

Review

Nature-Based Solutions for Urban Buildings—The Potential of Vertical Greenery: A Brief Review of Benefits and Challenges of Implementation

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Abstract

The global rapid urbanization intensifies environmental challenges related to climate change, such as air pollution and the urban heat island (UHI) effect in built environments. The need to optimize nature-based solutions (NBSs) is imperative to mitigate climate change and adapt to extreme weather phenomena. Against this background, this review offers an analysis regarding the integration of vertical greenery systems (VGSs) into urban environments so as to capitalize on their environmental, social, and economic benefits. Key aspects of the review include the positive role of VGSs in UHI mitigation, air quality improvement, stormwater management, and biodiversity enhancement, while examining social aspects (i.e., improved well-being and mental health, noise reduction, and urban built aesthetics). Finally, parameters related to economic benefits and energy efficiency are assessed. The submission further analyses the significant challenges that VGSs face, such as high maintenance costs, structural risks, plant health issues, fire hazards, and other limitations (legislative and technical). The crucial need for interdisciplinary collaborations among urban planners, architects, environmental engineers, and stakeholders is highlighted, in order to successfully integrate VGSs into urban buildings. Thus, this paper aims to identify key strategies for optimizing VGSs' implementation and provide valuable insights for policymakers and researchers aiming to enhance urban sustainability through vertical greening.

Keywords: vertical forests; living walls; green walls; vertical greening system; green building; barriers; risks; advantages; disadvantages; services



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1. Introduction

According to the United Nations (UN), over 55% of the world population already resides in cities, a number expected to rise to nearly 70% by 2050, accommodating an additional 3 billion people. Rapid urbanization poses significant challenges for urban populations, which are exposed to climate hazards [1,2]. Hence, the effects of climate

change, such as high greenhouse gas (GHG) emissions, as well as the urban heat island (UHI) effect [3], threaten urban populations and lead to severe social problems, such as thermal vulnerability, low resilience, poverty, health problems, and more [4–7]. In the same line, urbanization reduces the availability of green spaces in cities, resulting in a number of environmental problems. Urbanization often results in the loss of natural habitats, a decline in biodiversity, and the disruption of ecological processes such as pollination and biological control [8]. These impacts can lead to an ecosystem service deficit where the demand for ecosystem services in urban areas surpasses the available supply from the remaining natural areas. For example, changes associated with urbanization affect mental [9] and physical well-being, like cardiovascular diseases [10]. Additional negative effects also include temperature increases and the associated UHI effect, where heat-absorbing materials, coupled with the waste heat generated by energy use, lead to higher temperatures in urban areas [11]. This further leads to increased energy consumption for cooling of urban buildings, human health issues, and thermal discomfort [12,13]. Taking into consideration that cities currently account for more than 70% of the global energy consumption and carbon emissions [14], the need for efficient strategies to tackle UHI phenomena in cities is imperative, especially considering that this share is expected to increase significantly due to the warming trend driven by climate change in the next years [15].

In addition to energy-related and decarbonization aspects, UHIs are linked to important social parameters, such as fuel poverty and poor indoor living conditions. The inability to cope with increased temperatures during summer periods in buildings is a threat for urban inhabitants globally [16], even in cities that are not necessarily located within traditionally warm climates [17]. It is characteristic that mean projected changes in annual death rates per 100,000 people, resulting from the impact of climate change on daily temperature, are constantly rising [18]. This phenomenon leads to increased cooling demands, which are mainly covered by electricity (air conditioning systems), exposing low-income households further to the risk of energy poverty. Related studies reveal that heatwaves can lead to a 42–103% rise in cooling demands in eastern Chinese cities; 215–350% in Sydney, Australia [19]; and 32% in European cities [20]. The European Environment Agency (EEA) highlights that rising temperatures, aging populations, and aged urban buildings contribute to extreme heat exposure and rising cooling demands. In response, Europe is prioritizing urban cooling strategies and passive cooling techniques to address cooling-related energy poverty [21].

In this line, nature-based solutions (NBSs) are considered to be the most efficient strategy for the UHI mitigation [22]. More specifically, the urgent requirement to tackle UHI has increased the demand for the inclusion of nature in urban life and encouraged cities to review their environmental and urban planning regulations, focusing on developing greener and more sustainable living spaces. In this context, the integration of greenery into the architectural renovation of existing building stocks helps to create spaces that generate positive emotional responses and promote the well-being of the occupants, recognizing the inherent human need to connect with nature [23], in addition to reduced energy needs.

The question remains if the available urban surfaces are enough to cover the needs of NBS integration into urban canopies. Hence, urban environments vary globally in terms of their structural characteristics, green space availability, and microclimatic conditions. But cities share a common characteristic almost everywhere in the world; at least 40% of buildings in developed economies were built before 1980, when the first thermal regulations came into force [24]. Thus, buildings account for 60% of overall carbon emissions globally [25], while in Europe, almost 75% of the building stock is currently energy inefficient, and more than 85% of today's buildings will still be in use by 2050 [26].

Within this context, this paper explores the potential of integrating greenery into urban buildings, to enhance their environmental and energy performance, while also promoting improved living conditions. Greenery can be applied in many different forms on buildings: horizontally and vertically, outdoors and indoors [27]. While horizontal spaces accommodate plants, vertical spaces offer even more possibilities, allowing vegetation to be integrated into buildings' façades. Vertical greenery systems (VGSs) offer a sustainable solution and refer to structures that support vegetation and can be either attached or independent from a building's façade or interior wall.

Unlike green roofs, which have established classifications (i.e., extensive, semi-intensive, and intensive), VGSs lack a standardized classification system, leading to confusion and misunderstandings. This issue is compounded by the use of varied terminology for similar VGS structures across the scientific literature [28]. Many terms are used interchangeably or inconsistently to describe the same VGS types. For instance, "vertical garden", "vertical greening system", "green vertical system", and "vertical greenery system" are all used to describe VGSs in general [29]. Different names are often given to the same VGS construction types, even in scientific publications. For example, a hydroponic system may be called a geotextile felt system, a vegetated mat wall, a continuous living wall system, or simply cloth in different sources [30].

Vertical greenery systems can be classified according to the complexity of their construction and maintenance, typically using the terms extensive and intensive [31]. Green façades are typically categorized as extensive systems since they are considered simpler to construct and require less maintenance compared with living walls. Living walls are classified as intensive systems due to their complexity and higher degree of maintenance (often including supporting structures, growing media, and irrigation systems) [31].

The primary aim of this manuscript is to provide a concise review of the advantages and disadvantages of VGSs in urban environments. Since there are numerous systematic reviews that have focused on specific aspects of VGSs such as their economic sustainability [32], rainwater and sewage treatment [33], noise reduction [34], air temperature [35], thermal behavior, and reduction in greenhouse gas emissions [28], the present study aims to provide a comprehensive overview of the most recent findings regarding the benefits and drawbacks of VGSs.

Specifically, it seeks to address the following research questions:

- (i) What are the environmental, social, and economic benefits of VGSs, including their role in mitigating UHI effects, improving air quality, managing stormwater, enhancing biodiversity, and reducing energy consumption?
- (ii) What are the key challenges and risks associated with VGSs, such as potential structural damage to buildings, plant health issues, fire hazards, and high maintenance costs?
- (iii) What strategies can be adopted to maximize the benefits of VGSs while minimizing their disadvantages, particularly within the framework of urban planning and sustainable development?

More specifically, the objective of this review paper is to critically assess the benefits and challenges related to vertical greenery system (VGS) integration into urban environments under environmental, social, and economic aspects. The analysis includes the recent literature focusing on highlighting both the benefits of vertical greenery systems (VGSs) and their limitations and risks, underlining the necessary policy measures that are crucial for their successful implementation. The paper is organized as follows: Section 2 presents the methodology and selection criteria of the literature search, while Section 3 presents findings on environmental, social, and economic benefits, as well as limitations and risks of VGS integration in urban built environments. Section 4 discusses typological differences and

regulatory challenges, as well as policy planning considerations, and Section 5 concludes with identified limitations of this review and future research directions.

2. Methodology

To review the benefits and challenges of vertical greenery systems (VGSs), a two-step methodological approach was applied. First, a targeted literature search was conducted to ensure broad coverage of relevant studies. Second, an evaluation framework to classify and analyze the findings was developed. These steps are described in Sections 2.1 and 2.2.

2.1. Literature Search

This study was based on a structured narrative review rather than a full systematic review. The aim was to compile information from representative and influential contributions in the field of vertical greenery systems (VGSs), emphasizing their benefits, risks and implementation challenges.

The following keywords, either alone or in combination, were used to select research articles from the SCOPUS database: “green façades” OR “living walls” OR “green walls” OR “vertical greening” OR “vertical greenery” AND “benefits” OR “functions” OR “ecosystem services.” The initial search yielded 1159 records.

The dataset was then screened in successive stages, while titles and abstracts were first reviewed to exclude irrelevant documents, such as studies with no link to building applications or papers focused exclusively on unrelated ecosystems. Non-academic documents were excluded, as well as non-English publications, in order to ensure consistency in interpretation. Thereafter, the remaining records were subjected to full-text analysis, focusing on studies that addressed the built environment context, covering environmental, social, economic, or technical aspects of VGS. Both empirical studies (field measurements, simulations, and case studies) and comprehensive reviews were retained.

In parallel, backward and forward citation tracking was employed to capture additional relevant works not retrieved in the initial query. This process enabled the inclusion of classic references frequently cited in the VGS literature, as well as very recent contributions. In total, over 150 peer-reviewed publications formed the final dataset. These covered a broad geographic scope (Europe, Asia, North America, and beyond) and reflected the multidisciplinary nature of VGS research, from engineering and architecture to urban planning and environmental sciences.

The overall process is summarized in Figure 1, which illustrates the stepwise refinement from initial records to the final body of literature.

