessibility, safety hazards, plant deterioration, irrigation and drainage failures. Proposed guidelines integrate preventive design, construction quality, and long-term maintenance strategies.	X				X	X	X	X				X
43	Green Facades and Living Walls—A Review Establishing the Classification of Construction Types and Mapping the Benefits	Mina Radić, Marta Brković Dodig, Thomas Auer	2019	https://doi.org/10.3390/su11174579	External vertical greenery systems; living walls; green facades; classification of VGS construction types; VGS benefits	Systematic literature review examining construction-based classifications of green façades and living walls, their terminology and associated environmental, thermal, social and economic benefits, distinguishing empirical evidence from descriptive findings.	A standardized classification identifying 13 vertical greenery construction types, including four green façade and nine living wall categories, linked to ten benefits and their respective levels of empirical support.	X			The review identified 13 construction types and ten benefits across 93 sources. Thermal performance had the strongest empirical support, whereas air quality, hydrology, social and educational benefits required further investigation.	X			X	X	X						
44	Modeling of Vertical Greenery System As Passive Design Strategy for Mitigating Indoor Temperature	Ratih Widiastuti, Bangun I.R.H., Hana Faza R.S., Chely Novia B., Bintang Noor Prabowo, Mirza Ramandhika	2019	https://doi.org/10.18502/kss.v3i21.5003	Building envelope; Ecotect simulation; surface temperature; vertical greenery system	Evaluation of thermal performance of an existing geotextile living wall through Ecotect simulations and field temperature measurements, comparing vegetated and unvegetated office façade sections in Semarang, Indonesia.	A Revit-based building model analyzed in Ecotect, supported by field measurements comparing exterior and interior surface temperatures and evaluating the thermal effects of vegetation on an existing office building.	X			In Semarang, Indonesia, vegetated façade peak surface temperatures reached 29.13 °C externally and 25.41 °C internally, compared with 32.30 °C and 30.79 °C for bare walls, confirming reduced heat transfer.			X	X							

Table A1. *Cont.*

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45	Vertical Gardens in High-Rise Buildings—Modern Form of Green Building Technology	Hanna Golasz-Szolomicka, Jerzy Szolomicki	2019	https://doi.org/10.1088/1757-899X/603/2/022067		Comparative architectural review of vertical greenery technologies integrated into selected high-rise buildings in Milan, Italy; Nanjing, China; Sydney, Australia; Singapore; and Beirut, Lebanon, examining construction solutions and environmental benefits.	A comparative overview of prominent high-rise vertical garden projects, documenting structural configurations, vegetation arrangements, façade support systems and architectural strategies for integrating greenery into tall buildings.	X			The reviewed buildings demonstrate diverse approaches to integrating extensive vegetation, including planted balconies, hydroponic living walls and climbing façades. Structural support, wind resistance, irrigation and architectural integration emerge as important design considerations.	X				X	X				X		X
46	Observation to Building Thermal Characteristic of Green Façade Model Based on Various Leaves Covered Area	Ratih Widiastuti, Wahyu Caesarendra, Juliana Zaini	2019	https://doi.org/10.3390/buildings9030075	Building thermal characteristic; green façade; heat flow; leaves covered area	Experimental investigation of thermal behavior and heat transfer in miniature green façade models with 0%, 50% and 90% leaf coverage, using field measurements in Semarang, Indonesia.	Comparative experimental measurements and calculations of façade temperatures, heat fluxes, decrement factors and thermal time lags under three leaf coverage conditions in a scaled building model.		X		In Semarang, Indonesia, average wall heat flux decreased from 4.69 W/m^2 without vegetation to 3.88 W/m^2 at 50% leaf coverage and 1.61 W/m^2 at 90%, demonstrating improved thermal protection.		X		X			X					
47	Vertical greenery systems: from plants to trees with self-growing interconnections	Xiuli Wang, Wolfgang Gard, Helena Borska, Bob Ursem, J. W. G. van de Kuilen	2020	https://doi.org/10.1007/s00107-020-01583-0		Investigation of vertical greenery classifications, tree planting strategies and structural stability in high-rise vertical forests, considering Bosco Verticale in Milan, Italy, and self-growing tree connections tested in Delft, Netherlands.	A conceptual natural fixation system based on interconnected growing trees, supported by preliminary mechanical pulling tests and design recommendations addressing vegetation selection, wind resistance and structural stability.			X	Preliminary tests in Delft, Netherlands, demonstrated increased stiffness and reduced tree deflections through self-growing connections. The proposed approach could improve vertical forest stability and reduce artificial anchoring requirements, pending further validation.	X			X	X	X	X	X		X		X
48	Indirect green façade as an overheating prevention measure	Valentina Lesjak, Luka Pajek, Mitja Košir	2020	https://doi.org/10.14256/JCE.2797.2019	Vertical greenery systems; indirect green façade; solar radiation; façade surface temperature; operative temperature	Experimental and simulation-based assessment of an indirect green façade's shading effectiveness and influence on façade overheating and indoor operative temperatures during summer in Punat, Krk Island, Croatia.	A constructed indirect green façade prototype with monitored radiation and temperatures, combined with EnergyPlus simulations comparing indoor thermal comfort across façade orientations, vegetation configurations and residential wall types.		X		In Punat, Croatia, the green façade reduced incident solar radiation by up to 505 W/m^2 and façade temperatures by 13.5 °C. Simulated operative temperatures decreased by up to 6 °C.		X		X			X					

Table A1. *Cont.*

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49	Indoor Thermal Performance Analysis of Vegetated Wall based on CFD Simulation	Ratih Widiastuti, Juliana Zaini, Mochamad Agung Wibowo, Wahyu Caesarendra	2020	https://doi.org/10.37934/cfdl.12.5.8290	CFD simulation; building model; indoor thermal performance; vegetated wall	Numerical evaluation of indoor air and interior surface temperature distributions in a building model with and without a climbing-plant green façade, using CFD simulations validated against previous experimental measurements.	A SolidWorks-based three-dimensional building model and CFD simulations comparing bare and vegetated façades, incorporating thermal material properties, airflow modelling, mesh sensitivity analysis and validation with field measurements.	X			CFD simulations showed that green façades reduced indoor temperatures by approximately 1.7 °C and interior surface temperatures by up to 3.7 °C, with simulation-measurement surface temperature errors of 1.0–1.3 °C.		X		X								
50	Urban heat stress mitigation potential of green walls: A review	Kyra Koch, Tess Ysebaert, Siegfried Denys, Roeland Samson	2020	https://doi.org/10.1016/j.ufug.2020.126843	Climate change; Cooling; Green infrastructure; Green walls; Nature based solutions; Urban heat Island	Literature review and meta-analysis of outdoor green façades and living walls, investigating cooling mechanisms, climate-dependent performance and their potential to mitigate urban heat stress.	A synthesis of published experimental and modelling results, including green wall typologies, shading, evapotranspiration, insulation and ventilation mechanisms, with comparative thermal performance indicators.	X			The review identified shading as a principal wall-cooling mechanism, while evapotranspiration contributes to ambient cooling. Performance depends on leaf area, irrigation, climate and system configuration, with substantial variation across studies.	X			X		X	X			X		
51	An experimental study of vertical greenery systems for window shading for energy saving in summer	Xing Zheng, Tianchen Dai, Mingfang Tang	2020	https://doi.org/10.1016/j.jclepro.2020.120708	Shading coefficient; Vegetative; Vertical greening; Green façade; Energy saving; Solar shading system	Development and experimental evaluation of movable vegetated window shading using three climbing plant species, examining summer solar transmission, window heat flux and cooling consumption in Chongqing, China.	Two proposed movable green window shading configurations, simplified experimental models and a photovoltaic sensor-array method for measuring shading coefficients across vegetated window surfaces.			X	In Chongqing, China, dishcloth gourd shading with 80% coverage achieved a shading coefficient of 0.28, reducing cooling energy consumption by 11.5% and window heat flux by 64.8%.		X		X		X	X					X
52	Innovative module of expanded cork agglomerate for green vertical systems	Andreia Cortês, António Tadeu, Maria Inês Santos, Jorge de Brito, João Almeida	2021	https://doi.org/10.1016/j.buildenv.2020.107461	Green walls; Modular living wall; Insulation cork boards; Life cycle analysis; Mechanical tests	Development of an expanded-cork modular living wall, supported by comparative life cycle assessment and mechanical verification of materials and façade fastening solutions in Portugal.	A proposed modular cork-based living wall system, with environmental comparison of existing alternatives and mechanical, adhesion and durability testing for material selection.			X	Expanded cork agglomerate with a density of 140–160 kg/m^3 emerged as a technically suitable alternative to conventional plastic and metallic living wall components, with potential environmental advantages.			X			X		X	X	X	X	X

Table A1. *Cont.*

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53	Assessment of the Thermal Performance of Vertical Green Walls Using Overall Thermal Transfer Value Based BIM Simulation Method: Case Study of Residential Buildings in Sub-Tropics	Ali Ahmed Salem Bahdad, Sharifah Fairuz Syed Fadzil, Hilary Omatule Onubi	2021	https://doi.org/10.15627/jd.2021.23	Overall thermal transfer value; Vertical greenery; BIM; Building energy simulations	Simulation-based evaluation of vertical green wall thermal performance across six exterior wall configurations in a subtropical residential building, integrating OTTV calculations with BIM and EnergyPlus.	An OTTV-based BIM simulation workflow linking Autodesk Revit, DesignBuilder and EnergyPlus to compare wall thermal properties, indoor temperatures, cooling loads and heat gains.	X			The simulations found up to 1.2 °C indoor temperature reduction, 103.3 kWh cooling energy savings (13.63%) and 38.82% lower heat gains for the best vegetated wall configuration.	X			X		X						
54	Simulating and Comparing Different Vertical Greenery Systems Grouped into Categories Using EnergyPlus	Alberto Arenghi, Camilla Perra, Marco Caffi	2021	https://doi.org/10.3390/app11114802	Vertical Greenery Systems (VGS); classification; comparison of different types of VGS; mathematical modeling and thermohygrometric analysis; EnergyPlus	Comparative assessment of the thermohygrometric performance of different Vertical Greenery Systems through dynamic energy simulations, examining external wall surface and operative temperatures under summer and winter climatic conditions in Brescia, Italy.	A classification of Vertical Greenery Systems into three main categories and seven subcategories, with corresponding mathematical models integrated into EnergyPlus to enable consistent comparisons of their thermal performance.	X			In Brescia, Italy, simulations showed that heavy green walls reduced summer surface temperatures by up to 13 °C and operative temperatures by 9 °C, while Mur Vegetal achieved the highest winter operative temperature increase of 4 °C.	X			X	X	X	X					
55	Evaluation and Planning Decision on Façade Greening Made Easy—Integration in BIM and Implementation of an Automated Design Process	Jutta Hollands, Azra Korjenic	2021	https://doi.org/10.3390/su13169387	Building information modeling (BIM); façade greenery; urban green; decision support; automated planning process; vertical green; evaluation; green walls	Development and evaluation of a BIM-integrated automated planning methodology for five vertical greenery configurations, assessing placement, suitability, costs and design alternatives through a fictional residential building case study in Vienna, Austria.	Five parametric BIM greenery objects, a Revit project template and a Grasshopper-based automated design workflow supporting multicriteria evaluation, cost comparison, visualization and preliminary vegetation recommendations.	X			In Vienna, Austria, the fictional case study demonstrated automated generation and comparison of façade greening alternatives, integrating placement criteria, lifecycle costs and visualization. Maintenance costs emerged as substantial, while standardized data availability remained a limitation.	X				X	X	X	X				

