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Perspective

Vertical Greening Systems: A Perspective on Existing Technologies and New Design Recommendation

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Abstract: Vertical greening systems (VGSs) represent an emerging technology within the field of building-integrated horticulture that have been used to help counteract the global issues of urbanisation and climate change. Research and development within the field of building-integrated horticulture, despite being in the infancy stage, is steadily progressing, highlighting a broad range of achievable social, environmental, and economic benefits this sustainable development technology could provide. However, as VGS technology is relatively new, an array of different designs and technologies have been categorized collectively as VGSs, each having various performances towards the proposed and desired benefits. The purpose of this paper is to review existing VGS technologies and analyse the impact of implementation on sustainable development, and subsequently to propose a new VGS design that theoretically achieves the best possible outcomes when aiming to obtain the maximum benefits of installing a VGS. The resultant design creates new opportunities for VGS environmental amenities and maintenance, increases the scope of applications, and improves the environmental performance of the host building. The proposed design has the potential to transform VGSs beyond conventional functions of aesthetic greening to create novel ecosystems, which enhances the formation of habitats for a more diverse range of flora and fauna.

Keywords: urban greening; green technologies; vertical greenery systems; green façade; green wall; living wall

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1. Introduction

The increasing urban population highlights the need to reconsider the structure of cities, by pursuing concrete and strategic actions to preserve public health. Green spaces in urban areas are crucial for the physical and mental health of residents, but urbanisation and changes in land use are putting pressure on these areas [1]. To address this, strategies such as 'Green Infrastructure' and 'Nature-based Solutions' (NBSs) have been proposed to create more sustainable and livable cities [2]. Nature-based solutions are used to address environmental issues in urban areas and provide social and economic benefits [3]. Green infrastructure, which includes green spaces, green corridors, natural systems, green roofs, and green walls, is a network of multi-functional vegetated spaces [4,5].

Urban horticulture may be included in the set of NBSs that contribute to support mental health and welfare and to face societal challenges by applying a systemic approach. The benefits notwithstanding, urban forestry often faces resistance in cities due to space constraints, especially in densely populated metropolises [6]. This has led to increased research and development of space-effective GI technologies, such as green roofs and vertical greening systems (VGSs), which allow for new vegetated surfaces in otherwise inaccessible urban areas [7,8]. VGSs and green roofs are among the most achievable

and promising forms of green infrastructure in buildings, especially in compact cities [9]. In addition to the superficial aesthetic and ornamental benefits VGSs provide [10], a growing field of research on GI suggests VGS technology can help purify the air, reduce the urban heat island effect, enhance building efficiency via thermal and sound insulation, promote biodiversity in urban areas, and control stormwater [11–15]. However, as VGS technology is novel and recently developed, many technological design approaches have created differing solutions that all differ in how effectively they achieve eco-sustainability development goals.

From a sustainable engineering perspective, integrating horticulture in buildings satisfies the challenges posed by the impacts of urbanisation with respect to the beneficial impacts green walls have on the environment [16]. However, the solution of implementing green walls poses a number of engineering challenges, including those that can contribute to successful and long-term community engagement, budget constraints, as well as the selection of appropriate plant species and physical green wall systems that could be used [17]. Therefore, the design of a green wall must be carefully considered in order to create a long-term and effective solution that balances urban requirements and limitations.

The purpose of this paper is to review existing vertical greening system technologies in the field of building-integrated horticulture and to analyse the impact of implementation on sustainable development. We tested the hypothesis that, based on an assessment of existing VGSs, it is possible to design a new system that incorporates all of the advantages of the most common, existing systems whilst minimizing their disadvantages. Based on the information gathered on existing VGS systems, we propose a new VGS design that theoretically achieves the best possible outcomes. Due to the varied technologies that can be broadly defined as VGS, this perspective paper is divided into two parts: the first part involves analysing different technical VGS solutions that are currently used, while the second part involves making a recommendation for a new design that has the best theoretical performance. While previous investigations focused on the technical parameters that advance ornamental and practical roles of VGSs, the aim of the current work was to evaluate limitations of existing designs and to propose a design for a novel VGS.

2. An Introduction to Vertical Greening Systems

The concept of vertical greening systems (VGSs) or green walls generally refers to systems that can support vegetation that grows vertically up or on a wall surface. This allows VGSs to have minimal or limited ground level space [18–20]. VGSs cover at least part of a building façade with supporting structures to hold the vegetation, and can include a growth medium for the plant as well [20,21]. The term "vertical greening system" is used to describe all types of vegetated wall surfaces. There are different definitions, classification systems, and typologies used in the literature on green infrastructure, but green walls can generally be divided into two categories: green façades (GFs) and living walls (LWs) [22].

Green façades are the oldest form of VGS [23], mostly involving climbing plants, such as vines. They are characterized by plants that have their roots located at the base of the wall or in planter boxes located on the ground. Green façades have been divided into two categories: direct and indirect, based on the location of the vegetation [24]. Direct green façades are attached directly to the wall, while indirect green façades are supported by structures that the plants can climb on and cling to.