2.2. Evaluation Process

The analysis of the selected literature was structured through an evaluation framework designed to capture both well-established themes in the field and emerging issues identified during the review process. Initially, a set of decision parameters was defined *ex ante*, drawing on recurrent categories in previous reviews and key topics consistently addressed in the literature. These parameters are related to (i) environmental performance (e.g., air quality improvement, UHI mitigation, energy efficiency, stormwater management, and biodiversity), (ii) social benefits (e.g., noise reduction, well-being, and indoor comfort), (iii) economic outcomes (e.g., cost savings, durability, and property value), and (iv) risks and barriers (e.g., structural load, maintenance, legislative gaps, and costs).

During full-text analysis, the framework was refined *ex post* to integrate additional aspects that have gained prominence in recent years, including fire safety requirements and heritage conservation conflicts, as well as the adoption of digital tools such as building information modeling (BIM), digital twins (DT), and urban building energy models (UBEM).

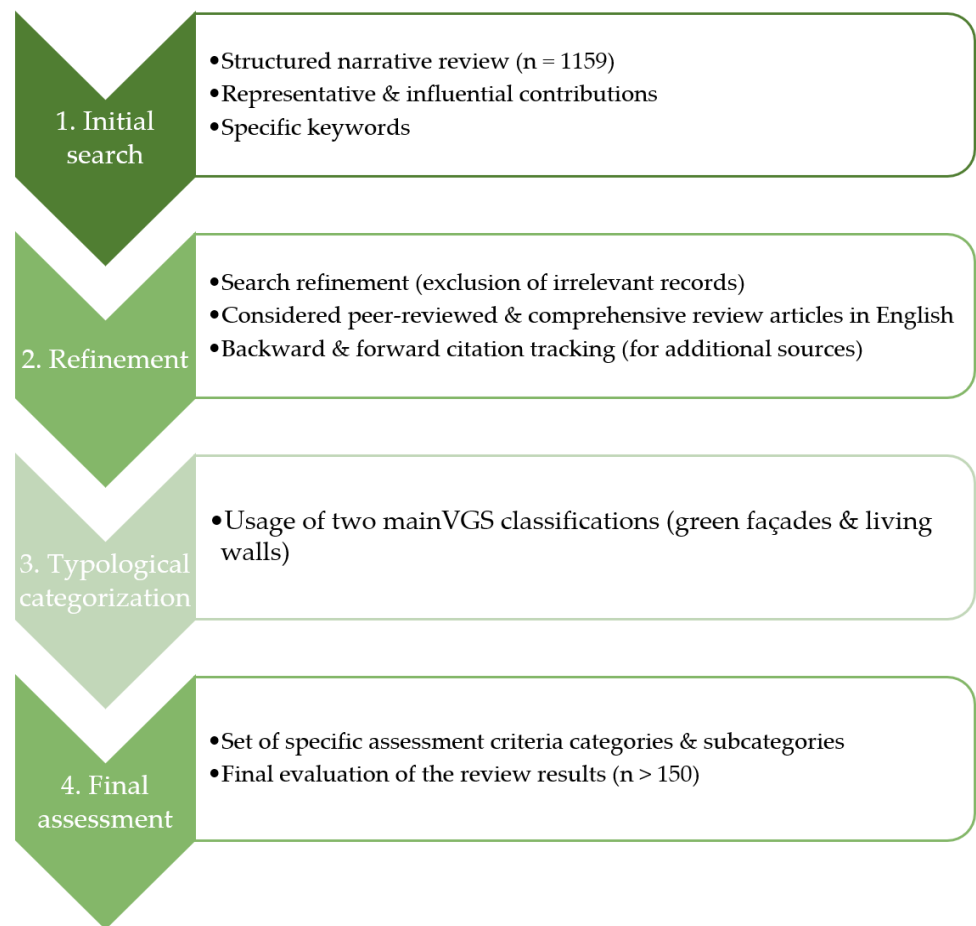


Figure 1. Literature search and screening process.

The key assessment parameters of the review analysis are summarized in Table 1, which presents the categories used to assess vertical greenery systems (VGSs) in terms of benefits, risks, and other important VGS-related factors. This framework ensured that the literature review was not limited to descriptive reporting but was instead guided by an integrated set of evaluation aspects, supporting comparison across studies and contexts.

Table 1. Key assessment parameters of the review analysis.

Key Decision Parameters			
Advantages	Disadvantages	Further Aspects and Restrictions	Technological Limitations
Environmental benefits	Threats to building condition and pathology	Costs	Scalability restrictions
Social benefits	Greenery failures	Legislative aspects	Digital integration of VGS
Economic benefits	Threats to building tenants	Typological and structural aspects	

2.3. Typology Breakdown

Although this paper does not organize the results of this literature review based on specific VGS typologies, it is important to note that the majority of the papers studied accept and use two main VGS classifications, namely, green façades and living walls. Thus, despite the inconsistencies described earlier, most studies agree on two main categories for VGSs based on their growing method or planting system, green façades and living walls [28,36], as follows:

- i. Green façades correspond to systems that use climbing plants, which grow on a building's façade. They can be further divided into direct and indirect green façades. In direct green façades, plants are attached directly to the building surface, using aerial roots or adhesion pads [29]. Additionally, in indirect green façades, plants are supported by structures such as cables, trellises, or meshes [37]. Additionally, green façades can be distinguished between single-skin, where plants grow directly on the wall or with minimal support, or double-skin, which have an air cavity between the plants and the wall [34].
- ii. Living walls, also known as green walls or vertical gardens, are more complex systems constructed using modular panels or continuous layers containing soil or artificial growing mediums [37]. They are further subdivided into modular systems (pre-vegetated panels containing soil or other growing mediums), continuous systems (based on a single support structure often using a geotextile felt system that also acts as the growing medium), and linear systems. The latter are a type of living wall systems that are characterized by the use of planter boxes, arranged one above the other in a linear fashion [29].

These typological distinctions are not central to the methodological framework itself but are taken into account in the subsequent results and discussion, where performance outcomes and feasibility are examined in relation to system type. This evaluation framework thus provides a transparent and systematic basis for structuring the literature review, while maintaining sufficient flexibility to integrate emerging issues and interdisciplinary perspectives relevant to the implementation of VGSs in urban environments.

3. Review Analysis

The review analysis is organized in two main subsections: (i) Section 3.1, which presents the advantages of VGS and provides an overview in Section 3.1.4, and (ii) Section 3.2, which examines the main disadvantages, barriers, and limitations and concludes with an overview in Section 3.2.4 (Figure 2). Each aspect is analyzed in detail within its respective subsection, followed by the concise overview at the end of the respective section.

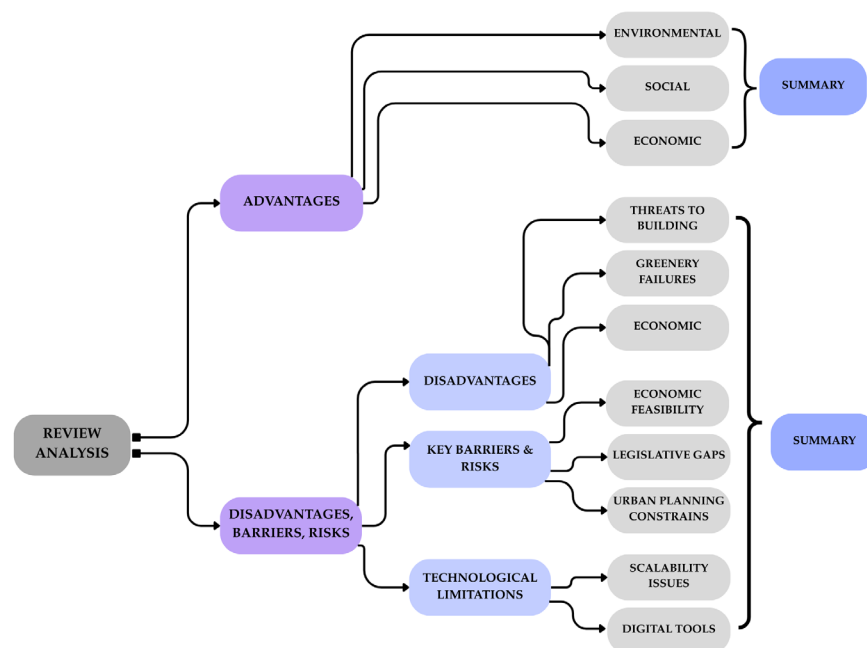


Figure 2. Organization of the review analysis and structure of Section 3.

3.1. Advantages from VGSs

3.1.1. Environmental Benefits

Urban air pollution, predominantly caused by vehicular emissions and industrial activities, is a persistent environmental and health concern. Vertical greenery systems offer numerous environmental benefits related to air quality [12,31,38]. Plants in VGSs act as natural air filters, capturing dust and cleaning the air. As detailed below, VGSs can influence the dispersion of air pollutants by generating mechanical turbulence, decreasing turbulent kinetic energy, and acting as a physical barrier to airflow [39]. Vertical greenery systems are more effective in removing particulate matter (PM), including fine and ultra-fine particles from the air, compared with gas pollutants. The deposition process, where particulate matter is deposited on leaves, is the key mechanism in mitigating pollution [40]. Vertical greenery systems have been shown to reduce the concentrations of various air pollutants, including nitrogen dioxide (NO₂), PM₁₀ and PM_{2.5}, ozone (O₃), sulfur dioxide (SO₂), and carbon monoxide (CO) [41]. Some studies have found green walls can reduce up to 40% of O₃ and between 11.7% and 40% of NO₂, 42% and 60% of PM₁₀, 3.5% of SO₂, 1.34% of CO, and 1.34% of PM_{2.5} [14].

Moreover, the roots of plants in VGS can remove toxic chemicals from the soil, including volatile organic compounds (VOCs), trichloroethylene (TCE), benzene, toluene, and xylene [30]. Through photosynthesis, plants in VGS also absorb carbon dioxide and release oxygen, thereby contributing to the reduction in carbon dioxide (CO₂) emissions and increasing carbon storage and sequestration [30]. In terms of indoor air quality, botanical biofiltration systems in green walls can biodegrade and break down a wide range of VOCs. These systems operate with low energy input while significantly improving indoor air quality [42] and can reduce CO₂ concentrations by 5–50% [43].