Table A1. *Cont.*

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56	The Impact of Indoor Living Wall System on Air Quality: A Comparative Monitoring Test in Building Corridors	Yiming Shao, Jiaqiang Li, Zhiwei Zhou, Fan Zhang, Yuanlong Cui	2021	https://doi.org/10.3390/su13147884	Vertical greenery system; indoor living wall system; indoor air quality; carbon dioxide; particulate matter	Experimental investigation of indoor living wall effects on carbon dioxide, particulate matter, temperature and humidity in two comparable office building corridors in Nanjing, Jiangsu Province, China.	A ten-month comparative monitoring study of corridors with and without a 10.6 m^2 modular indoor living wall, including pollutant concentration measurements and statistical analysis.		X		In Nanjing, China, the living wall reduced CO_2 concentrations by 12–17% and PM2.5 by 8–14%. Average temperature decreased only 0.13 °C, while relative humidity increased by 3.1–6.4%.			X							X		
57	A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate	Marta Chàfer, Gabriel Pérez, Julià Coma, Luisa F. Cabeza	2021	https://doi.org/10.1016/j.enbuild.2021.111236	Life cycle assessment (LCA); Green wall; Green facade; Environmental impact; ReCiPe; GWP	Comparative life cycle assessment of a modular living wall, a double-skin green façade and a bare reference building, using experimental energy data from Puigverd de Lleida, Catalonia, Spain.	A 50-year environmental impact comparison using ISO 14040/44, ReCiPe and global warming potential indicators, incorporating measured operational energy consumption, materials, maintenance and end-of-life scenarios.	X			Operational energy accounted for up to 90% of 50-year environmental impacts. VGS reduced annual burdens by approximately 1%, with nearly 50% reductions in summer; manufacturing and maintenance particularly affected living walls.	X			X		X		X	X	X		
58	Psychological and physiological effects of a green wall on occupants: A cross-over study in virtual reality	Seungkeun Yeom, Hakpyeong Kim, Taehoon Hong	2021	https://doi.org/10.1016/j.buildenv.2021.108134	Green wall; Biophilia; Virtual reality; Indoor environment; Stress level; Physiological response	Experimental evaluation of psychological and physiological responses to virtual indoor green walls of different sizes, involving 27 participants in a controlled laboratory at Yonsei University, Seoul, South Korea.	A virtual reality cross-over experiment comparing rooms without greenery and with 2 m^2 or 8 m^2 green walls, supported by anxiety questionnaires, heart-rate variability, electrodermal and EEG measurements.		X		In Seoul, South Korea, the smaller virtual green wall produced stronger relaxation responses, whereas the larger wall increased stress indicators, suggesting that more extensive greenery does not necessarily improve perceived well-being.			X									
59	Vertical Greenery Systems: a comprehensive review	Manoj Kumar Rajak, Ravish Kumar, Rahul Biswas	2022	https://doi.org/10.53272/icrrd.v3i3.3	Vertical Greenery Systems; VGS; Green Infrastructure	Literature review of vertical greenery systems examining typologies, construction components, plant selection, maintenance, thermal performance and environmental benefits within sustainable building design and urban greening.	An organized synthesis of VGS technologies, including green façades and living walls, their support systems, growing media, irrigation, vegetation and reported energy-saving effects.	X			The review identifies shading, insulation and evapotranspiration as principal thermal mechanisms and highlights the importance of vegetation, materials, supporting components and maintenance in improving VGS performance.	X			X	X	X	X	X		X		

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type				Topics							
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
60	Evaluation of effects of a green wall as a sustainable approach on reducing energy use in temperate and humid areas	Kimia Karimi, Mohammad Farokhzad, Gholamreza Roshan, Mahnaz Aghdasi	2022	https://doi.org/10.1016/j.enbuild.2022.112014	Green façade; Thermal performance; Energy saving; Educational building; Vertical greening system (VGS)	Simulation of thermal performance and energy consumption in an educational building using different green wall configurations and plant species in Gorgan, Golestan Province, Iran.	Comparative building energy simulations of green façades and living walls using Sedum, Parthenocissus tricuspidata and Hedera helix, supported by measurements from an existing vegetated building.	X			In Gorgan, Iran, simulations indicated reduced wall heat transfer and building energy use with vertical greenery. Sedum performed best among the evaluated species, with outcomes dependent on system configuration.	X			X		X	X					
61	The Building Stock Rehabilitation: The Contribution of Vertical Greenery Systems (VGS)	Alessandro Lo Faro, Angela Moschella, Grazia Lombardo, Angelo Salemi, Gaetano Sciuto, Francesco Nocera, Vincenzo Costanzo	2022	ISBN: 978-84-09-42253-1	Green walls; Patrimonio costruito; Sostenibilità; Riqualificazione	Critical review of green façade and living wall technologies for retrofit applications, with attention to performance, construction compatibility and rehabilitation of existing buildings.	A comparative discussion of VGS typologies, retrofit requirements, technological constraints and recommendations for applying vertical greenery to existing building stock.	X			The review finds that shading-related cooling benefits depend on envelope design, climate and system choice, while anchorage, irrigation and maintenance complicate retrofitting existing buildings.	X			X	X	X		X				X
62	Vertical Green Structures to Establish Sustainable Built Environment: A Systematic Market Review	Ozge Ogut, Nerantzia Julia Tzortzi, Chiara Bertolin	2022	https://doi.org/10.3390/su141912349	Vertical green structures; market classification; green facades; living walls; sustainability; materials; green infrastructures; sustainable facade	Systematic review of 142 commercial vertical greenery products from 58 manufacturers, examining technological classifications, construction materials, maintenance, economic characteristics and environmental sustainability.	A market-based taxonomy and comparative product database classifying green façades and living walls by cultivation methods, materials, supporting structures, modular configurations and sustainability criteria.	X			Of 142 products, 24 were green façades and 118 living walls. The review identified substantial differences in materials, system complexity, maintenance and environmental sustainability.	X				X	X	X	X		X	X	X
63	Effect of Leaf Area Index on Green Facade Thermal Performance in Buildings	Fabiana Convertino, Evelia Schettini, Ileana Blanco, Carlo Bibbiani, Giuliano Vox	2022	https://doi.org/10.3390/su14052966	Green infrastructure; vertical greenery system; heat transfer; solar transmissivity; latent heat; solar shading; cooling mechanisms	Assessment of the influence of leaf area index on solar shading, evapotranspiration and summer cooling performance of a south-facing evergreen green façade through measurements and simulations in Valenzano, Bari, Italy.	Mathematical relationships quantifying solar transmissivity, shading and latent heat as functions of leaf area index, developed using experimental measurements and simulations of different vegetation densities.	X			In Valenzano, solar transmissivity decreased by 54% per LAI unit increase. Cooling benefits increased with foliage density but became marginal beyond LAI 6; shading contributed approximately 63% of total cooling.		X		X			X					

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
64	Vertical Greenery as Natural Tool for Improving Energy Efficiency of Buildings	Carlo Alberto Campiotti, Lorenzo Gatti, Alessandro Campiotti, Luciano Consorti, Patrizia De Rossi, Carlo Bibbiani, Rosario Muleo, Arianna Latini	2022	https://doi.org/10.3390/horticulturae8060526	Green wall; green façade; vertical greenery system (VGS); building acclimatization; energy saving; wall surface temperature (ST); heat flux (HF); green factor (Kv); *Parthenocissus quinquefolia* (L.) Planch	Experimental assessment of thermal performance, cooling electricity savings and associated CO_2 reductions of a detached deciduous green façade, using multiyear measurements at the ENEA Casaccia Research Center near Rome, Italy.	A three-year experimental dataset and adapted green factor Kv model quantifying vegetation shading, façade surface temperature reductions, heat flux variations, cooling electricity savings and avoided carbon emissions.		X		Near Rome, Italy, vegetation reduced July façade surface temperatures by up to 13 °C. Estimated cooling electricity savings reached 2.22 and 1.94 kWh/m^2, avoiding 985 and 862 g CO_2/m^2 in 2019 and 2020.		X		X								
65	Optimization of Indoor Thermal Performance Through Orientation and Vertical Greenery Percentage Analysis in High-Rise Residential, Malaysia	Hazril Sherney Basher, Ahmad Sanusi Hassan, Farhana Mohd Razif	2022	https://doi.org/10.37934/arfmts.100.3.6777	Vertical Greenery System; thermal performance; orientation; window wall ratio; energy saving	Simulation-based assessment of façade orientation and vegetation coverage effects on indoor temperatures and cooling energy demand in an eighth-floor residential condominium unit in Penang, Malaysia.	IESVE simulations comparing north, south, east and west façade orientations and 0%, 45% and 100% vegetation coverage, quantifying indoor temperatures and annual cooling energy demand.	X			In Penang, Malaysia, east-facing greenery achieved 1.43 °C temperature reduction and 17.1% cooling energy savings. Full west-facing coverage achieved 1.42 °C reduction and 16.9% savings, slightly outperforming 45% coverage.		X		X								
66	A comparative study on green wall construction systems, case study: South valley campus of AASTMT	Adel Samy El Menshawy, Abdelaziz Farouk Mohamed, Nayera Mahmoud Fathy	2022	https://doi.org/10.1016/j.cscm.2021.e00808	Urban sprawl; Carbon footprints; Albedo; Urban greening; Living architecture; Green walls	Comparative assessment of green wall construction technologies and conceptual design of a modular living wall intervention for the AASTMT South Valley campus in Aswan, Aswan Governorate, Egypt.	A conceptual planter-box living wall proposal featuring 0.75 m × 0.60 m × 0.30 m modular units, irrigation and anchoring details, supported by technical comparisons and architectural visualizations.			X	The Aswan, Egypt, design proposal envisaged 4765 m^2 of vegetated coverage against a 3250 m^2 site footprint, with expected thermal, environmental and visual improvements not verified through post-installation monitoring.	X			X	X	X	X	X		X	X	X
67	Effect of green wall installation on urban heat island and building energy use: A climate-informed systematic literature review	T. Susca, F. Zanghirella, L. Colasuonno, V. Del Fatto	2022	https://doi.org/10.1016/j.rser.2022.112100	Green wall; Green façade; Living wall; Vertical greenery; Urban heat island; Building energy use	Climate-informed systematic review of green façade and living wall impacts on building heating and cooling demand and urban heat island mitigation across different climate zones worldwide.	A PRISMA-based synthesis of 51 publications comprising 647 case studies, with statistical comparisons by climate, orientation, season, system type and urban configuration.	X			Across reviewed climates, green walls reduced heating demand by up to 16.5% and cooling demand by approximately 51%. Reported urban cooling reached about 5 °C, with some dense urban configurations reaching 8 °C.	X			X						X		