Living walls, also known as "free-standing" green walls, have the capacity to increase the diversity of plants grown vertically, the goal of which is to obtain a more even vegetated coverage on multistorey buildings [25]. They are designed as continuous with pockets for plants and substrate that are attached to the wall or as pre-planted modular fixtures. Both continuous and modular types are indirect systems that contain and separate the plant-growing media from the wall surface of the building. This makes living walls different from green façades, because they allow plant growth at height without the need for the plants to have roots in the ground surface at the base of the building. Despite their ornamental and aesthetic value, the materials used to make living walls can be expensive, and these

systems require frequent maintenance, potentially influencing their effectiveness relative to their cost in most contexts [26]. Additionally, the plant species appropriate for such systems can require specific technical knowledge. Modular living walls include a wide range of systems that differ in components, including structure, mass, and assembly/installation complexity, making them more flexible and adaptable to the user's needs.

Existing VGSs are classified based on their construction characteristics [11,19,27], and are presented with the following design parameters in mind: structure, type of vegetation that can be supported, material, method of irrigation, and drainage; maintenance requirements; and finally aesthetic value [28,29]. This allows for the critical analysis of VGS design models based on these criteria, which have the potential to supply one or more forms of ecosystem or community amenity. The principal aspects of each design are identified and are presented in the following sections.

The VGSs were categorized into designs [11] that maintain the differentiation between green façades and LWS (Figure 1).

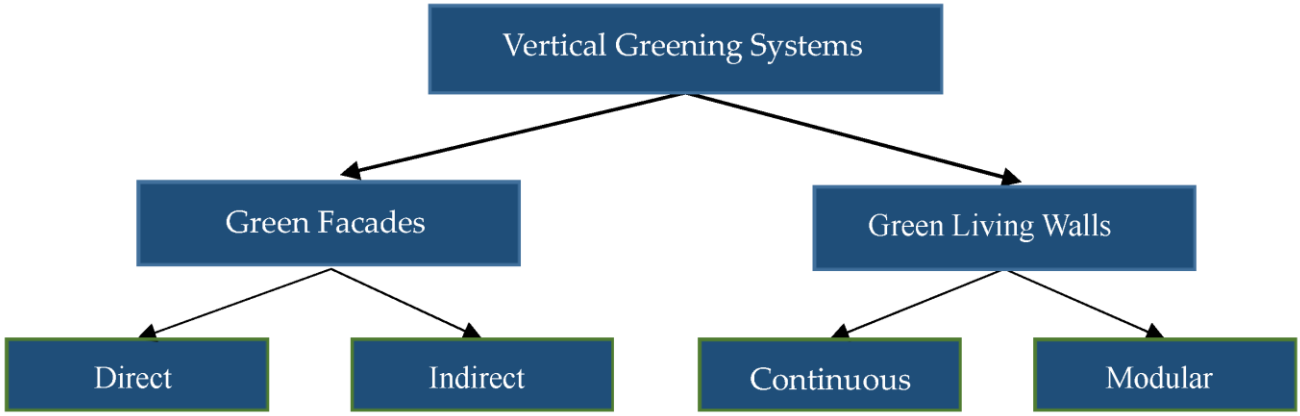

Figure 1. Classification of VGS design based on previous categorizations.

2.1. Green Façades: Direct and Indirect Greening

Direct green façades (Figure 2) are in part not too dissimilar to historical architecture techniques applied in parts of Europe, covering cottages and chateaus with vines and climbing plants [23] to reintroduce vegetation into the urban environment. Direct green façades are the simplest and most cost-effective VGS design that is practical for use in densely populated urban areas, particularly in outdoor settings.