The improvement of air quality due to VGSs (Figure 3) is related, among others, to plant species and diversity, plant size, leaf area index, wind direction, and humidity levels [31,44]. Additionally, the location and design of the green wall, including topography, as well as external parameters such as traffic volume and environmental conditions, significantly influence its performance [41]. However, it is important to note that the aerodynamic effects of plants included in VGSs can often lead to reduced air ventilation, potentially leading to pollutant accumulation [40]. This phenomenon has been observed particularly in street canyons with dense roadside vegetation in high-traffic urban areas [45].

Vertical greenery systems can also significantly contribute to reducing temperature in urban areas. Through the process of transpiration, where moisture is released from plant stomata into the air, combined with the process of evaporation, VGSs help lower ambient temperatures, counteracting the UHI effect. Additionally, by providing shade, VGSs can cool both the surrounding air and building surfaces [46]. They also reduce the amount of energy emitted from heat-absorbing materials like concrete and asphalt, which are key contributors to the UHI effect [38]. As result, greenery on buildings supports healthier microclimates, offering cooler and more comfortable conditions within urban spaces compared with the surrounding areas [23]. Earlier studies have shown that green walls can reduce air temperatures by 0 °C to −8.7 °C during the day and by −0.1 °C to −3.7 °C at night, while the maximum air temperature reduction between the building and its vegetated surface can reach 6.4 °C [28]. While vegetation increases humidity via transpiration, contributing to temperature reduction, it is important to note that in tropical regions, increased humidity levels may actually have a negative effect on thermal comfort levels [47].

VGSs also function as an insulation layer, helping to regulate indoor temperatures and reduce heat losses in the winter, although some studies indicate that VGSs may increase building heat demand during the heating period [41]. In summer, VGSs can significantly

lower wall surface temperatures. For instance, the maximum internal and external wall surface temperature can be reduced by up to 1.6 °C and 10.5 °C [48]. Other studies report air temperature reductions ranging from −0.3 °C to −31.9 °C during the day and +2.0 °C to −6.0 °C at night [49]. Hence, buildings with green walls benefit from reduced energy consumption due to the cooling effect of the VGS, providing energy savings of more than 15% [50], in some cases reaching up to 20% [43]. Compared with other forms of urban greenery such as parks and street trees, VGSs may be less effective for thermal regulation but are still useful in dense urban environments where available urban spaces are limited [10].



Figure 3. A green façade integrated into the building of the Directorate of Urban Environment Management in Thessaloniki. This building is located next to a major traffic artery, and accordingly, the VGS contributes to mitigating traffic-related emissions and air pollution.

The design and structure of VGSs and the type, density, and arrangement of vegetation, as well as the construction materials used, play a critical role in their performance [10]. Orientation is also a key factor affecting their thermal performance; studies have shown that west-facing VGS are particularly effective in wall temperature reductions [51]. The effectiveness of a VGS depends also on local climate and weather conditions, resulting in various outcomes across different regions [41]. Selection of plant species, taking into account geographic context, is necessary not only to optimize the VGS's performance but also to avoid increased humidity, which reduces thermal comfort in tropical regions [47]. Variations also exist as a result of the prevailing wind direction and the time of day [10]. Finally, VGSs tend to be more effective in densely built-up areas than in sparse developments.

While VGSs can effectively reduce air temperatures in their immediate surroundings, their cooling impact diminishes with increasing distance from the installation [49]. The matter of the scale of their application in urban environments is also crucial. Thus, it is important to note that most studies assessing the effect of VGSs on urban outdoor and indoor thermal comfort have been conducted on a micro-scale. As such, the thermal regulation of microclimates may not scale up linearly from individual buildings to neighborhood or city-wide applications [52].

Another benefit of VGSs relates to the fact that they can reduce the amount of stormwater runoff from buildings by capturing and retaining rainwater on plant leaves and stems and within the substrate [23]. Hence, green façades can intercept a significant amount of precipitation, reducing the amount of water that reaches drainage systems. This helps to slow down

the flow of water into storm sewers, reducing the risk of flooding [30]. Furthermore, green façades, along with green roofs, may reduce stormwater runoff by 4% [30].

The amount of interception can vary widely, with fully foliated façades intercepting between 54% and 94% of total rainfall, while twiggy façades intercept from 10% to 55% [53]. Green façades also delay the flow of water, with fully foliated façades delaying through-flow by at least 30 min, compared with about 15 min for twiggy façades [53].

VGS can also remove pollutants from stormwater through processes like adsorption, sedimentation and filtration. This is due to the “rhizosphere effect” which refers to the physical and biochemical changes in the soil around plant roots, which is important for regulating nutrient cycling [42]. Vertical greening is suitable for injection into underground water wells [54], and some VGSs can treat gray water for non-potable uses [55]. Additionally, VGSs can contribute to water savings, with estimates of 40–50% water savings through implementation of green walls [56].

The effectiveness of green façades in stormwater management is influenced by several factors such as plant species, the density of vegetation cover, and the overall health and maintenance of the system. A key component is the substrate (or growing medium), which plays a crucial role in regulating water flow, supporting plant growth, and filtering pollutants [33]. Substrate characteristics such as size, porosity, type, and depth directly affect the system’s capacity for filtration, pollutant removal, and water retention. Selecting plants with high water absorption capacity is also crucial [55]. Ornamental and climbing plants with fast growth rates are often preferred, as well as plants with good nutrient uptake capabilities [33,57]. However, due to their vertical orientation, green walls may have smaller surface area and limited ability to directly intercept rainfall compared with green roofs [49]. It is important to note that regarding the impact of VGS on water quality, studies have shown that VGS can negatively impact runoff water quality through the introduction of nutrients and contaminants into runoff [42].

Vertical greening systems can also provide various benefits for biodiversity in urban environments, creating new habitats for fauna and flora by providing nesting sites, food sources, and shelter [58]. VGSs function as natural vertical habitats, such as cliffs or vegetated waterfall [59], and can support a range of species, from microorganisms to birds [14]. Different types of VGSs may attract different faunal communities. For example, climbing plants on green façades have been found to host species similar to those on cliffs, while modular green walls can host communities similar to those near waterfalls [60].

Living walls can be also designed to provide specific functions that may be missing in the urban environment, for example, by incorporating species that support pollinators [61]. Green walls can also serve as vertical corridors for wildlife, allowing movement from the ground to green roofs. They may also function as ecological corridors enabling wildlife movement between fragmented green spaces. This facilitates the dispersal of seeds, insects, and small animals across urban landscapes [62].

The type of vertical greenery can affect faunal composition. Different vertical greening systems, such as green façades and living walls, tend to host different assemblages. For example, green façades may support beetle and spider communities similar to those found in hot, dry habitats, while modular panel and felt-layer green walls are more likely to harbor fauna similar to those found near waterfalls [60]. The extent and the connectivity of the VGS with other types of green infrastructure is also critical in shaping their role in supporting fauna [11].

Plant species selection also affects the biodiversity supported by green walls. Some species like ivy may have a greater thermoregulation effect and support more invertebrates [60]. Greater vegetation thickness has been linked with animal species richness

and abundance, likely due to the increased habitat volume and quality [11]. Furthermore, increased plant diversity support greater biodiversity than monocultures [60].

While some studies have suggested that the biodiversity value of green façades may be low [60], long-term studies are needed to better understand the performance of VGSs in supporting biodiversity over their life cycle. Additional studies are also needed to assess the influence of different plant species [28] and how animal communities are shaped over time in these artificial habitats [58].

In summary, although performance is highly context-dependent (climate, exposure, irrigation regime, and maintenance), VGSs have a series of important environmental benefits, namely, the following:

- i. Foliage protects façades from solar radiation and UV, wind, and driving rain, stabilizing near-wall moisture, as well as temperature regimes.
- ii. Leaf canopies capture particulate pollutants and can reduce near-façade noise; effects vary by species and morphology.
- iii. Systems retain stormwater (especially modular living walls), easing peak runoff and enabling reuse, as well as the support of gray water concepts in buildings.
- iv. Habitat provision supports urban biodiversity when native, climate-fit species are used and biomass is managed.
- v. Urban microclimate benefits (localized UHI mitigation and improved outdoor comfort) depend on canyon geometry, orientation, and coverage ratio.

3.1.2. Social Benefits

Green walls offer multiple social and health-related benefits, particularly for noise reduction. Noise pollution is considered one of the leading causes of environmental degradation in cities, having multiple effects on people's health [35]. In addition to their acoustic benefits, green walls can offer restorative neuropsychological effects, improved cognitive performance, and fewer discomfort symptoms [34].

The effectiveness of sound reduction is affected by factors including plant species, substrate, green wall dimensions, and shape, as well as the relative orientation and distance to the noise source [8,63]. The arrangement of the modules within a green wall also influences their effectiveness in sound reduction [35]. According to earlier studies, noise reduction values range from 5 to 10 decibels (dB) [8], while other studies have identified that green walls in inner-city buildings have attenuated traffic noise from 2.6 to 5.1 A-weighted decibels (dBA) [41]. Lower sound frequencies are absorbed mainly by the substrate, while plant elements block higher frequencies, through reflection and scattering of sound waves [8]. Furthermore, the presence of greenery can lead to a subjective experience of lower noise levels, even when actual sound pressure measurements do not indicate a significant difference [64]. Nonetheless, additional research is needed to better understand noise absorption capacity of green walls in open spaces and under real-world conditions with diverse noise sources [35].

Vertical forests have been shown to positively influence the psychological and emotional well-being of citizens. For instance, Wei et al. [65] noted that vertical forests are associated with increased emotional positivity, including indicators related to smiling and happiness. Similarly, Rakhshandehroo et al. [66] attribute the therapeutic values of the vertical greenery to the biophilic relationship between individuals and their natural environment, a connection that is fundamental in easing the mental stress caused by living conditions in urban areas [66]. The reduction in anxiety levels and the promotion of social cohesion, contributing to improved living conditions, has also been noted [67]. These social benefits are particularly evident in densely populated cities, where limited access to open spaces leads to growing rates of loneliness and social isolation [68]. Beyond the

facilitation of emotional well-being and social engagement, vertical green buildings may also enhance cognitive functioning and productivity. Natural elements integrated into the built environments have long been associated with improved concentration, creativity, and mental efficiency. Kuo et al. [69] demonstrated that exposure to green elements significantly enhanced residents' sense of safety and security, leading to improved cognitive and decision-making performance. Further evidence on the psychological effect of vertical green structures comes from environmentally certified buildings. Holmgren et al. [70] found that occupants of green-certified buildings reported greater satisfaction and higher cognitive performance, especially when their indoor environment was cooler.