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
68	Early-stage design of a low-embodied carbon and cost-effective green facade system	Maricruz Solera Jimenez, João Cortesão, Sanda Lenzholzer, Ralf Walker	2023	https://doi.org/10.1016/j.jobe.2023.106588	Climate adaptation; Green facade system; Cost-effectiveness; Embodied carbon; Prototype	Iterative development of a low-carbon, cost-effective modular greenery system through product benchmarking, environmental and cost assessments, and structural and hydrological prototype testing in the Netherlands.	An early-stage modular green façade prototype, designed using BIM and 3D printing, incorporating recycled materials, optimized substrate, modular connections and evaluated structural and hydrological properties.			X	The research identified recycled materials, lightweight façade-based geometry, water-retentive substrates and modular connections as effective strategies for reducing embodied carbon and cost in a prototype.			X			X	X	X	X	X	X	X
69	Assessment of the potential of green wall on modification of local urban microclimate in humid tropical climate using ENVI-met model	George Thomas, Jobin Thomas, Gianny Mariya Mathews, Sachin P. Alexander, Jan Jose	2023	https://doi.org/10.1016/j.ecoleng.2022.106868	Urban microclimate; Green wall; ENVI-met; Thermal comfort; Building simulation	Modelling of green-wall effects on seasonal campus microclimates using ENVI-met calibrated with field measurements at Pathanamthitta, Kerala, India.	A validated ENVI-met comparison of existing campus conditions and a hypothetical green-wall scenario, estimating seasonal ambient air-temperature changes.	X			Simulated green walls reduced ambient air temperature by 1.3–1.6 °C in winter and 0.4–0.5 °C in summer, with local maximum reductions of 1.9 °C and 0.8 °C.		X		X			X					
70	Living wall plants are affected by and affect temperature: how to (not) measure plants' temperature in an Living wall experiment	Maren Stollberg, Alexander von Birgelen	2023	https://doi.org/10.20944/preprints202306.0856.v1	Plants; living wall; cooling effect; temperature; microclimate; vertical greenery systems; urban green infrastructure; climate change adaption; temperature sensor; thermal imaging	Experimental investigation of plant temperature, cooling effects, and measurement methods in textile-based living walls with different vegetation compositions, orientations, and sensor positions during a three-year trial in Geisenheim, Germany.	An experimental assessment of temperature measurement methods using sensors and infrared imaging, comparing planting variants, measurement distances, wall orientations, and microclimatic effects in textile-based living wall systems.		X		In Geisenheim, Germany, vegetation temperatures varied with air temperature, plant species, orientation, and sensor placement. Cooling effects were localized near living walls, highlighting measurement limitations and the importance of plant selection and experimental configuration.			X	X			X	X				
71	Experimental Assessment of the Thermal Influence of a Continuous Living Wall in a Subtropical Climate in Brazil	Murilo Cruciol-Barbosa, Maria Solange Gurgel de Castro Fontes, Maximiliano dos Anjos Azambuja	2023	https://doi.org/10.3390/su15042985	Vertical garden; green wall; thermal behavior; shading; thermal performance; green infrastructure	Experimental assessment of the thermal influence of a continuous living wall on external and internal façade surface temperatures, cavity air temperature, and thermal stability during summer in Bauru, São Paulo, Brazil.	A full-scale continuous living wall installed on an existing building, with field measurements comparing vegetated and bare façade sections, surface temperature variations, thermal delay, and cavity air conditions.		X		In Bauru, São Paulo, Brazil, the living wall reduced external surface temperatures by up to 10.6 °C and internal temperatures by 2.9 °C, increased thermal delay, and improved cavity temperature stability.			X	X			X	X				

Table A1. *Cont.*

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72	Vertical Greening Systems: A Perspective on Existing Technologies and New Design Recommendation	Peter J. Irga, Fraser R. Torpy, Daniel Griffin, Sara J. Wilkinson	2023	https://doi.org/10.3390/su15076014	Urban greening; green technologies; vertical greenery systems; green façade; green wall; living wall	Critical assessment of existing vertical greenery technologies and development of a conceptual hybrid façade system addressing structural limitations, plant diversity, maintenance accessibility, water management and environmental performance.	A conceptual Tessellated Double Green Perforated Façade combining modular growing substrates, fibre-reinforced concrete structural elements, integrated water recycling, maintenance access and interconnected openings supporting vegetation and urban biodiversity.			X	Building on comparisons of existing systems, the proposed unbuilt façade design could improve vegetation diversity, habitat connectivity, water efficiency, maintenance access and passive cooling, but these benefits remain theoretical and require experimental validation.			X	X	X	X	X	X		X		X
73	Green Façade to Improve Building Energy Performance in Summer and Winter	Fabiana Convertino, Ileana Blanco, Giuliano Vox, Evelia Schettini	2023	https://doi.org/10.1007/978-3-031-30329-6_116	Green Infrastructure; Heat Transfer; Shading; Thermal Barrier; Energy saving	Experimental evaluation of summer and winter thermal performance of a south-facing evergreen double-skin green façade compared with a bare wall, examining microclimatic conditions and heat transfer in Valenzano, Italy.	A two-year experimental assessment comparing vegetated and bare wall temperatures, radiation and convective heat exchanges, and daily energy savings using an instrumented prototype with Rhyncospermum jasminoides vegetation.		X		In Valenzano, Italy, the green façade achieved daily energy savings of 1.70 MJ/m^2 in summer and 0.07 MJ/m^2 in winter, providing solar shading, evapotranspirative cooling and reduced heat losses.		X		X									
74	Thermal Performance of Green Façades: Research Trends Analysis Using a Science Mapping Approach	Ileana Blanco, Fabiana Convertino	2023	https://doi.org/10.3390/su15139981	Building energy efficiency; energy saving; bibliometric analysis; thermal comfort; urban heat island effect; vertical greenery systems	Bibliometric investigation of scientific research on green façade thermal performance and urban microclimatic effects published between 1999 and 2022, identifying research trends, thematic clusters, international collaborations and knowledge gaps.	A science mapping analysis of 270 Scopus-indexed publications using VOSviewer, generating bibliometric networks, keyword clusters, publication trends and an overview of emerging research directions in green façade thermal performance.	X			The analysis identified 270 publications and three principal research clusters: thermal behavior and energy modeling, urban design and large-scale effects, and sustainable building management, revealing increasing multidisciplinary research activity.		X		X									

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
75	Moss as a Multifunctional Material for Technological Greenery Systems	Valeria Marsaglia, Guido Brusa, Ingrid Paoletti	2023	https://doi.org/10.15274/tpj.2023.08.01.3	bryophytes; green envelopes; moss; nature-based solutions; technological greenery	Qualitative literature review investigating moss biological characteristics, environmental functions and technological applications in living walls and building envelopes, including bioreceptive materials, biofiltration and bioelectricity generation.	A comparative overview of moss-based façade technologies, bioreceptive concrete panels, modular living walls and experimental architectural applications, identifying material properties, cultivation requirements and technological development opportunities.	X			The review identifies mosses as promising lightweight, water-retentive and low-maintenance greenery materials. Existing prototypes demonstrate opportunities for bioreceptive construction, modular façade systems, pollutant filtration and bioelectricity generation, although further validation is needed.			X			X	X	X		X	X	X
76	Evaluating the efficiency of a living wall facade as a sustainable energy-saving alternative in hot arid regions	Ayah Mohamed Ramadhan, Ayman Hassaan Mahmoud	2023	https://doi.org/10.1186/s44147-023-00259-9	Energy consumption; Living green wall; Saving energy; Thermal comfort; Hot; Arid climate	Simulation-based comparison of three vertical greenery configurations for reducing cooling demand and improving thermal comfort in a residential building in Al Rehab City, New Cairo, Egypt.	A DesignBuilder and EnergyPlus simulation comparison of a four-storey residential building, evaluating conventional façades against direct, indirect and planter-box greenery configurations.	X			In New Cairo, Egypt, simulated planter-box greenery achieved the lowest energy demand among the investigated configurations, with reported energy savings reaching approximately 75% relative to the reference case.	X			X		X						
77	Improving Indoor Environmental Quality—Measuring the Potential Contribution of Vertical Greenery Systems	Aini Jasmin Ghazalli, Cris Brack	2023	https://doi.org/10.6007/IJARBSS/v13-i7/17965	Green Building; Green Wall; Sustainable Cities; Environmental Quality; Retrofit	Integrative literature review examining how indoor and outdoor vertical greenery retrofits can improve indoor environmental quality and contribute to LEED, Green Star and Malaysian GBI certification criteria.	A comparative assessment of three green building rating systems, mapping potential vertical greenery contributions to indoor air quality, thermal comfort, acoustics, visual quality and certification credits.	X			The review identifies potential contributions of vertical greenery to indoor environmental quality criteria, particularly air quality, thermal comfort, acoustics and visual comfort, while noting that several certification requirements still need mechanical or managerial interventions.	X			X						X		
78	Responses to Viewing an Indoor Vertical Greenery System: A Case Study	Aini Jasmin Ghazalli, Cris Brack	2023	https://doi.org/10.6007/IJARBSS/v13-i7/17951	Human Response; Restorativeness; Vertical Greenery System; Indoor; Retrofitting	Experimental investigation of emotional, cognitive and behavioural responses to an indoor living wall at the Australian National University in Canberra, Australian Capital Territory, Australia, comparing onsite and photographic viewing.	An installed indoor pocket-based living wall assessed through onsite and online Short-Version Revised Restoration Scale surveys, supported by pedestrian traffic observations before and after installation.		X		In Canberra, Australia, respondents reported predominantly positive restorative experiences, with onsite viewing generally producing higher scores than photographic viewing. Findings suggest psychological benefits, although further validation is required.			X								

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
79	Property managers' awareness of the potential benefits of vertical greenery systems on buildings	Ayodele Samuel Adegoke, Job Taiwo Gbadegesin, Timothy Oluwafemi Ayodele, Samson Efuwape Agbato, Joseph Bamidele Oyedele, Timothy Tunde Oladokun, Emmanuel Onyinyechukwu Ebede	2023	https://doi.org/10.1080/15623599.2022.2095196	Fuzzy synthetic evaluation; green façade; green wall; property managers; sustainability; vertical greenery systems	Survey-based assessment of property managers' awareness of environmental, social and economic benefits associated with vertical greenery systems in Lagos, Lagos State, Nigeria.	A questionnaire dataset of 121 valid responses, analysed through descriptive statistics and fuzzy synthetic evaluation to determine professional awareness levels across 16 potential greenery benefits.		X		In Lagos, Nigeria, property managers showed limited overall awareness of vertical greenery benefits (2.60/5), with environmental, social and economic awareness scores of 2.65, 2.58 and 2.53, respectively.	X										
80	Living Walls in The City: Community Values and Expectations	R. A. Bustami, R. Rawlings, S. Beecham, J. Ward, D. Y. S. Mah	2023	https://doi.org/10.30880/ijie.2023.15.06.009	Green infrastructure; living wall; urban heat island	Survey-based investigation of community values, owner motivations and perceived benefits and costs of living walls, involving local government authorities and building owners and managers in Australia.	Survey findings from 19 local government authorities and 20 living wall owners and managers, addressing social acceptance, aesthetics, implementation expectations and perceived opportunities and barriers.		X		Australian survey respondents associated living walls with strong aesthetic and social value, indicating positive acceptance of vertical greenery. The available excerpt does not provide detailed quantitative findings.			X								
81	Optimisation of Building Green Performances Using Vertical Greening Systems: A Case Study in Changzhou, China	Yue Yang, Kai Hu, Yibiao Liu, Zhihuang Wang, Kaihong Dong, Peijuan Lv, Xing Shi	2023	https://doi.org/10.3390/su15054494	Vertical greening system (VGS); building green performance; real-time monitoring; thermal environment; indoor air quality; energy conservation	Experimental evaluation of indoor and outdoor vertical greenery effects on thermal comfort, indoor air quality and electricity consumption in an operational green-certified building in Changzhou, Jiangsu Province, China.	A 90-day Internet of Things monitoring dataset comparing four indoor locations, supplemented by energy-consumption comparisons and documentation of external and internal planted wall installations.		X		In Changzhou, China, indoor temperatures decreased by up to 0.7 °C, PM10 by 20.7% and formaldehyde by 33.3%. Annual electricity consumption was approximately 25% below comparable buildings.			X	X						X	
82	Economical sustainability of vertical greeneries in tropical climate	G.D.C. Jayakody, K.G.N.H. Weerasinghe, G.Y. Jayasinghe, R.U. Halwatura	2023	https://doi.org/10.1016/j.enbuild.2023.113580	Cost-benefit analysis; DesignBuilder; Net present value; Internal rate of return	Economic comparison of direct green façades, indirect green façades and living walls using simulated cooling savings and local installation and maintenance costs for a Colombo, Western Province, Sri Lanka, office building.	A DesignBuilder-based energy and cost–benefit model evaluating three vertical greenery types through net present value, internal rate of return, payback period and benefit–cost ratios under three economic scenarios.	X			In Colombo, Sri Lanka, simulated cooling savings reached 12.93%, 15.36% and 26.76% for direct façades, indirect façades and living walls. Direct façades were economically viable, whereas living walls showed negative net present values.	X			X				X				

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
83	Sustainable Design of Vertical Greenery Systems: A Comprehensive Framework	Mitra Manouchehri, Joaquín Santiago López, Mercedes Valiente López	2024	https://doi.org/10.3390/su16083249	Vertical greenery system; green wall; green facade; living wall; decision making	Comparative investigation of VGS classification approaches and design criteria to establish a comprehensive framework for selecting appropriate green façades and living walls.	A comprehensive classification and decision-making framework derived from 15 original VGS classification studies, incorporating construction technology, installation, vegetation, performance and maintenance considerations.	X			The framework integrates previously fragmented VGS classifications and provides structured technological and design criteria to support informed system selection across varying project conditions.	X				X	X	X	X				X
84	A Systematic Review of Economic Sustainability of Vertical Greenery Systems in Buildings	Irfan Haider Khan, Taiyaba Munawer	2024	https://doi.org/10.5130/AJCEB.v24i1/2.8710	Vertical Greenery System; Living Walls; Green Facades; VGS Benefits; Economic Sustainability; Economic Performance	Systematic review of the economic viability of green façades and living walls, analysing installation, maintenance, replacement costs and financial performance across 17 published studies.	A comparative evidence synthesis of lifecycle costs, net present values, internal rates of return and payback periods, including inflation-adjusted cost comparisons for different VGS technologies.	X			The review found that energy savings and property-related benefits can offset VGS costs in some cases, while high initial expenditure, lengthy payback periods and negative net present values limit viability.	X							X				
85	A review on the mechanisms behind thermal effect of building vertical greenery systems (VGS): methodology, performance and impact factors	Meifang Su, Pengyu Jie, Peixian Li, Feng Yang, Zishuo Huang, Xing Shi	2024	https://doi.org/10.1016/j.enbuild.2023.113785	Vertical greenery systems (VGS); Mechanisms; Methodology; Performance; Impact factors; Thermal effects	Review of thermal mechanisms, research methods and design factors influencing green façades and living walls, based on experimental and numerical literature.	A structured synthesis of VGS research methods, shading, evapotranspiration, insulation and wind-barrier effects, including design recommendations.	X			Shading is identified as the dominant cooling mechanism, contributing approximately twice as much as evapotranspiration; plants, substrate, climate and VGS configuration strongly affect performance.	X			X	X	X	X					
86	Technological Greenery. Exploring cutting-edge solutions for performant Greenery integration in building envelope design	Valeria Marsaglia	2024	https://doi.org/10.1016/j.enbuild.2024.114920	Technological Greenery; Building Envelope Design; Vertical Greening Systems; Green roofs; Regenerative design; Green building	Review of innovative greenery technologies integrated into building envelopes, including vertical greenery, green roofs and hybrid solutions for multiple ecosystem services.	An illustrated catalogue of technological greenery solutions classified by primary functions: thermal insulation, air purification, electricity generation and food production.	X			The review maps multifunctional technological options and performance evidence, showing how vegetation can be integrated with building-envelope technologies for regenerative design.	X			X	X	X				X		

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
87	Assessing the Impact of Vertical Greenery Systems on the Thermal Performance of Walls in Mediterranean Climates	Francesco Nocera, Vincenzo Costanzo, Maurizio Detomaso, Gianpiero Evola	2024	https://doi.org/10.3390/en17205090	Green façade; dynamic simulations; thermal inertia; indoor thermal comfort; TRNSYS; heavyweight wall	Dynamic simulation of indirect green façade effects on lightweight, Poroton and lava-stone walls using a validated experimental module in Catania, Sicily, Italy.	A TRNSYS model comparing three building-wall configurations with and without vegetation, evaluating interior surface temperatures, heat flux fluctuations and thermal inertia under Mediterranean conditions.	X			In Catania, Italy, simulations showed that greenery reduced peak interior surface temperatures of heavyweight walls by up to 1.0 °C, with stronger relative benefits for lightweight construction.		X		X								
88	Reducing Glare on Building Facade by Implementing Vertical Greenery Shading—user-sensation vs. luminance-measurement	Luciana Kristanto, Sri Nastiti Nugrahani Ekasiwi, Asri Dinapradipta	2024	https://doi.org/10.1051/e3sconf/20245190 3023	Not indicated	Experimental assessment of visual discomfort and window luminance using hanging vegetation of two leaf densities in a mock-up office workspace in Surabaya, East Java, Indonesia.	A comparative dataset of luminance measurements and glare sensation votes from 32 participants under unshaded windows and Vernonia elliptica shading at LAI 0.75 and 1.5.		X		In Surabaya, Indonesia, vegetation with LAI 1.5 reduced window luminance by 54.3–56.1%, improving reported glare comfort. LAI 0.75 reduced direct-light luminance by 35.3–53.6%.		X					X					
89	Assessing light performance of vertical greenery shading in tropical climate	Luciana Kristanto, Sri Nastiti Nugrahani Ekasiwi, Asri Dinapradipta	2024	https://doi.org/10.1088/2515-7620/ad277b	leaf area index; vertical greenery system; light performance; facade shading; tropical climate	Experimental assessment of the relationship between foliage density, daylight illuminance and window luminance using Vernonia elliptica shading on west- and north-facing glazed test boxes in Surabaya, East Java, Indonesia.	Comparative illuminance and luminance measurements from two 1 m cubic test boxes, testing uncovered glass and vegetation with leaf area indexes of 0.6, 1.16 and 1.7.		X		In Surabaya, Indonesia, denser Vernonia elliptica foliage reduced transmitted daylight and window luminance more effectively, particularly at low solar altitudes, confirming leaf area index as a significant shading parameter.		X					X					
90	Exploratory Analysis of a Novel Modular Green Wall's Impact on Indoor Temperature and Energy Consumption in Residential Buildings: A Case Study from Belgium	Milana Radujković, Alexis Versele, Hilde Breesch	2024	https://doi.org/10.3390/en17215267	Energy-efficient design; vertical greenery systems; modular green wall; building performance simulation	Assessment of summer cooling, winter insulation and energy consumption of an existing wastewater-purifying modular living wall through field monitoring and validated DesignBuilder simulations in a residential building in Ghent, Belgium.	A validated DesignBuilder energy model and experimental temperature measurements assessing the thermal performance of a modular living wall comprising 40 steel-framed panels with geotextile substrates and integrated irrigation.	X			In Ghent, Belgium, simulations showed indoor operative temperature reductions up to 3.5 °C in summer and increases of 1.4 °C in winter, with estimated annual heating energy savings of 6%.			X	X		X						X