Beyond their psychological impact, the implementation of VGSs softens the harsh lines and the monotony of urban areas dominated by steel and concrete. They also serve as tools that raise public awareness and promote sustainable urban development. Educational programs developed to highlight the economic and environmental benefits of green roofs and façades have the potential to engage a wider audience and increase interest in these practices [71]. Moreover, recent research has shown that psychological responses to vertical green buildings may vary by gender. Nevárez-Favela et al. [72] observed that women, in general, reported higher levels of perceived tranquility and emotional activation than men following their exposure to living walls and rooftop gardens. These findings highlight the importance of considering diverse user experiences and psychological needs when designing green buildings.

In addition to aesthetic and psychological benefits, VGSs can also contribute to urban agriculture [73]. This creative approach, apart from its social benefits, could be factored into economic analysis in the future.

Overall, depending on their orientation, plant type, irrigation, and building typology, VGSs have a positive contribution on thermal comfort and living conditions in buildings, namely, the following:

- i. Biophilic exposure and views to greenery correlate with improved well-being, stress reduction, and perceived comfort.
- ii. Visual amenity and green space creation enhance streetscape quality and cultural identity, especially in dense districts.
- iii. Shading and cooler microclimates near façades improve outdoor thermal comfort for passers-by and ground-floor users.
- iv. Potential noise perception benefits in traffic-exposed settings.
- v. Social acceptance rises with good aesthetics, clear maintenance plans, and transparent risk management (e.g., pests and fire).

3.1.3. Economic Benefits

Vertical greenery systems can significantly reduce energy consumption for heating and cooling [14]. Acting as natural insulation, VGSs promote cooling loads' reduction during the summer period [37], with studies showing potential energy savings of up to 40–60% in Mediterranean climates [74]. A systematic review by Khan et al. [32] found that earlier studies estimate annual savings for living walls up to EUR 2036.17, EUR 1337.41 for direct green façades, EUR 1160.41 for indirect green façades, and EUR 1045.67 for indirect green façades with planters.

Beyond energy efficiency, VGSs enhance structural durability, through the protection of building façades from weathering, resulting in cost savings related to maintenance and repairs [32,37]. The development of such architecture reinforces the durability and survivability of the building structure. The thermal insulation mitigates rainfall and temperature fluctuations, which degrade stability and functional performance of building structure [75,76]. The leaves and branches of vegetation act as natural barriers to harmful

ultraviolet (UV) radiation, which otherwise can cause material breakdown, discoloration, and decomposition of construction materials [76].

Furthermore, vertical greening offers notable economic benefits including branding and marketing opportunities for developers, businesses, and local authorities. Vertical greenery systems can increase real estate values and rental income, with some sources suggesting that incorporating vegetation in both the interior and exterior of buildings can increase property values by 7 to 20%, especially in cases where they support the access to new open living spaces [30]. This is particularly true for commercial properties, where aesthetic and functional enhancement influence marketability and rental pricing [37].

Against this background, governments around the globe provide financial incentives, such as tax reductions or exemptions, for installing VGSs. These incentives help reduce the initial costs and make projects financially more viable, as well as promoting their wider adoption [77–79]. Further types of economic benefits are reported also by Akinwolemiwa et al. in their case study, showcasing the positive influence of affordable VGS installations, which resulted in new jobs and multiple benefits for the local community [80].

Vertical greenery systems can also generate economic savings through their ability to manage stormwater and filter gray water [57,81]. Biomass harvested from plant pruning can also have some monetary value, which is nevertheless lower compared with other, more substantial benefits [82]. Finally, VGSs have been shown to improve hygrothermal comfort, which could potentially reduce sick leave for office employees, by promoting healthier work environments [32,83].

In conclusion, the main economic benefits of VGSs can be summarized as follows:

- i. There is reduced HVAC energy use for heating and cooling, where the degree of reduction varies with climate, orientation, and system type.
- ii. Façade protection due to reduced weathering can defer maintenance and extend the service life of historic building surfaces.
- iii. Stormwater retention may unlock fee reductions and incentives where applicable; some cities offer green-infrastructure subsidies.
- iv. Property value increase and productivity gains (in office and retail buildings) are reported in several case studies.

3.1.4. Summary of the Literature Review Regarding Key Benefits of VGS

Table 2 provides an overall synthesis of the ecosystem services offered by vertical greenery systems, classified into environmental, social, and economic categories. This table complements the detailed discussion above, condensing the benefits identified into a structured overview.

Table 2. Summary of the key environmental, social, and economic benefits provided by vertical greenery systems (VGSs).

Category	Benefits Provided	Details/Examples	References
Environmental	Air quality improvement	Removal of PMs; reduction in NO ₂ , O ₃ , SO ₂ , and CO; VOC biodegradation	i.e., [39]
	Climate regulation	Ambient/surface cooling; UHI mitigation; carbon sequestration; improved microclimates	i.e., [43]
	Energy efficiency	Thermal insulation; reduced heat gain/loss; energy savings	i.e., [48]
	Stormwater management	Rainfall interception/retention; delayed runoff; pollutant removal	i.e., [53]
	Biodiversity support	New habitats; vertical corridors; higher richness with thicker/more diverse vegetation	i.e., [11]

Table 2. Cont.

Category	Benefits Provided	Details/Examples	References
Social	Noise reduction	Traffic/urban noise attenuation	i.e., [8]
	Psychological and health benefits	Stress reduction; enhanced cognition; safety; social cohesion; restorative/biophilic effects	i.e., [65]
	Aesthetic and cultural value	Visual quality; sustainability awareness; educational programs	i.e., [71]
	Urban agriculture	Potential façade-based food production with community engagement	i.e., [73]
	Hygrothermal and thermal comfort (IEQ)	Improved indoor environmental quality and comfort (cooler/healthier spaces)	i.e., [70]
Economic	Energy cost savings	Reduced heating/cooling loads; up to 40–60% savings reported in Mediterranean climates	i.e., [37]
		Effective retrofitting measure while respecting heritage façade preservation	i.e., [84]
		Overall reduced energy demands in various climates	i.e., [85,86]
	Building durability	Protection from UV, rainfall, and thermal swings; lower maintenance/repair costs	i.e., [75]
	Property value and branding	Higher real-estate value; improved marketability and rental income; branding opportunities	i.e., [37]
	Public incentives and job creation	Tax reductions/subsidies; local employment from VGS projects	i.e., [77]
	Water management-related savings	Savings from stormwater/gray water management and associated fees/uses	i.e., [57]
	Biomass byproducts	Monetary value from pruning residues (minor relative to other benefits)	i.e., [82]
	Reduced sick leave and productivity gains	Better environmental conditions for residents linked to fewer absences and better work performance	i.e., [83]
	Minimize degradation risks	Notable fluctuations' reduction in surface and air temperature, relative humidity, solar irradiance, and particulate matter	i.e., [87]

While the benefits of VGS are evident across environmental, social, and economic dimensions, the literature also highlights significant disadvantages and risks, which are examined in Section 3.2.

3.2. Disadvantages, Key Barriers, Risks, and Limitations of VGSs

3.2.1. Disadvantages of VGSs

Threats to Building Condition and Pathology

By means of greenery in buildings, in addition to their benefits, their incorporation imposes challenges and concerns, particularly regarding the building's structural integrity and plants' health (Table 3). One of the most common challenges is the potential damage to building façades. Greenery buildings introduce complex structural, environmental, and vegetation-related interactions, intensifying threats to building health and requiring robust assessment frameworks [88].

Vegetation, especially in aged and poorly maintained buildings, can compromise wall integrity. For example, self-climbing plants, such as ivy (*Hedera helix*), can root into cracks or weakened sections of historic walls or poorly maintained buildings. These

plants can dislodge masonry by growing beneath or between blocks [89]. In addition, sidings, tiles, or loosely fitting cladding are particularly vulnerable. These elements can be lifted or displaced by plants growing underneath them. External wall plaster must be sufficiently strong to support the weight of the plants. Inadequate structural support can lead to cracking or detachment of the plaster over time. Furthermore, depending on the plant removal methods employed, they can leave behind visible “scarring” on building surfaces. This is especially true for surfaces that are painted or made from wood or masonry (Figure 4). These marks are visible after green layer is removed and are created due to the etching effect of the sap of the root cells [89].

Table 3. Threats to building conditions.

Threat	Impact on Plant Health
Root penetration (growth/action)	Wall and foundation integrity (i.e., cracks)
Plant direct attachment/green layer removal	Wall and foundation integrity (i.e., lifted blocks, cracks, scarring, and plaster removal/local wetness)
High level of moisture (due to evapotranspiration)	Mold development/indoor and outdoor dampness/material covers damages/slow drying
High level of moisture (due to watering/irrigation systems)	Water leaks/water pooling/dripping water/indoor and outdoor dampness/mold development/corrosion/streaking/material covers damages
Soil moisture changes	Wall and foundation integrity (i.e., potential instability issues, and subsidence)
Soil microbial flora and organic acids	Concrete erosion
Additional weight and stresses (plants/planting media)	Potential instability issues (e.g., reinforced concrete planting balcony)
Wind	Structural integrity (i.e., cracks, collapses, blown out, and debris)



Figure 4. Green façade on a company’s building in Thessaloniki with recorded damages on vegetation and the building’s envelope.

Furthermore, tree roots can cause direct damage to buildings and infrastructures, although the foundations of newly constructed buildings are typically engineered to withstand such impacts [90]. Over time, however, tree and plant roots may become unmanageable and result in structural and external fissures in buildings. As trees mature, tree roots exert significant force while seeking nutrients and moisture from the soil. These tree roots can take advantage of any cracks in the walls or façades or flaws in a building's foundation exacerbating structural weaknesses. Cracks and possible instability may result from the roots pushing on the building's framework as they spread and grow. This typically happens when trees are given insufficient space; as they grow, their roots begin to extend and move beneath structures [23,91].