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type					Topics						
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
91	Use of Vertical Greenery Systems for the domestic scale treatment of greywaters for fit-for-purpose reuse. Applicability and future prospects.	Ruggero Todesco	2024	https://doi.org/10.1088/1755-1315/1402/1/012018	Greywater reuse; Vertical Greenery Systems; Domestic wastewater reuse	Design and feasibility assessment of modular vertical greenery systems for decentralized domestic greywater treatment and non-potable reuse across residential building typologies in Southern Italy, including water balances and economic assessments.	A conceptual modular living wall treatment system with detachable planted containers, metal supporting structure, greywater pre-treatment, recirculation tanks, pumps and piping, supported by residential water balance and cost assessments.			X	Southern Italian residential water balance estimates indicate that the proposed system could meet non-potable water demand. Estimated investment payback periods range from 14 years in Catanzaro to 18–19 years in L'Aquila, Italy.			X			X		X		X	X	X
92	Investigating the Effect of Living Walls on Cooling Energy Consumption in Various Urban Microclimates, Building Heights, and Greenery Coverage Areas	Vahid Bakhtyari, Kaveh Fattahi, Khosro Movahed, Anna Franz	2024	https://doi.org/10.3390/su16020920	Living wall; coupling simulation; urban microclimate; cooling energy consumption; greenery coverage	Simulation-based evaluation of living wall effects on cooling energy consumption and outdoor microclimates across different building heights and vegetation coverage scenarios in Shiraz, Fars Province, Iran.	A coupled ENVI-met and EnergyPlus simulation framework comparing vegetated and unvegetated urban blocks with 48 residential buildings, assessing ambient temperatures, greenery coverage and building cooling energy demand.	X			In Shiraz, Iran, simulated living walls reduced ambient air temperature by an average of 1.35 °C and up to 2.25 °C, achieving cooling energy savings up to 15%, including a 4.3% microclimate contribution.			X	X						X		
93	Living Walls and Green Façades: An Implementation Code for Energy Simulation	Valeria Nesci, Ilaria Ballarini, Pietro Rando Mazzarino, Vincenzo Corrado	2024	https://doi.org/10.3390/buildings14072040	Vertical greenery systems (VGSs); green façade; living wall; numerical modelling; building energy simulation; EnergyPlus	Development of enhanced mathematical models for green façades and living walls, integrating vegetation and substrate heat transfer processes into EnergyPlus to assess building thermal performance.	Two Python (version 3.8) plugins implementing green façade and living wall heat balance models in EnergyPlus, tested through an adapted ASHRAE 140 BESTest building simulation.	X			Simulation results demonstrated that integrating detailed vegetation and substrate heat balances into EnergyPlus enables assessment of green façade and living wall cooling benefits, supporting more accurate building energy modelling.	X			X	X							
94	Sustainability Assessments of Living Walls in the Mediterranean Area	Francesco Barreca, Giuseppe Davide Cardinali, Roberto Bruno, Natale Arcuri	2024	https://doi.org/10.3390/buildings14103222	Living wall; sustainability; nature-based solution; energy performance; LCA	Comparative energy and life cycle assessment of four vertical greenery configurations applied to a four-storey university residential building under construction in Reggio Calabria, Calabria, Italy.	EnergyPlus building simulations and cradle-to-grave life cycle assessment using One Click LCA, comparing four planted façade configurations against a reference building without vertical greenery.	X			In Reggio Calabria, Italy, the best annual solution achieved 24% energy savings, while life cycle assessment indicated approximately 210,000 kg CO_2eq reduction compared with the reference building.			X	X		X				X	X	

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type				Topics							
								Theo-reti-cal/Soft-ware Simu-lation	Exp. in Real-World Condi-tions	De-sign/Con-ceptual-iza-tion/Cre-ation of VGS		VGS	GF	LW	Ther-mal Bene-fits	Clas-sifica-tion	Tech. Con-figu-ra-tion	Vege-ta-tion	Main-te-nance	LCA	Env. Bene-fits	Mod-ular-ity & Ind.	Sup-port/An-choring
95	Optimising vertical greening systems for sustainabil-ity: an integrated design approach	Ensiyeh Farrokhirad, Marina Rigillo, Manfred Köhler, Katia Perini	2024	https://doi.org/10.1080/14786451.2024.2411831	Sustainable green wall; climate adaptation; integrated design approach; urban resilience	Investigation of gaps in vertical greenery design practices through scientific literature, international guidelines and interviews with producers, addressing environmental, social and economic sustainability throughout system development.	A proposed Vertical Greening Integrated System (VGIS) design framework organizing pre-design, design, construction, maintenance, monitoring and disposal into coordinated decision-making phases.	X			The study identified inadequate performance objectives, neglected pre-design assessments, insufficient monitoring and limited user involvement. Its six-phase framework integrates technical, environmental and socioeconomic criteria for more sustainable VGS design.	X				X	X	X	X		X		
96	The effect of vertical greenery systems on building energy per-formance: Overall thermal transfer value-based comparative analysis	R.A.A. Munsif, Harshini Mallawaarachchi, Dimuthu Vijerathne	2025	https://doi.org/10.31705/WCS.2025.100	Building Energy Performance; High-rise Buildings; Overall Thermal Transfer Value; Tropical climate; Vertical Greenery System	Comparative evaluation of vertical greenery effects on high-rise building envelope performance using Overall Thermal Transfer Value calculations for two buildings in Colombo, Sri Lanka.	An OTTV-based comparative assessment quantifying differences in building envelope thermal performance between a high-rise building incorporating vertical greenery and a conventional high-rise building.	X			The analysis in Sri Lanka found average OTTV values of 3.681 W/m^2 without VGS and 3.527 W/m^2 with VGS, corresponding to a 4.18% reduction.	X			X								
97	The effect of vertical façade greenery in virtual urban envi-ronments on human emotion	Delia Lendenmann, Sara Irina Fabrikant	2025	https://doi.org/10.5194/agile-giss-6-34-2025	Urban; UNSDG 11; vertical green space; emotion; experiment; virtual reality	Controlled investigation of emotional responses to simulated green and conventional urban façades using immersive virtual reality and physiological measurements at the University of Zurich, Zurich, Switzerland.	A virtual reality experiment involving 34 analysed participants, five urban scenes, self-reported emotional ratings and electrodermal activity measurements comparing vegetated and non-vegetated façades.		X		In Zurich, Switzerland, participants viewing virtual vegetated façades reported lower arousal and greater relaxation than participants viewing conventional façades, supporting potential emotional benefits of urban greenery.		X										
98	Benefits and barriers of vertical greenery systems in Delhi: Evaluating design pro-fessionals' perceptions	Irfan Haider Khan, Taiyaba Munawer	2025	https://doi.org/10.1007/s44274-025-00248-0	Built environment; Climate change mitigation; Green facades; Green walls; Living walls; Nature-based solutions	Empirical survey of architects, landscape architects, urban planners and VGS vendors investigating perceived benefits, implementation obstacles and adoption attitudes in Delhi National Capital Region, India.	A statistical assessment of 390 professional questionnaires using descriptive analysis, exploratory factor analysis and non-parametric tests, identifying perceived benefits and barriers to VGS adoption		X		In Delhi, India, respondents recognized environmental and thermal benefits but identified high costs, maintenance requirements and weak regulatory support as principal barriers to VGS adoption.	X							X		X		

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
99	Fully exploiting solar energy with building envelops: Experimental study on an adjustable photovoltaic green facade	Chunying Li, Jixing Xie, Ruixue Liu, Junyi Tan, Xiaojiao Zhu, Na Li, Haida Tang	2025	https://doi.org/10.1016/j.enbuild.2025.115431	Adaptive photovoltaic green facade; Solar energy; Distributed renewable energy utilization; Building energy saving	Experimental evaluation of an adjustable photovoltaic shading system combined with climbing vegetation, using three comparative test boxes in Shenzhen, Guangdong, China.	A built adjustable photovoltaic green-façade prototype and comparative thermal, daylight and photovoltaic power measurements against green-only and bare façades.			X	The hybrid system reduced average window temperature by 5.2 °C and interior air temperature by 7.7 °C; tracked PV operation increased daily power generation relative to fixed angles.		X		X		X				X		
100	Towards a Regenerative and Climate-Resilient Built Environment: Greening Lessons from European Cities	Francesco Sommese, Lorenzo Diana, Simona Colajanni, Marco Bellomo, Gaetano Sciuto, Grazia Lombardo	2025	https://doi.org/10.3390/buildings15111878	urban resilience; green infrastructure; nature-based solutions; best practices; regenerative design	Critical review of urban greening policies, plans and case studies across European cities, examining green roofs, façades and open spaces for climate resilience.	A comparative framework of European policies and selected urban best practices, providing planning lessons for regenerative and climate-resilient cities.	X			Greening interventions offer multiple environmental and social benefits, but effective implementation depends on integrated planning, stakeholder cooperation, financial support and scalability.	X									X		
101	Numerical Analysis on the Cooling Performance of Vertical Greening as Natural Shading Devices	Ratih Widiastuti, Iqbal Firmansyah, Alaya Fadlu Hadi Mukhammad, Juliana Zaini, Dina Shona Laila	2025	https://doi.org/10.1051/e3sconf/202567405002		Numerical investigation of green façade cooling performance through ANSYS Fluid Fluent (ANSYS 2024R2) CFD simulations, evaluating indoor air and exterior wall surface temperatures and comparing predictions with previously published experimental measurements.	A CFD-based thermal model of a vegetated building envelope, incorporating material properties, airflow boundary conditions, mesh sensitivity analysis and validation against previous experimental temperature datasets.	X			CFD simulations indicated indoor air temperature reductions of up to 2.5 °C and exterior wall surface temperature reductions of 4.4 °C, with deviations from previous experimental measurements generally within 1.5 °C.		X		X								
102	Nature-Based Solutions for Urban Buildings—The Potential of Vertical Greenery: A Brief Review of Benefits and Challenges of Implementation	Ifigeneia Theodoridou, Katerina Vatitsi, Maria Stefanidou, Vachan Vanian, Theodora Fanaradelli, Makrini Macha, Adamantis Zapris, Violetta Kytinou, Maristella Voutetaki, Theodoros Rousakis, Giorgos Mallinis, Constantin Chalioris	2025	https://doi.org/10.3390/urbansci9100398	Vertical forests; living walls; green walls; vertical greening system; green building; barriers; risks; advantages; disadvantages; services	Narrative literature review examining environmental, thermal, social and economic benefits of vertical greenery systems alongside maintenance, structural safety, implementation risks and policy barriers affecting urban buildings.	An integrated literature evaluation framework synthesizing more than 150 publications, organizing vertical greenery benefits, risks, financial constraints, technological limitations and implementation recommendations for sustainable urban development.	X			The review identifies substantial environmental and thermal benefits but highlights maintenance costs, structural deterioration, vegetation failures, fire safety and regulatory gaps as barriers requiring integrated design, monitoring and coordinated urban policies.	X			X			X	X		X		

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type			Topics								
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
103	Thermal modeling of living walls: A review	Eva Zavrl, Tej Žižak, Primož Poredoš, Ciril Arkar	2025	https://doi.org/10.1016/j.rser.2024.115009	Living walls; Mathematical model; Heat transfer; Evapotranspiration; Green roofs; Water balance; Thermo-physical properties	Critical review of mathematical heat and mass transfer models for living walls, examining foliage, growing media, moisture distribution, air cavities and building-envelope thermal response.	A unified comparative framework of existing living wall thermal models, identifying calculation assumptions, validation limitations and research gaps in radiation, convection, evapotranspiration and water balance.	X			Existing living wall models frequently oversimplify moisture distribution, vertical radiation exchange and air cavity behavior. Improved boundary conditions, material property modelling and experimental validation are needed for reliable thermal predictions.			X	X	X	X	X					
104	The Effect of Climate on Thermal Loads in Living Walls	Rosmina A. Bustami, Simon Beecham, James Hopeward, Martin Belusko, Ahmad A. M. Khairulzaim	2025	https://doi.org/10.3390/environments12030078	Urban heat island; living wall; thermal load; nature-based solutions; green wall; green infrastructure; vertical garden; sustainable drainage systems	Simulation-based assessment of living wall effects on residential heating and cooling loads across seven Australian cities, examining climatic influences, shading, evapotranspiration and comparison with conventional passive design strategies.	Calibrated AccuRate Sustainability simulation models for two residential building designs, quantifying living wall energy performance under different climates, orientations and thermal boundary conditions.	X			Australian simulations showed potential cooling savings of 10–16% in idealized scenarios but below 1% for typical homes. Benefits were greatest in Perth and Adelaide, while colder climates showed increased heating demand.			X	X								
105	Assessment of Seismic Performance and Structural Health Monitoring of a Retrofitted Reinforced Concrete Structure with Polyurethane-Based Interventions and Vertical Greenery Systems	Theodoros Rousakis, Vachan Vanian, Martha Lappa, Adamantis G. Zapris, Ioannis P. Xynopoulos, Maristella E. Voutetaki, Stefanos Kellis, George M. Sapidis, Maria C. Naoum, Nikos A. Papadopoulos, Violetta K. Kytinou, Martha Karabini, Athanasia Thomoglou, Constantin E. Chalioris	2025	https://doi.org/10.3390/polym17233104	Vertical forest; seismic retrofitting; structural health monitoring (SHM); piezoelectric sensors (PZT); renovation; seismic polymer joint; fiber rope; resilient design	Experimental seismic assessment of a retrofitted reinforced concrete frame incorporating simulated living wall structures and concrete planters, testing anchoring configurations under progressively increasing earthquake excitation in Xanthi, Greece.	Shake-table test results comparing eight simulated living wall connections and five planter anchoring arrangements, supported by accelerometers, strain gauges, displacement sensors and piezoelectric structural health monitoring.		X		In Xanthi, Greece, the retrofitted frame withstood seismic excitation up to 1.40 g and 2.62% drift without collapse. Living wall frames remained stable despite localized anchorage damage; steel-rod planter anchoring performed best.			X			X					X

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type				Topics							
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
106	Evaluating vertical greenery systems for thermal comfort in composite climates: insights from a case–control experiment in Delhi, India	Irfan Haider Khan, Taiyaba Munawer	2025	https://doi.org/10.1108/USS-12-2024-0077	Vertical greenery systems; Green facade; Thermal comfort; Composite climate; Urban sustainability; Delhi	Experimental assessment of a direct green façade's effects on surface temperatures, indoor air temperature, humidity and adaptive thermal comfort during the monsoon season in Delhi, India.	A case–control monitoring dataset comparing a mature vegetated façade with a bare wall from June to September 2023, evaluated through three adaptive thermal comfort models.		X		In Delhi, India, the façade reduced external surface temperatures by up to 16.6 °C and indoor air temperatures by up to 5 °C, while indoor humidity reached 81%, potentially affecting comfort.		X		X							
107	Benefits and monetary values of vertical greening systems: A semi-systematic review	Sini Chen, Francesca Olivieri, Liping Peng, Jing Li	2025	https://doi.org/10.1016/j.buildenv.2025.113463	Vertical greening systems; Living walls; Green facades; Benefits; Monetary values; Mechanisms	Semi-systematic review of 132 studies assessing environmental, building-scale and individual benefits of green façades and living walls, alongside economic valuation methods and influencing performance factors.	A comparative synthesis of VGS benefits and monetization approaches, ranking economic returns and proposing system-selection recommendations for renovations, new buildings and greywater integration.	X			Water management and wall longevity showed the greatest economic benefits. Living walls generally delivered stronger benefits, but direct green façades were the only systems consistently producing positive net economic returns.	X			X			X	X		X		
108	Systematic review of plant selection in vertical greenery systems for urban sustainability: Current research, knowledge gaps, and future directions	Miktha Farid Alkadri, Aprilia Yolanda, Raisa Putri Alifa, Ricky Purbaya, Dalhar Susanto, Noor Fajrina Farah Istiani, Muhammad Suryanegara	2025	https://doi.org/10.1016/j.enbuild.2025.116136	Vertical Greenery Systems (VGS); Plant selection; Plant species; Performances; Green Façade	Systematic review of plant selection strategies for green façades and living walls, examining botanical characteristics, climate adaptability, maintenance technologies and urban sustainability performance across 98 selected studies.	A structured literature synthesis and ATLAS.ti thematic coding framework identifying plant selection factors, species-performance relationships, maintenance technologies and future research priorities for vertical greenery applications.	X			The review identified plant adaptability, leaf characteristics, irrigation, substrate management and species selection as critical to VGS performance, recommending climate-appropriate vegetation and integrated maintenance strategies to improve long-term sustainability.	X			X			X	X		X		
109	Development and environmental evaluation of magnesia-based bioreceptive panels for vertical green facades	Jae Heun Lee, Sung Rok Oh, Neung Won Yang	2025	https://doi.org/10.1016/j.conbuildmat.2025.141890	Magnesia composites; Bioreceptive concrete; Moss; Vertical greening systems; CO_2 reduction; Fine dust reduction	Development and experimental evaluation of magnesia-based bioreceptive panels incorporating moss, investigating material composition, bioreceptivity, mechanical properties and air pollution mitigation under laboratory and outdoor conditions in South Korea.	Optimized magnesium phosphate cement panels containing foaming agents and superabsorbent polymers, tested for workability, compressive strength, moss attachment, moisture retention, carbon dioxide and particulate matter reduction.			X	Laboratory tests showed that moss-covered magnesia panels reduced CO_2 concentrations by up to 40% and fine dust by 30%. Short-term outdoor testing supported their potential for vertical greening applications.			X		X	X	X			X		

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
110	Efficiency of tropical plants and smart green wall on reduction of fine particulate matters (PM2.5 and PM0.3–1.1) in a closed-system chamber	Janjira Muenrew, Sarayut Rakarcha, Anchalee nuammee, Prateep Panyadee, Wittaya Tala, Nuttipon Yabueng, Somporn Chantara	2025	https://doi.org/10.1016/j.eti.2025.104268	Smart green wall; Air pollution reduction; PM2.5; Phytoremediation; Particle count	Development and laboratory evaluation of an IoT-enabled smart green wall using ten tropical plant species to remove smoke-derived fine particulate matter in controlled chambers in Chiang Mai, Thailand.	A smart vertical planting prototype with 191 potted plants, structural frame, water storage and automated controls, tested alongside individual species for particulate matter reduction.			X	In controlled tests in Chiang Mai, Thailand, PM2.5 fell from 300 to 89 $\mu g/m^3$ with the smart wall versus 121 $\mu g/m^3$ without it after one hour; real-world effectiveness remains unverified.			X			X	X	X		X			X
111	Integration of Vertical Greenery in Existing Buildings. Design and Application of a Construction System	Gaetano Sciuto, Livia Lauria, Alessandro Lo Faro, Grazia Lombardo, Angela Moschella	2025	https://doi.org/10.1007/978-3-032-06978-8_38	Sustainability; Climate change; Vertical Greenery System; Redevelopment	Design of an adaptable modular green façade support system for retrofitting post-war residential buildings, using morphological and dimensional analyses of the Monte Po neighborhood in Catania, Sicily, Italy.	The VGF4EB modular steel framework, comprising standardized tubular components, threaded joints, anchoring plates, planters, climbing supports and integrated irrigation, dimensioned for different existing building configurations.			X	The proposed system accommodates variations in floor heights, balcony projections and façade geometry through standardized interchangeable components, demonstrating design adaptability across residential building typologies in Catania, Italy.		X				X	X					X	X
112	Environmental impacts and benefits of vertical greenery systems in humid subtropical climate: A comprehensive life cycle perspective	Cleila Navarini Valdameri, Camila Ester Hollas, Karina Guedes Cubas do Amaral, Marcela Valles Lange, Alessandro Sanches-Pereira, Marcelo Bortoli, Débora Mela, Priscila Soraia da Conceição, Fernando Simon Westphal	2026	https://doi.org/10.1016/j.jclepro.2025.147351	Living walls; Green façades; Life Cycle Assessment; Recyclable materials; Urban buildings; Energy efficiency	Experimental and life cycle comparison of a living wall using recycled packaging-board planters, a trellis green façade and an unshaded room in Francisco Beltrão, Paraná, Brazil.	A comparative dataset of monitored thermal performance, seasonal energy savings and life cycle environmental impacts for living wall and green façade technologies employing different materials.		X		In Paraná, Brazil, living walls and green façades reduced summer energy use by approximately 18% and 9%, respectively. Life cycle results highlighted the environmental importance of recyclable construction materials.	X			X		X			X	X		
113	Seasonal thermal performance of geopolymer wall with phase change material and green façade: Southern Italy study	Rosa Francesca De Masi, Valentino Festa, Antonio Gigante, Silvia Ruggiero, Francesca Villano	2026	https://doi.org/10.1016/j.solener.2026.114372	Energy efficiency; Green façade; Passive cooling; Phase change material; Thermal buffering	Five-month experimental monitoring of a geopolymer wall with phase change material and modular green façade under real climatic conditions in Southern Italy.	Thermal measurements of conventional, PCM-enhanced and vegetated wall configurations, complemented by numerical assessments of annual energy performance.		X		The hybrid façade reduced heat fluxes by up to 3 W/m^2 and surface temperature amplitudes by 12%; PCM lowered indoor heat release by 16% in tested conditions.		X		X		X						