Trees can also indirectly contribute to structural damage in historical buildings and monuments, especially when planted in areas with shrinkable soil types, which expand and contract in response to fluctuations in soil moisture changes [92]. This phenomenon occurs only where the roots penetrate, causing differential subsidence in the soil and leading to damage in the overlying masonry structures [91]. Underground infrastructure, such as drainage systems, is also vulnerable. Roots are commonly attracted to the moisture surrounding drainage pipes, which maintain a lower temperature than the surrounding soil [93]. Another concern for greenery-covered buildings is the erosion of concrete and the structural demands imposed by the added weight. In VGSs, such as vertical forests, reinforced concrete planting balconies are commonly used, typically divided into an inner part for living and an outer part for planting. The reinforced concrete planting balcony must bear the weight of the soil and plants, as well as the stresses caused by the root growth [94]. Over time, the microbial flora and organic acids in the soil can erode the concrete. Consequently, the reinforced concrete planting balcony is susceptible to damage over time, and its safety must be carefully evaluated and monitored [95].

Due to the process of evapotranspiration, plants release water vapor into the surrounding air, particularly during summer, increasing humidity and making walls more susceptible to dampness [96]. In addition, plants incorporated into VGSs require systematic watering and irrigation, but excessive watering can result to leaks and damage to the building structure and its components [97]. A further concern related to self-climbing plants is that if they are not properly maintained, they can obstruct architectural features designed to prevent water ingress such as drip grooves, leading to an increase in moisture levels [98]. Moisture-related problems are especially common in vertical green façades and living walls, where water run-off cause streaking or even corrosion (Figure 5). In some cases, this external moisture can penetrate interior surfaces, increasing the risk of mold growth within connected indoor spaces [99]. These issues are more pronounced when self-climbing plants are directly attached to walls. Although such plants can offer protection against precipitation, incomplete vegetation coverage may lead to localized wetting.

Greenery Failures

In addition to the potential structural damages to buildings, elevated vegetation itself is subject to degradation over time (Table 4). Plants used in VGSs require consistent watering in order to remain healthy; insufficient watering or poorly designed irrigation systems can cause plant stress and wilting, leading ultimately to plant death and accumulation of bio-debris (Figure 6). Environmental stressors common to urban areas such as urban pollution, UHI effects, and high wind exposure can negatively affect plant health. These effects are more pronounced at greater building heights [100]. Limited growing space can also result in distorted vegetation especially regarding trees, which require adequate space for both root expansion and canopy development [46].



Figure 5. Corrosion phenomena of a metal infrastructure in the building of the Directorate of Urban Environment Management of the Municipality of Thessaloniki, Thessaloniki, Greece.

Table 4. Threats to plant health.

Threat	Impact on Plant Health
High level of moisture	Pests/degradation of planting media
Low level of moisture	Plant stress/dry vegetation/dead plants
Improper maintenance	Wilting/vegetation gaps/degradation of planting media data
	Overgrown vegetation/dead biomass/bio-debris/vegetation gaps/degradation of planting media/compaction
Inadequate space data	Data distorted vegetation growth
Environmental stressors (harsh sunlight and strong wind) data	Plant stress/dehydration
Extreme winds	Uprooting/mechanical stress/dehydration/reduced plant growth rate/wilting/bended trees/falling bio-debris



Figure 6. Distorted growth of trees and bio-debris at a planted balcony in Thessaloniki, Greece.

High-rise buildings are exposed to intense winds [23]. Vegetation, such as trees planted on balconies, in high-rise buildings can modify their aerodynamic profile, reducing local wind pressure and wind loads on the structure [27]. However, wind affects the greenery systems depending on its intensity, orientation, and frequency. Strong winds may induce mechanical stress on vegetation, resulting in physical damage, dehydration and uprooting [101]. Additionally, wind deteriorates transpiration rates, reducing moisture from plant tissues and soil [36], with negative impacts on plant growth and wilting. Tree stability after rainfall is also lower due to an increase in soil moisture saturation. Consequently, trees are more susceptible to uprooting due to winds. The main damages regarding planting media concern loss and media compaction and malfunctions of the irrigation systems. Wrong material selection, inadequate maintenance, and material aging processes may lead to serious degradation [102]. Similarly, irrigation systems' function may be affected by improper design and poor water quality. This may result in vegetation dryness, plant mortality, and gaps in vegetation coverage [31].

Threats to Building Tenants

Beyond threats to building condition and greenery failures, VGSs also poses several risks to building occupants health and safety (Table 5). Integrating large amounts of organic materials on building façades in the form of vegetation can introduce significant fire risk [103]. As a result, the implementation of VGSs require strict building codes, installation of fire suppression systems, and appropriate maintenance practices to mitigate fire risk [23]. Dry vegetation is highly susceptible to ignition and facilitates fire propagation along the façade (Figure 7). In some cases, overgrown vegetation can form a “fuel ladder” that facilitates fire spread and transmission to upper floors and to neighboring structures.

Table 5. Summary of threats to building tenants.

Threat	Impact on Plant Health
Dead plants	Aesthetics/utility/energy needs (increased during summer)
Overgrown vegetation	Insects/aesthetics/energy needs (increased during winter)/utility/reduced sunlight/view/living space occupation
High moisture level	Health issues/pests/insects/mold development
Fire	Safety/evacuation obstruction/chimney effect
Wind	Fallen objects/bio-debris/turbulence

Experimental studies examining different plant species with variable moisture contents have shown that the transient heat release of healthy vegetation is relatively low upon ignition; however, it escalates as the moisture content diminishes. More specifically, during a full-scale fire test to analyze fire spread on the green façade of a high-rise building, it was observed that fire did not extend beyond the storey of origin. This was due to 1.60 m horizontal concrete projections at each ceiling level. These projections managed to block fire spread to upper storeys [104]. Adequate irrigation is also important for fire risk mitigation and decreased combustibility [23,105]. Proper plant selection with lower flammability, combined with systematic maintenance protocols, is important for enhancing fire resilience of VGSs [100,105].

In addition, VGS implementation poses aesthetics and practical challenges that affect both quality of life and buildings' appearance (Table 4). Common issues such as dead plants, bare patches within green façades, and uncontrolled plant growth are frequently occurring problems [96]. In addition, health-related concerns are likely due to potential

mold development, pest breeding, and insects. The introduction of non-native species may disrupt the local ecological balance, highlighting the need for careful plant selection.

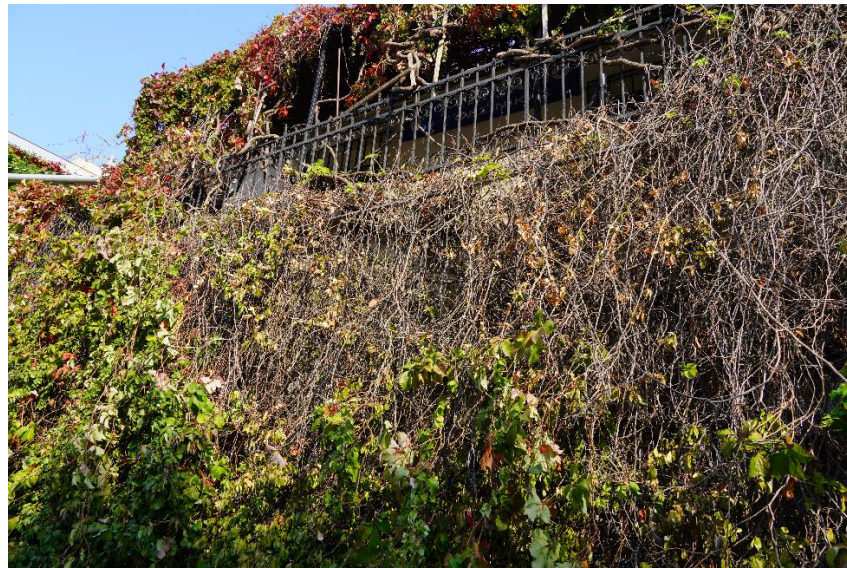


Figure 7. Excess dry matter within the green façade in the building hosting the Historical Archives of Macedonia, Thessaloniki, Greece.

The systematic maintenance of greenery by experts, as well as the potential building repair, entails additional costs, for example, in case of earthquake damages [106], which can also pose additional financial burdens to residents.

In terms of utility, greenery can reduce living space or obstruct views and natural sunlight. Without proper maintenance, plants can grow uncontrollably, covering windows and blocking natural light. This can lead to an unappealing building façade [23].

Plant traits, such as foliage density, affect sunlight availability for building tenants. In addition to appropriate plant species selection, factors such as building façade orientation also influence natural sunlight and should be taken into consideration when integrating VGSs into buildings [107]. Vertical greenery systems can also block incoming solar radiation during winter resulting in increased heating demands [108].

In addition, especially in warm and humid climates, or in cases of poor irrigation and drainage conditions, VGSs may support mosquito breeding in stagnant water areas [109], often extensive. Such stagnant water is potentially dangerous due to the accommodation of disease-carrying mosquitoes (e.g., vectors of dengue fever and malaria), leading to unlivable conditions for building tenants.

In addition to mosquitoes, stagnant water can encourage algae and mold growth, further degrading indoor and outdoor air quality and creating slip hazards [110]. Stagnant water may also emit foul odors and attract other insects, and therefore, VGS designs involving water (i.e., irrigated living walls) must take into consideration that odor emission and insect breeding are significant challenges that must be carefully addressed treatment [33].

Vertical gardens introduce dense vegetation on building surfaces, which can allow the development of habitats for small reptiles within their dense foliage. While one goal of green façades is to support urban biodiversity, the presence of undesired insects or small reptiles is cited as a concern in the literature review [111]. Thus, especially in warm climates, dense and poorly maintained vegetation in VGSs can provide shelter for pests such as insects, spiders, lizards, or even rodents, while also attracting birds. Poor maintenance (i.e., failure to prune or remove fallen leaves) worsens the problem as clogged gutters and decaying organic matter create ideal conditions for infestations. Hence, without regular

care, a vertical garden may shift from supporting beneficial wildlife to becoming a nuisance, particularly when located near building entries or windows [111].