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
114	Assessing the energy performance of integrated living wall systems: a dynamic numerical model coupled with TRNSYS for building energy simulations	Roberto Bruno, Antonio Cristaudo	2026	https://doi.org/10.1016/j.enbuild.2026.117073	Living walls; Heat and mass transfer; Dynamic numerical simulations; BES; Building energy performances	Development and validation of a dynamic heat and moisture transfer model for living walls, assessing building energy performance under different façade orientations, irrigation rates and vegetation parameters.	A MATLAB-based living wall numerical model coupled with TRNSYS, validated against experimental temperature, heat flux and substrate moisture measurements and applied to dynamic energy simulations.	X			Simulations predicted cooling savings of 8 and 6 kWh/m^2 for south- and east-facing walls, respectively, and heating savings of 10 and 6 kWh/m^2 with summer-only irrigation.			X	X			X					
115	A comprehensive review of design parameters and performance indicators of vertical greenery systems in tropical climates	Kelly Loh, Ali Ghahramani	2026	https://doi.org/10.1016/j.enbuild.2026.117705	Environmental and societal benefits; Green infrastructure; Sustainable urban design; Tropical climate adaptation; VGS deployment strategies; VGS evaluation framework	Systematic review of outdoor vertical greenery performance in tropical climates, examining relationships between design parameters, thermal and environmental indicators, vegetation characteristics and system configurations across 35 experimental studies.	A standardized VGS evaluation framework identifying eight design parameters and twenty performance indicators, supported by cross-study comparisons, statistical tests and design recommendations for tropical environments.	X			Modular living walls generally provided stronger cooling, particularly on east- and west-facing façades, but involved greater maintenance and life-cycle costs. Denser foliage improved cooling while potentially increasing humidity.	X			X		X	X	X		X		
116	Vertical greening systems with native species: an ecological approach to urban air quality improvement	Caterina Dalsasso, Mattia M. Azzella, Maria Rosaria Bruno, Antonella Campopiano, Annapaola Cannizzaro, Federica Angelosanto, Serena Baiani, Romeo Di Pietro, Fabrizio Tucci, Roberta Zarcone	2026	https://doi.org/10.1016/j.enbuild.2026.117680	Biodiversity; Native species; Vertical greening systems; Green walls; Air quality; Ecosystem services	Experimental comparison of particulate matter retention by five native plant species naturally growing on urban walls at three locations in Rome, Lazio, Italy, assessing their suitability for future VGS applications.	A botanical species-selection approach supported by scanning electron microscopy, particle counting and statistical comparison of fine and ultrafine particulate matter accumulated on native plant leaves.		X		In Rome, Italy, Centranthus ruber showed the highest overall particulate retention, while Parietaria officinalis performed worst. Cymbalaria muralis and Capparis spinosa showed particularly effective capture of particles smaller than 1 micrometre.	X						X			X		
117	Adapting vertical greenery strategies to address climate change in China	Yu Bi, Ding Fan, Bin Zhu, Xiayan Liao, HuaQing Wang, Ahmed Mohsin Alsayah	2026	https://doi.org/10.1016/j.egyr.2026.109043	VGS; Biodiversity; Climate resilience; Water conservation (SDG 6); Urban sustainability	Multi-climate assessment of green façades and living walls across eight Chinese cities, integrating field measurements, remote sensing and modelling to examine cooling, biodiversity, air quality and water conservation.	An integrated comparison of modular, felt-based and cable-supported VGS, incorporating monitoring across 24 sites, irrigation strategies, biodiversity indicators and climate-specific implementation recommendations.		X		Across eight Chinese cities, VGS reduced surface temperatures by 2.5–7.3 °C. Smart irrigation reduced water use by 38–59%, while native and more diverse planting supported greater biodiversity.	X			X		X	X	X		X		

Table A1. *Cont.*

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								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
118	Urban heat mitigation with building-scale green technologies: vertical greenery systems, cool materials and building-integrated photovoltaics	Ruijun Zhang, Yuqing Lin, Weijun Li, Shaobo Wang, Shi-jie Cao	2026	https://doi.org/10.1016/j.enconman.2026.121097	Urban heat mitigation; Vertical greenery system; Cool materials; BIPV; Numerical modelling	Numerical comparison of vertical greenery, cool materials and building-integrated photovoltaics for urban heat mitigation, cooling demand and carbon emissions in a hypothetical urban block in Ningbo, Zhejiang Province, China.	A coupled EnergyPlus and ANSYS Fluent simulation framework evaluating three building-envelope technologies across 81 buildings, comparing microclimate, cooling loads, plant configurations and carbon outcomes under extreme heat.	X			In simulated extreme heat conditions in Ningbo, China, greenery and cool materials generally reduced thermal stress, while photovoltaics sometimes increased local warming. The VGS scenario increased estimated carbon emissions by approximately 6.6%.			X	X			X			X		
119	Life cycle based experimental study on fire mechanism of modern building facade	Zhen Ni, Ruiyi Tang, Hongtu Zhou, Denvid Lau, Cheuk Lun Chow	2026	https://doi.org/10.1016/j.jobe.2026.117202	Facade fire; Fire spread mechanisms; Multi-fuel interaction; Moisture effect; Vertical greenery systems	Experimental investigation of ignition, heat release, smoke production and vertical flame spread in modern façade systems, including vegetation under different moisture conditions, using representative scenarios associated with Hong Kong and London.	A comparative fire-behavior framework supported by cone calorimetry and laboratory-scale façade experiments, evaluating three plant species, moisture-dependent combustibility and interactions between façade materials and configurations.		X		Green vegetation delayed ignition through moisture retention, while dried plants supported sustained combustion and vertical flame spread. Fire behavior depended strongly on species and moisture content, emphasizing vegetation maintenance for façade safety.	X					X	X	X				
120	A Systematic Review of Vertical Greenery: Environmental Impacts, Architectural Innovations, and Future Directions	Yiming Shao, Ding Ding, Jingyang Zhao	2026	https://doi.org/10.3390/su18147153	Vertical greenery; environmental impact; indoor environmental quality; building energy consumption; biophilic design; practical innovations	Systematic review of indoor and outdoor vertical greenery, examining environmental performance, architectural innovations, technological developments and research trends through scientific literature, patent databases and built project examples.	A PRISMA-based synthesis of 71 research articles, 25 selected patents and 15 built projects, incorporating bibliometric analysis and a structured overview of technological innovations and future development directions.	X			The review identified established thermal and air-quality benefits alongside growing innovation in structural systems, intelligent management and architectural applications. It highlighted research gaps in long-term performance and emerging technologies.	X			X	X	X	X	X	X	X	X	X
121	Climate-adaptive energy performance of green facades in a composite climate	Irfan Haider Khan, Neda'a M. Jaradat, Taiyaba Munawer	2026	https://doi.org/10.1016/j.enbuild.2026.117393	Vertical greenery system; Direct green facade; Climate-adaptive design; Composite climate; Energy simulation; Climate resilience	Assessment of seasonal thermal and energy performance of a deciduous direct green façade using one-year field monitoring and calibrated building simulation in New Delhi, Delhi, India.	A seasonally calibrated Design-Builder/EnergyPlus simulation framework incorporating monthly foliage coverage, leaf area index and shading variations, validated against monitored temperatures and applied to annual energy and orientation scenarios.	X			In New Delhi, India, monitored summer reductions reached 3.2 °C on exterior surfaces and 2.2 °C indoors. Simulations predicted approximately 8% annual cooling savings for west-facing façades and 25% for all orientations.		X		X			X					

Table A1. *Cont.*

N	Title	Authors	Years	DOI	Keywords	Subject of the Study	Output of the Study	Analysis Type			Results	System Type				Topics							
								Theoretical/Software Simulation	Exp. in Real-World Conditions	Design/Conceptualization/Creation of VGS		VGS	GF	LW	Thermal Benefits	Classification	Tech. Configuration	Vegetation	Maintenance	LCA	Env. Benefits	Modularity & Ind.	Support/Anchoring
122	Impact of vertical greenery system on indoor air quality: Case study in a Luxembourg administrative building	C. Falzone, J. Martin, AC. Romain	2026	https://doi.org/10.1016/j.buildenv.2026.114318	Vertical greenery system (VGS); Indoor air quality; Volatile organic compounds; Mold; Formaldehyde	Experimental assessment of five indoor living walls in an operational administrative building in Luxembourg, examining formaldehyde, volatile organic compounds and airborne mold spores over 46 weeks.	A 46-week indoor air quality monitoring dataset comparing locations with and without living walls, assessing chemical pollutant reduction, fungal contamination and the influence of ventilation and maintenance.		X		In Luxembourg, living walls were associated with formaldehyde reductions of up to 40% in selected zones, while mold spores increased. Overall VOC reductions were inconsistent, highlighting ventilation and maintenance trade-offs.			X				X	X		X		
123	Structural Imbalance and Life-Cycle Cost Coverage in Vertical Greenery Systems: A Systematic Literature Review	Nitchaya Phatthanaphan, Tarid Wongvorachan, Duangkamon Wutisun, Sathirat Singkham, Sippakorn Petsirasan, Chaniporn Thampanichwat, Suphat Bunyarittikit, Sanawete Sirirat	2026	https://doi.org/10.3390/buildings16071353	Vertical greenery systems; life-cycle cost; cost analysis; systematic review; sustainable construction	Systematic literature review examining the distribution, integration and comparability of life-cycle cost components reported for vertical gardens and green façades across 136 scientific publications from 2021–2025.	A bibliometric and thematic assessment categorizing VGS expenditure into five cost groups, identifying reporting inconsistencies, fragmented cost coverage and gaps in comprehensive economic life-cycle evaluation.	X			Among 136 studies, 112 addressed installation and operation costs, 108 maintenance and only eight design costs. Just two covered all five cost categories, demonstrating fragmented economic life-cycle assessment.	X							X				
124	The Reduction of Building Energy Demand by a Living Wall System in a Central European Climate	Maria Hartmann, Hayder Alsaad, Morteza Mosayebzadeh, Conrad Voelker	2023	https://doi.org/10.26868/25222708.2023.1534	Living wall, Ventilated facade, Energy demand, Sensitivity analysis, EnergyPlus	Simulation-based investigation of heating and cooling energy savings from ventilated living walls on a residential building in Weimar, Germany, considering façade orientation, vegetation coverage and existing insulation levels.	A modified and validated EnergyPlus green wall model incorporating longwave ground radiation and ventilated cavities, enabling comparative simulations of building energy demand and conventional façade renovation strategies.	X			In Weimar, Germany, southeast-facing greenery reduced cooling demand by 10.6% and heating demand by 0.2%. Complete façade coverage achieved 22.6% cooling savings but only 0.24% annual energy savings.			X	X								
125	Thermal Performance of Living Walls for Passive Cooling in Contemporary Buildings	Agung Murti Nugroho, Hanief Ariefman Sani, Fernanda Ayuning Putri, Astari Hapsari Putri	2026	https://doi.org/10.32664/1cysws30	Air Temperature Reduction; Living Wall; Passive Cooling	Experimental comparison of living walls and conventional wooden shading in semi-outdoor hotel corridors in Surakarta, Central Java, Indonesia, assessing orientation, plant species and foliage density.	Seven-day field monitoring of air temperature and humidity, infrared surface temperature measurements, and comparative analyses of different planted wall configurations and wooden shading systems.		X		In Surakarta, dense Portulaca grandiflora and Epipremnum aureum vegetation reduced corridor air temperatures by approximately 0.9 °C, compared with 0.2 °C for Chlorophytum comosum; wooden shading sometimes performed better.			X	X			X				