3.2.2. Key Barriers and Risks for the Successful VGS Implementation Costs and Economic Feasibility

The life cycle cost of a VGS is an important factor in evaluating their overall performance, particularly in relation to a building's full life cycle performance. Thus, VGS costs (Table 6) can be analyzed based on three specific phases: (i) building integration, (ii) maintenance, and (iii) disposal [112]. High initial costs and maintenance can hinder the economic sustainability of some VGSs [37], which include the costs of design, materials, transportation, and labor [82]. In addition, installation costs for green façades are generally lower than those for living walls as they require fewer materials and are less complex [14,46]. More specifically, a study reported that a green façade can cost only 12.01% of the overall cost of a living wall [113], while another study estimated the cost of a green façade to be approximately one fifteenth that of a living wall [114]. Maintenance costs are also a significant factor in the life cycle cost of VGSs and contribute the most to the life cycle costs [114]. The maintenance costs for a VGS vary, depending on the type of system, complexity, materials used, location, and plant species [59,115]. Again, green façades generally require less maintenance than living walls, with the latter depending on more complex irrigation systems and nutrient delivery [14]. Wonk et al. [86] performed extensive research on VGSs, especially by means of their thermal and acoustic evaluation. Their findings indicate a significant potential for cooling load reduction and energy demands, through the reduction in exterior wall surface temperatures. Although VGSs perform well in terms of acoustic comfort, researchers highlight that they should not be used as a sound insulation solution, due to their high cost of installation and maintenance [116].

Additionally, indirect VGSs present lower risk of damage to building façades and costs of maintenance, presenting higher overall cost-effectiveness. In contrast, direct systems are more expensive than indirect ones especially when considering both installation and maintenance costs [9,32].

Beyond energy conservation, VGSs protect building façades from climatic stress, reducing maintenance costs and prolonging the lifespan of existing building façades. Moreover, adopting a VGS can increase the value of a property by improving cultural, functional, and aesthetic conditions by 15% [117].

Hence, the balance between the initial integration of VGSs and their maintenance costs, as well as the financial benefits they offer (energy conservation, higher property values, and potential national incentives), is varying according to the system's complexity and the climatic conditions of the applied area [14,112,118]. Although the research does not offer enough data to support a broader analysis, studies have begun to shed light on these dynamics. Another key aspect for the economic feasibility of VGS applications is scalability, which is further analyzed in Section 3.2.3. More specifically, the cost expenses and savings differ among various application scales, i.e., a single-building VGS integration or a large-scale VGS application in a whole neighborhood [119]. Thus, integrating VGSs on a larger scale may benefit from economies of scale, reducing per-unit costs for materials and maintenance. However, large-scale projects require detailed design to tackle problems like varying building designs, specific microclimatic improvement goals, and the integration with existing urban infrastructure using the same VGS system [120]. To support larger-scale projects that can demonstrate the positive benefits of VGSs on a city scale, the use of specific technology is needed, as described in Section 3.2.3.

In addition to investment, maintenance, and disposal costs, incentives are becoming a part of VGSs' life cycle cost assessments. This is due to the fact that the benefits of VGSs

extend beyond the individual building and its residents to the broader public (energy savings, UHI mitigation, and improved air quality). This multifaceted role of a VGS is leading stakeholders to design and promote incentive structures based on promising cost–benefit analyses. Hence, traditional evaluations that only consider energy savings of the building(s) where a VGS is applied overlook the wider environmental and social gains of vertical greenery. Focusing purely on private returns is not reflecting the actual benefits of VGS building integration [121].

Table 6. Summary of cost-related barriers of VGS.

Aspect	Description	Implications
High installation costs	Modular living walls and irrigation systems require substantial upfront investment.	Limits adoption in low-budget projects; often requires subsidies or incentives.
Maintenance expenses	Regular irrigation, pruning, plant replacement, and inspections are cost-intensive.	Increases life cycle costs; may discourage owners without long-term financial planning.
Cost–benefit uncertainty	Lack of standardized life cycle cost analyses across climates and typologies.	Investors face uncertainty about payback; weakens business cases.
Externalities often excluded	Ecosystem services (cooling, air quality, and health) not monetized in many feasibility studies.	Underestimation of true benefits; policy undervaluation.

All the above lead to policy implications, with cities offering subsidies or requiring green infrastructure to take advantage of VGSs' external benefits. For example, Singapore's Urban Redevelopment Authority allows developers to count vertical green walls toward up to 10% of the mandated landscaping area for new projects [122]. Additionally, the National Parks Board in Singapore launched the Skyrise Greenery Incentive Scheme, a grant that covers 50% of the installation cost of green roofs and walls (SGD 200 per m²) to boost their integration into the built environment [123]. Such economic incentives are important to boost large-scale implementation of VGSs in cities. To secure their feasibility, they should be backed by empirical evidence from digital modeling tools so as to quantify the height of the investment, as well as energy and cooling paybacks, UHI mitigation, and more. Against this background, some municipalities are already embedding requirements or incentives for vertical greenery in building codes and green building rating systems (e.g., bonuses in floor–area ratios for buildings that include vegetated façades or points in green building certifications such as the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK and Leadership in Energy and Environmental Design (LEED) in the US [124]).

Legislative and Regulatory Gaps

The application of VGSs must be in line with national energy and building/construction codes. They dictate minimum energy and building envelope requirements, as well as specific restrictions in terms of available surfaces for the integration of greenery in existing buildings. These parameters are important to consider when designing large-scale NBS retrofitting measures, especially VGS strategic integration scenarios in cities. Accordingly, financial incentives cannot be efficiently designed without understanding these restrictions, related to the described urban built typologies of each area.

More specifically, most building codes worldwide lack explicit provisions for vertical greenery systems, leading to indirect restrictions [125]. Fire safety codes pose one of the most important risks of VGS implementation failure [104]. For instance, European regulations foresee non-combustible exterior cladding on tall buildings, a fact that can preclude or complicate the integration of VGSs in buildings. In Germany, stakeholders

report that extensive fire protection rules and other public-law requirements (especially for retrofits) pose major barriers to green façade projects [126].

Similarly, in the US, the lack of standardized guidelines within the International Code Council (ICC) forces engineers to study VGSs with conventional façade regulations, increasing uncertainty and costs [127].

National energy performance codes also present a challenge as many national Energy Performance of Buildings Directives (EPBDs) do not recognize the cooling and insulating benefits of VGSs. For example, the European EPBD focuses on conventional insulation, failing to account for external green walls as a compliant energy-saving measure [128].

In addition, zoning laws and urban planning policies further restrict VGS adoption, classifying them as exterior modifications that encroach on floor-area limits or setback requirements. It is characteristic that some cities like New York and Hamburg have revised their zoning policies to support green infrastructure and VGS implementation, but many regions still lack such enabling regulations.

Despite the multiple benefits of VGSs, existing national building laws, energy codes, and zoning policies often hinder their large-scale implementation. The absence of standardized guidelines leads designers to develop individual compliance paths, resulting in bureaucratic and technical complexity, as well as legal uncertainty. Future regulations should explicitly integrate VGSs, ensuring fire safety, energy efficiency, and urban planning policies align to support their adoption. In Table 7, a summary of the key legislative gaps is provided.

Table 7. Key legislative and regulatory gaps for VGS.

Aspect	Gap	Impact
Building codes	No explicit VGS provisions	Uncertainty, delays in approval
Fire safety	Lack of test protocols/flammability classes	Limits use on high-rises, case-by-case approval
Heritage preservation	Restrictions on façade alterations	Hinders use in historic lefts
Planning/zoning	Absence in development procedures	Missed integration with urban greening targets
Incentives/policies	Few targeted subsidies (focus on roofs)	Lower economic feasibility
Maintenance/liability	Undefined owner responsibilities	Liability concerns, discourages adoption

Typological, Technical, and Urban Planning Constraints

Urban buildings differ from neighborhood to neighborhood, from city to city, country to country, according to their usage, climatic conditions, and year of construction. Even in a single urban built environment, building typologies significantly vary, especially by means of their year of construction, which influences the materials of their envelope and their static efficiency [129]. In addition, urban density also differs, affecting both the canopies and the construction system of buildings [130]. Hence, densely built urban environments can suffer from overshadowing, affecting the potential for VGS integration due to the overall built system of an assessment area. In addition, dense urban areas are often characterized by continuous building systems, leaving very few available areas for VGS applications and with very low flexibility.

In addition to linking the built environment with VGS integration potential, it is important to understand building-related typological restrictions. Thus, the integration of green systems into existing buildings requires a thorough revision of structural performance of the building under additional load caused by the greenery and associated equipment. Especially when the retrofitting concerns older or historical buildings, information about their structural details is scarce [131], and there is uncertainty about the construction techniques that were used.

For retrofitted buildings the weight of vegetation and additional water should be taken into account when calculating the structural load. Using lightweight recycled plastics and media will significantly reduce the overall weight. With regard to green façades and living walls, the necessity of drilling through the masonry, often uneven, to connect fixings and the stability problems this entails must be carefully planned. Of particular importance is the calculation of the dimensions of the fixings [132]. Furthermore, the anchorage could be designed to be non-invasive and allow the green façade to be installed on any building and structural system (wood, concrete, steel, or masonry) through a precise dry connection to the load-bearing structure [133].

Vegetation maintenance and management are critical components of the successful implementation of a VGS. To reduce the likelihood of a fire starting and spreading, it is crucial to maintain the vegetation within certain size ranges and prevent vegetation from drying out. As part of a VGS installation, comprehensive fire safety plans should also be developed, including the integration of suitable evacuation routes and fire suppression systems.

Thus, VGSs must comply with structural, envelope moisture, and fire-safety requirements, although they are often treated under the same provisions as cladding systems. Thus, especially in the case of VGS high-rise applications, evidence should be required concerning limited flame spread and façade compartmentation (e.g., horizontal fire breaks), as well as irrigation and its monitoring to prevent biomass desiccation.

Particularly for historic centers, façade interventions may conflict with conservation rules and substrate fragility. Hence, VGS implementation on historic building façades must be aligned with established and local conservation principles and policies in order to prevent the exposure of the building's aged materials to risk, while maintaining its historical architectural identity. In this line, several preservation national and local guidelines emphasize minimal intervention and preservation of authenticity, aiming to avoid any alterations to historic façades [134]. The attachment method (mechanical or chemical anchoring of the system to the façade) of a VGS is important as it may lead to deterioration of vulnerable building façades in historic buildings. Similarly, the relationship between the root system and the external wall materials needs to be assessed, to avoid damage caused by root expansion and the risk of moisture penetration [135].

In addition to risks of VGS integration into historic building façades, the literature review highlights their positive impact as well. Hence, recent research shows the multi-faceted benefits of integrating vertical green systems into historic buildings. In this line, a comprehensive meta-analysis study was conducted, highlighting the fact that vertical greening substantially stabilizes microclimate conditions adjacent to historic surfaces. Thus, by notably reducing fluctuations in surface and air temperature, relative humidity, solar irradiance, and particulate matter, VGSs are able to minimize degradation risks such as salt crystallization, freeze–thaw damage, and chemical weathering [87]. A case study in Italy found that installing a green wall on a rear building façade of a historic building, can lead to significant energy consumption reductions in both summer and winter according to dynamic energy simulations, posing VGSs as an effective retrofitting measure while respecting heritage façade preservation [84]. Similarly, another study found that ivy-covered masonry reduced winter heat loss by up to 37% after two years, with surface temperatures maintained several degrees warmer than bare walls, confirming VGSs as effective thermal buffers [85]. In hot climates, researchers observed that vertical greenery lowered wall surface temperatures by up to 11–16 °C at midday, reducing indoor cooling loads and smoothing thermal fluctuations [86]. These findings indicate that VGS retrofits can substantially improve the environmental performance of heritage buildings without invasive interior alterations.

Beyond energy savings, VGSs also help mitigate material decay by creating more stable microclimatic conditions. Namely, De Groeve et al. reported that green façades dampen temperature and humidity extremes adjacent to historic surfaces, thereby reducing risks of freeze–thaw damage, salt crystallization, and thermal stress, while also filtering airborne particulates that contribute to stone weathering [87]. Empirical monitoring similarly showed that ivy-covered historic walls had fewer frost damages and less pollution staining than bare sections, acting as a protective “biolayer” when growth was well managed [136]. These results suggest that carefully designed and maintained VGSs can not only lower operational energy use but also extend the service life of historic façades, provided that non-invasive, reversible systems are employed and regular maintenance is ensured. The main typological and urban planning barriers analyzed in this section are summarized in the following table (Table 8).

Table 8. Typological, technical, and urban planning constraints.

Aspect	Gap	Impact
Structural load	Not all façades suitable	Safety risks, retrofit limitations
Orientation/microclimate	North/ west façades, wind exposure	Uneven plant growth, higher failure rates
Design integration	Lack of standardized systems	Case-by-case customization, higher costs
Urban context	Limited space in dense/historic areas	Restricts large-scale implementation

3.2.3. Technological Limitations

Scalability Restrictions

The literature review shows that there is a shortage in research concerning the quantification of the benefits from a large-scale VGS application in urban built environments. To date, researchers analyze the benefits of VGS applications based on either single building assessments or small-scale studies. Despite the fact that researchers presented solutions for other city-scale building integrated NBS solutions, such as green roofs [137], VGSs have not been analyzed accordingly. Researchers pinpoint the gap in comprehensive, long-term data on city-scale VGS implementation approaches, leading to uncertainties that cannot support broader urban policies. The reason behind these challenges is that the evaluation of the potential of NBS solutions for larger building groups or even cities is remarkably complex [138].

Against this background, the need for advanced technologies is urgent. To support building integrated NBSs, such as VGSs, reliable city-scale feasibility tools must be available, which must take into consideration all aspects of technical, legislative, and typological restrictions described previously. Additionally, there is no standardized evaluation framework or datasets for multiscale applications, although they are crucial for scaling up VGSs [139].

In this line, considerations must also be made regarding the numerous typologies included in built environments among buildings. Moreover, different built systems affect the total area of available surfaces, while the age and the construction of each building influence their architectural characteristics and, therefore, limit the options of suitable VGS systems. This approach is crucial to create solid procedures that will ensure optimized, feasible VGS investments. Reliable quantifications of city-scale VGS applications in terms of their costs, risks, and benefits will lead to feasible investments and sustainable policy design. Technology can support VGSs’ establishment as a valid strategy for UHI mitigation and large-scale urban building retrofitting.

The main parameters that restrict a large-scale assessment of VGS applications into urban built environments are summarized in Table 9.

Table 9. Summary of scalability restrictions parameters.

Aspect	Gap	Impact
Economies of scale	High cost per m ² for small/isolated projects	Limits adoption beyond pilot buildings
Resource demand	Water/energy requirements increase at district scale	Stress on urban infrastructure, especially in dry climates
Maintenance logistics	Lack of centralized services	Inconsistent quality, high costs for dispersed projects
Urban planning	No city-wide integration frameworks	Fragmented deployment, missed synergies
Policy framework	Few municipal mandates or incentives	Reliance on voluntary or showcase projects

Digital Analysis Tools of VGSs' Integration

The integration of digital tools into sustainability and decarbonization assessments is a part of the latest global developments. Both the European Union (EU) and global stakeholders are systematically promoting building information modeling (BIM) and digital twin (DT) technologies to enhance feasibility in urban planning, sustainability, and infrastructure management. It is characteristic that the EU takes specific initiatives like the CitiVERSE, in order to integrate digital twin technologies to create dynamic, real-time digital replicas of cities, facilitating improved decision-making and urban management [140]. The Renovation Wave also recognizes the need for the uptake of investments into digital and innovative technologies since buildings' digital twins, enabled by 3D mapping data, may provide crucial information on how the building's real-time energy and environmental performance, its construction characteristic, and its potential to save energy, improve microclimatic conditions and optimize its environmental performance [141]. In the same line, the European EUBIM Task Group aims to encourage the use of BIM in public works, while globally, the United States, the United Kingdom, and various Asian countries have implemented policies mandating or encouraging BIM usage in construction projects [142].

Thus, urban building energy modeling (UBEM), digital twins, and BIM-based simulations are pivotal in quantifying how vertical greenery systems (VGSs) improve urban built environments. The integration of VGSs into city-scale building energy models can support the calculation of actual available façade areas and determine typological and constructional characteristics, as well as quantifying the expected reductions in cooling loads in larger scales. In addition, by capturing 3D geometry and plant physics in BIM, researchers can accurately simulate shading, evapotranspiration, and insulation effects of VGSs on building envelopes.

BIM-based decision support systems can streamline the design process for the efficient integration of VGSs into existing buildings. Hollands et al. integrated façade green wall components into BIM and even automated parts of the design evaluation process, providing a prototype for how planners might rapidly generate and compare greening options for a building [121].

In summary, the convergence of UBEM, digital twin technology, and BIM is providing urban decision-makers with robust evidence of VGS benefits at scale, which are crucial for crafting supportive policies, from financial incentives and technical guidelines to sustainability mandates. These tactics are the broad implementation of vertical greenery systems as a strategy for greener, more resilient cities.

As outlined in the previous section, large-scale assessment of VGS implementation is essential for the accurate evaluation of both their positive impacts and the actual surface area available. Thus, without appropriate digital solutions, such assessments are not feasible, resulting in time-consuming manual processes that hinder the adoption of VGSs as

a viable option for urban built environments and discourage potential investors. The main barriers associated with the absence of holistic digital tools are summarized in Table 10.

Table 10. Digital analysis tools of VGS integration.

Aspect	Gap	Impact
Modeling accuracy	Limited simulation models for VGS (energy, microclimate, and water)	Underestimation or overestimation of benefits; weak decision support
BIM/urban digital twins	Poor integration of VGS modules	Difficulty in large-scale planning and performance monitoring
Monitoring technology	Few standardized sensors/IoT protocols	Limited real-time data for maintenance and optimization
Decision-support tools	Lack of user-friendly, multi-criteria platforms	Barriers for architects, planners, and municipalities
Data availability	Sparse long-term performance datasets	Hinders validation and policy uptake

3.2.4. Summary of the Literature Review Regarding Disadvantages, Barriers, Risks, and Limitations of VGS

Table 11 consolidates the principal barriers, risks, and constraints associated with vertical greenery systems (VGSs), including building pathology, plant health, occupant safety/utility, costs, regulatory context, technical/typological limits, and scalability, providing a concise complement to the narrative in Sections 3.2.1–3.2.3.

Table 11. Summary of key barriers, risks, and constraints for vertical greenery systems (VGSs).

Category	Barrier/Risk	References
Building condition and pathology	Wall/foundation integrity due to root penetration and growth	i.e., [90]
	Visible scarring on masonry/wood/painted surfaces after plant removal	i.e., [89]
	Façade dampness due to moisture from evapotranspiration	i.e., [96]
	Streaking/corrosion due to moisture from irrigation/leaks	i.e., [97]
	Structural/local damage due to added weight and stresses in balconies	i.e., [27,94,95]
	Structural damage in historical buildings due to fluctuations in soil moisture changes	i.e., [92]
	Differential subsidence in soil and damage in the overlying masonry walls	i.e., [91]
Greenery failures (plant health)	Plant stress/mortality due to irrigation faults	i.e., [31]
	Plant health issues due to biotic (i.e., pests) and abiotic stressors (pollution, UHI, and intense sun/wind)	i.e., [36]
	Distorted growth (roots/canopy) due to space constraints	i.e., [46]
	Dehydration and uprooting due to extreme winds	i.e., [101]
	Degradation of the VGS due to poor material selection and maintenance, as well as material aging process	i.e., [102]
Threats to building tenants (health, safety, and utility)	Interior dampness and mold due to leaks, water pooling	i.e., [90]
	Increased fire risk due to dry biomass/“fuel ladders”	i.e., [104]
	Aesthetic/utility impacts due to dead patches and/or plant overgrowth	i.e., [96]
	Health risks due to mold, reptiles, insects in stagnant water, etc.	i.e., [98,109]
	Bio-debris hazards around façades and balconies due to winds	i.e., [23]

Table 11. Cont.