References

1. UN-Habitat. Nairobi. Available online: https://unhabitat.org/ (accessed on 5 May 2026).
2. Gregorčič, T.; Ogrin, M.; Repe, B.; Savić, S. Combining interdisciplinary field measurements and ENVI-met simulations for comparative assessment of outdoor human thermal comfort across local climate zones. *Sustain. Cities Soc.* **2026**, *142*, 107304. [CrossRef]
3. Bibri, S.E. Data-driven smart eco-cities of the future: An empirically informed integrated model for strategic sustainable urban development. *World Futures* **2023**, *79*, 703–746. [CrossRef]
4. Gunapala, R.; Gangahagedara, R.; Wanasinghe, W.C.S.; Samaraweera, A.U.; Gamage, A.; Rathnayaka, C.; Hameed, Z.; Abdel Baki, Z.; Madhujith, T.; Merah, O. Urban agriculture: A strategic pathway to building resilience and ensuring sustainable food security in cities. *Farm. Syst.* **2025**, *3*, 100150. [CrossRef]
5. Chafer, M.; Perez, G.; Coma, J.; Cabeza, L.F. A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate. *Energy Build.* **2021**, *249*, 111236. [CrossRef]
6. Manso, M.; Castro-Gomes, J. Green wall systems: A review of their characteristics. *Renew. Sustain. Energy Rev.* **2015**, *41*, 863–871. [CrossRef]
7. Cruciol-Barbosa, M.; Fontes, M.S.G.C.; Azambuja, M.A. Experimental assessment of the thermal influence of a continuous living wall in a subtropical climate in Brazil. *Sustainability* **2023**, *15*, 2985. [CrossRef]
8. Perez, G.; Coma, J.; Sol, S.; Cabeza, L.F. Green facades for energy savings in buildings: The influence of leaf area index and facade orientation on the shading effect. *Appl. Energy* **2017**, *187*, 424–437. [CrossRef]
9. Vox, G.; Blanco, I.; Schettini, E. Green façades to control wall surface temperature in buildings. *Build. Environ.* **2018**, *129*, 154–166. [CrossRef]
10. Hunter, A.; Williams, N.; Rayner, J.; Aye, L.; Hes, D.; Livesley, S. Quantifying the thermal performance of green façades: A critical review. *Ecol. Eng.* **2014**, *63*, 102–113. [CrossRef]
11. Susca, T.; Zanghirella, F.; Colasuonno, L.; Del Fatto, V. Effect of green wall installation on urban heat islands and building energy use: A climate-informed systematic literature review. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112100. [CrossRef]
12. Koch, K.; Ysebaert, T.; Denys, S.; Samson, R. Urban heat stress mitigation potential of green walls: A review. *Urban For. Urban Green.* **2020**, *55*, 126843. [CrossRef]
13. Wang, R.; Helbich, M.; Yao, Y.; Zhang, J.; Liu, P.; Yuan, Y.; Liu, Y. Urban greenery and mental well-being in adults: Cross-sectional mediation analyses on multiple pathways across different greenery measures. *Environ. Res.* **2019**, *176*, 108535. [CrossRef] [PubMed]
14. Yeom, S.; Kim, H.; Hong, T. Psychological and physiological effects of a green wall on occupants: A crossover study in virtual reality. *Build. Environ.* **2021**, *204*, 108134. [CrossRef]
15. Viecco, M.; Vera, S.; Jorquera, H.; Bustamante, W.; Gironás, J.; Dobbs, C.; Leiva, E. Potential of particulate matter dry deposition on green roofs and living wall vegetation for mitigating urban atmospheric pollution in semiarid climates. *Sustainability* **2018**, *10*, 2431. [CrossRef]
16. Ottelé, M.; van Bohemen, H.D.; Fraaij, A.L.A. Quantifying the deposition of particulate matter on climbing vegetation on living walls. *Ecol. Eng.* **2010**, *36*, 154–162. [CrossRef]
17. Muenrew, J.; Rakarcha, S.; Nuammee, A.; Panyadee, P.; Tala, W.; Yabueng, N.; Chantara, S. Efficiency of tropical plants and smart green walls in reducing fine particulate matter (PM2.5 and PM0.3–1.1) in a closed-system chamber. *Environ. Technol. Innov.* **2025**, *39*, 104268. [CrossRef]
18. Su, J.G.; Jerrett, M.; de Nazelle, A.; Wolch, J. Does exposure to air pollution in urban parks follow socioeconomic, racial, or ethnic gradients? *Environ. Res.* **2011**, *111*, 319–328. [CrossRef] [PubMed]
19. Giuliano, W.M.; Accamando, A.K.; McAdams, E.J. Lepidoptera-habitat relationships in urban parks. *Urban Ecosyst.* **2004**, *7*, 361–370. [CrossRef]
20. Bahrami, P. *Green Walls in High-Rise Buildings*; Images Publishing Group: Mulgrave, VIC, Australia, 2014.
21. Nguyen, C.N.; Muttil, N.; Tariq, M.A.U.R.; Ng, A.W.M. Quantifying the benefits and ecosystem services provided by green roofs—A review. *Water* **2022**, *14*, 68. [CrossRef]
22. Manouchehri, M.; López, J.S.; López, M.V. Sustainable Design of Vertical Greenery Systems: A Comprehensive Framework. *Sustainability* **2024**, *16*, 3249. [CrossRef]
23. Küenzlen, M. *Ökologische Stadterneuerung*; C.F. Müller: Karlsruhe, Germany, 1984.
24. Wessolek, G. Stadtökologie. In *Stadtökologie*; Sukopp, H., Wittig, R., Eds.; Gustav Fischer: Stuttgart, Germany, 1998.
25. Köhler, M. Green Facades—A View Back and Some Visions. *Urban Ecosyst.* **2008**, *11*, 423–436. [CrossRef]
26. Köhler, M.; Grau, U. Experiences with Eco Architecture in Berlin: Lessons Learned from the 1980s for Today's Solutions. In *Multifunctional Urban Green Infrastructure*; Briz, J., Köhler, M., de Felipe, I., Eds.; Editorial Agrícola Española: Madrid, Spain, 2019; pp. 211–228.

27. Ogut, O.; Tzortzi, N.J.; Bertolin, C. Vertical green structures for creating a sustainable built environment: A systematic market review. *Sustainability* **2022**, *14*, 12349. [CrossRef]
28. Ottelé, M.; Perini, K.; Fraaij, A.L.A.; Haas, E.M.; Raiteri, R. Comparative life cycle analysis for green façades and living wall systems. *Energy Build.* **2011**, *43*, 3419–3429. [CrossRef]
29. Bustami, R.; Belusko, M.; Ward, J.; Beecham, S. Vertical greenery systems: A systematic review of research trends. *Build. Environ.* **2018**, *146*, 34–52. [CrossRef]
30. Yin, H.; Kong, F.; Middel, A.; Dronova, I.; Xu, H.; James, P. Cooling effect of direct green façades during hot summer days: An observational study in Nanjing, China using TIR and 3DPC data. *Build. Environ.* **2017**, *116*, 195–206. [CrossRef]
31. Urrestarazu, M.; Burés, S. Sustainable green walls in architecture. *J. Food Agric. Environ.* **2012**, *10*, 792–794. [CrossRef]
32. Manso, M.; Castro-Gomes, J. Thermal analysis of a new modular system for green walls. *J. Build. Eng.* **2016**, *7*, 53–59. [CrossRef]
33. Cortês, A.; Tadeu, A.; Santos, M.I.; de Brito, J.; Almeida, J. Innovative module of expanded cork agglomerate for green vertical systems. *Build. Environ.* **2021**, *188*, 107461. [CrossRef]
34. Li, C.; Xie, J.; Liu, R.; Tan, J.; Zhu, X.; Li, N.; Tang, H. Fully exploiting solar energy with building envelopes: Experimental study on an adjustable photovoltaic green facade. *Energy Build.* **2025**, *332*, 115431. [CrossRef]
35. Urban Jungle|Prato. Stefano Boeri Architetti. Available online: https://www.stefanoboeriarchitetti.net/project/prato-urban-jungle/ (accessed on 26 May 2026).
36. Sommese, F.; Diana, L.; Colajanni, S.; Bellomo, M.; Sciuto, G.; Lombardo, G. Toward a Regenerative and Climate-Resilient Built Environment: Greening Lessons from European Cities. *Buildings* **2025**, *15*, 1878. [CrossRef]
37. Sciuto, G.; Lauria, L.; Lo Faro, A.; Lombardo, G.; Moschella, A. Integration of Vertical Greenery in Existing Buildings: Design and Application of a Construction System. In *Envisioning the Futures: Designing and Building for People and the Environment*; Albatici, R., Dalprà, M., Gatti, M.P., Maracchini, G., Torresin, S., Eds.; Lecture Notes in Civil Engineering; Springer: Cham, Switzerland, 2025; Volume 765, pp. 706–728.

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