Category	Barrier/Risk	References
Costs and economic feasibility	Significant capital expenditures, initial costs, alongside installation costs and substantial operational expenditures	i.e., [14,37,82,112,119]
	Other interventions might be more effective for specific benefit (i.e., primary sound insulation is more cost-effective)	i.e., [116]
	Feasibility depends on climate, complexity, and scale	i.e., [14,59,114]
	Maintenance costs due to earthquake damages	i.e., [106]
	Increased heating costs due to reduced solar heat gains	i.e., [108]
	Indirect VGSs present higher overall cost-effectiveness	i.e., [9,32]
Legislative and code barriers	Code gaps create indirect restrictions/uncertainty	i.e., [129]
	Fire safety requirements by legislation	i.e., [90,104,126]
	National energy performance codes may not credit insulating benefits of VGS	i.e., [90,128]
Typological, technical, and planning constraints	Building heterogeneity and density limit available areas	i.e., [130]
	Variety of local building typologies linked to various underlying constructions, blocking unified large-scale implementations	i.e., [129,130]
	Lack of non-invasive systems to install VGS	i.e., [90,131–133]
	Conservation constraints in historic façades	i.e., [90,131,134,135]
	Lack of systematic maintenance protocols	i.e., [90]
Technological limitations	High complexity for the evaluation of the potential of NBS solutions for larger building groups or even cities	i.e., [138]
	Lack of standardized evaluation framework or datasets for multiscale applications	i.e., [139]
	Micro- to city-scale gap, predominantly single-building studies	i.e., [90,117]
	Robust deployment at large scale depends on UBEM/DT/BIM adoption	i.e., [90,121]

4. Discussion

4.1. Framework of the Review Analysis Results

The literature review revealed that the performance and feasibility of vertical greenery systems (VGSs) are highly context- and scale-dependent. At the building level, factors such as construction year, structural capacity, façade orientation, microclimate, and tenant needs determine whether a system is viable or not. In addition, green façades are generally more cost-effective due to simpler design and lower maintenance, although their environmental benefits often increase gradually. On the other hand, living walls provide immediate environmental and aesthetic gains but at higher installation and operational costs and with stricter fire-safety demands. Moreover, plant species and root system selection remain critical for avoiding structural damage, while careful design is needed to manage wind stress and fire safety.

At the neighborhood scale, heterogeneity in typologies, age of buildings, and ownership complicates uniform deployment. Local climatic conditions affecting irrigation, water availability, and systematic maintenance are also important aspects of a viable VGS design. Furthermore, at the city level, adoption is constrained by diverse regulatory frameworks. Hence, disparities in national fire safety rules, minimum renovation standards, and heritage preservation guidelines hinder a unified European approach. Technical challenges become even more complex when considering environmental constraints, such as droughts and irregular rainfall, which increase dependence on irrigation systems. Water recycling and gravity-fed irrigation strategies have been proposed to mitigate these challenges, although these systems require regular inspection and maintenance to avoid failures.

It becomes obvious that the successful implementation of VGSs demands alignment between typology and context, alongside compliance with structural and legislative requirements. Additionally, in order to maximize the benefits of VGS applications, large-scale approaches are crucial, and supporting them remains a complicated task. Thus, without robust standards and supportive frameworks, scaling up from single buildings to neighborhood or city-wide strategies remains difficult.

4.2. Policy Landscape and the Future of VGSs in Urban Built Environments

For all the reasons described in the previous section, the adoption of vertical greenery systems (VGSs) across Europe remains fragmented, reflecting different national and municipal approaches. Countries such as Germany and Austria have long traditions of façade greening supported by subsidies, while France's 2015 biodiversity law mandated green roofs or solar panels on new commercial buildings, indirectly stimulating vertical greening [124].

In contrast, VGS implementation in Southern and Eastern Europe is mostly limited to pilot projects, largely due to the absence of incentives and clear regulations [124].

Although they are mostly hit by intense heat waves and suffer the consequences of climate change. A further limitation of this discussion is the insufficient treatment of urban planning frameworks, regulatory compliance, and integration in historic buildings dominating EU city centers, where façade interventions often face additional restrictions due to heritage conservation rules, structural fragility, and stringent fire-safety standards [124]. This disparity underlines the strong influence of local frameworks and economic support mechanisms on the efficient penetration of VGSs in urban built environments.

In Europe, recent policy developments form a more supportive context for the implementation of VGSs. More specifically, the Energy Performance of Buildings Directive (EPBD) recast explicitly recognizes building-integrated greenery alongside energy and solar provisions for the first time [143]. Similarly, the Renovation Wave Strategy promotes holistic retrofits that include nature-based solutions [144], while the EU Biodiversity Strategy for 2030 and the Nature Restoration Law introduce binding greening targets for cities [145,146]. In parallel, the EU Taxonomy for Sustainable Activities lists green roofs and walls as eligible sustainable measures, providing a gateway to green finance and ESG-linked investments [147]. Together, these instruments could align incentives across the EU, provided they are implemented through clear technical guidance and funding channels on national and municipal levels. The New European Bauhaus (NEB) further reinforces this agenda by linking climate goals with culture, aesthetics, and social inclusion, explicitly encouraging urban greening and building-integrated nature as part of its call for “beautiful, sustainable and inclusive” urban transformations [148]. At the same time, the Covenant of Mayors (CoM) provides a practical framework for municipalities to integrate VGSs into their Sustainable Energy and Climate Action Plans (SECAPs), translating EU climate targets into local actions and allowing cities to share best practices across Europe [149,150]. Together, these instruments could align incentives across EU, national, and municipal levels, provided they are implemented through clear technical guidance and funding channels.

The question remains, though, how these relatively new EU guidelines and incentives can be successfully translated into local and municipal actions. The transition from high-level strategies to concrete implementation often requires (i) integration of VGS targets into local zoning plans and building codes; (ii) development of standardized technical specifications to ease permitting and compliance; (iii) creation of funding mechanisms and subsidies accessible to building owners; and (iv) robust monitoring frameworks to measure energy, climate, and biodiversity outcomes at the district scale. Without this

vertical alignment between EU policy, national legislation, and municipal governance, there is a risk that VGSs will remain a renovation practice for single-building projects.

Such examples can be found on a global scale in numerous cities. For instance, in Singapore, the LUSH program combines legal requirements with subsidies, which resulted in over 100 hectares of skyrise greenery within a decade [151]. Cities worldwide have adopted diverse policies to accelerate green roof uptake. Toronto and San Francisco mandate installations on new or renovated buildings, while Washington, DC, offers rebates and tax credits. Austin and Portland provide zoning bonuses, and many other municipalities reduce stormwater fees to reward the environmental services of vegetated roofs [152]. These examples demonstrate that where binding requirements and economic incentives converge, vertical greening can move rapidly from pilot projects to mainstream practice, a lesson that could guide the EU in translating its policy ambitions into widespread implementation.

5. Conclusions

The continuous expansion of urban fabric and the human distancing from nature, along with environmental degradation and climate change, create the need for urban greening solutions. As open green spaces continue to shrink, a relatively new concept has emerged to maximize the use of available urban surfaces for greenery. Vertical greenery systems are an approach to incorporate nature into cities, offering benefits such as climate change mitigation and adaptation, as well as improved public well-being.

From an environmental perspective, VGSs contribute to air purification, UHI mitigation, stormwater retention, and enhanced biodiversity. From a social perspective, they improve aesthetics, reduce noise, and promote mental well-being by strengthening the human–nature connection. From an economic perspective, they can reduce energy consumption, lower operational costs, extend façade durability, and increase property values.

However, this review also highlights significant gaps and challenges. These include (i) high installation and maintenance costs that delay widespread uptake; (ii) structural and fire-safety concerns, especially for retrofitted or historic buildings; (iii) uncertainties regarding long-term plant performance and irrigation efficiency, as well as life cycle durability; (iv) limited recognition of VGSs in building codes and energy performance standards; and (v) scarce evidence on their performance at the neighborhood or city scale. In particular, the lack of systematic integration into urban planning frameworks and heritage conservation rules restricts their application in European historic centers, where such buildings dominate. Therefore, in order to accelerate the benefits of large-scale VGS implementation and transform it into a mainstream mitigation and adaptation measure, it is essential to move beyond isolated showcase projects and pursue strategies that enable systematic, city-wide deployment.

The findings of this review are important to plan the acceleration and scale-up for VGS implementation in urban areas, but the results are limited by its narrative scope and English-language publication reliance, which may reduce global representativeness. Consequently, future research should focus on the following:

- Long-term monitoring of VGS performance in terms of durability, energy use, biodiversity, and user acceptance.
- Standardized evaluation frameworks that include environmental, social, and economic metrics, enabling more robust cost–benefit assessments.
- Fire-safety and structural testing, particularly for tall buildings and heritage façades.
- Digital tools (BIM, UBEM, and digital twins) for large-scale simulation of available surfaces, costs, benefits, and risks to inform policy.
- Policy and planning integration, including zoning, building codes, and conservation guidelines tailored to historic contexts.

- Scaling-up approaches that bridge the gap between single-building studies and city-wide implementation, to take advantage of the full climate and health co-benefits.

Overall, VGSs comprise a significant promise as a nature-based solution for sustainable cities. Yet their transformation from single-building demonstration projects to established urban practice requires specific steps. These are (i) tailored technical guidelines; (ii) targeted incentives; (iii) urban planning integration schemes; and (iv) interdisciplinary collaboration among industry, engineers, planners and policymakers. Only through such alignment can VGSs contribute systematically to Europe's decarbonization, climate adaptation, and quality-of-life goals.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building information modeling
BREEAM	Building Research Establishment Environmental Assessment Method
CO	Carbon monoxide
EEA	European environment agency
EPBD	Energy Performance of Buildings Directives
EU	European Union
ICC	International Code Council
LEED	Leadership in Energy and Environmental Design
NBS	Nature-based solution
NO2	Nitrogen dioxide
PM	Particulate matter
SO2	Sulfur dioxide
UHI	Urban heat island
UK	United Kingdom
UN	United Nations
US	United States
VGS	Vertical greenery system
VOC	Volatile organic compound

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