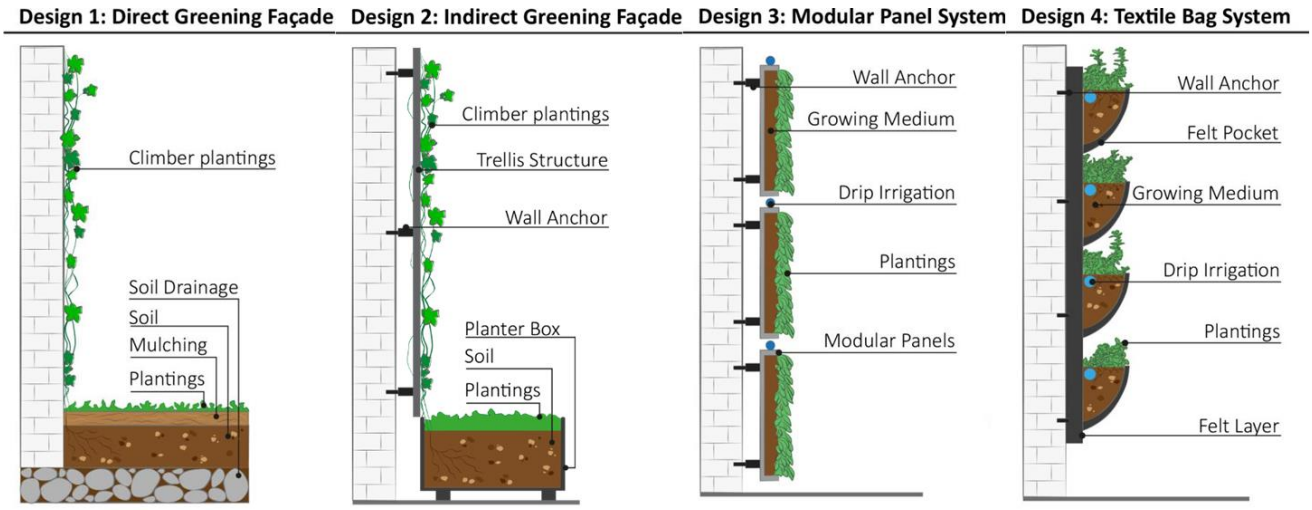

Figure 2. Categorization of various VGS designs.

Indirect green façades use vertical support structures, such as bamboo, wood, steel, aluminium, or high-density polyethylene, to encourage plant growth in specific directions and facilitate complete coverage of the building's façade surface. This type of green wall is used as a cost-effective solution. Direct green façades, on the other hand, rely on self-clinging plants, such as English ivy, Boston ivy, and grape species, which use tendrils or clinging roots to adhere and grow across a wall surface. In order to cover large areas of a building surface, this type of green wall can take a longer time. Plant species that are evergreen can provide ornamental value year-round in this system [30]. Indirect green façades also allow for the use of climbing plants that rely on a support structure. Wire netting is commonly used for slower-growing plant species to ensure extensive coverage [31], while cable trellising can be used for faster-growing plants.

Both types of green walls provide similar benefits in terms of building thermal performance and energy savings [32], but are not as effective in reducing noise penetration and reverberation compared to other systems due to the lack of plant-growing medium which acts as an insulating barrier for the building façade [33]. Irrigation at height for these green walls is typically not required, and manual irrigation is sufficient; however, if automated watering is required, irrigation systems such as drip, sprinkler, or wicking can be installed within the planter box.

2.2. Modular Panel Systems

Modular panel systems comprise pre-made and pre-vegetated panels. Commonly, this type of VGS is characterized by a structural waterproof box that usually contains an inorganic or organic light-weight plant growth substrate, enveloped in a geotextile material and incorporates an irrigation/fertilization system to support vegetation growth. Additionally, the drainage overflow must be located at the base of this type of VGS.

Waterproofing of modular VGS panels is required to maintain and protect the integrity of the building wall surface from water damage. Modular panel systems are designed to be fastened to the building through a support structure, which creates a void space separation in between the wall surface and the VGS panel, thus providing improved thermal and sound insulation benefits compared to other VGSs [34]. Due to the versatile structure, modular panel systems are ideal for immediate coverage of large building surfaces. This design system supports a wider range of plants than those suitable for green façades, and can include perennial species. Pre-vegetated modules allow for an immediate aesthetically pleasing result after installation; however, consistent maintenance is crucial in preserving the high-impact ornamental appeal. In most cases, irrigation at height is not required, because plants are placed at the base of the building façade. Manual irrigation is sufficient to maintain these VGSs, although drip, sprinkler, or wicking-based irrigation can be installed in the planter box, especially if automatic watering is needed.

2.3. Textile Bag Systems

The textile bag system is made of a durable textile material, such as felt or cloth, that can endure weathering in addition to the mass of the plants and substrate. Plants and growing materials, such as coir, are placed in pockets made of the textile material. The method of watering the plants, called 'fertigation', is chosen based on the type of growing material used. Drainage holes are cut near the base of each pocket to remove excess water. This system is lightweight and flexible for use on sloped surfaces and can be used for both large and small projects, such as domestic gardens. However, the design of the pockets limits the amount of space for plant roots.

3. Comparison between VGS Design Models

There are several requirements that must be met before the Direct Greening Façade will be appropriate for use on a building. In these systems, plants are grown directly on the façade material. Over time, there may be the potential in some instances, depending on plant species and building age and integrity, for roots to penetrate mortar joints and

to displace and erode the mortar, potentially enabling water ingress. Additionally, it is essential to provide a waterproof membrane at the base of the wall to prevent penetrating dampness. Maintenance of the structural elements of these walls may be obscured by the planting, the degree of which will vary depending on orientation and species choice. The primary advantages of this design are simplicity and scalability, with the height to which plants will grow determined by the plant species specification. This design requires a reasonable area of land between the building and land boundary to account for the ground-level planting. Costs per square metre of covered vertical surface will be lowest for this simple design compared to the other systems, but these systems have limited noise-abatement capabilities [28]. Stormwater usage is potentially very good, if appropriate guttering, downpipe direction, and drainage systems can be incorporated [35]. These walls provide low potential for biodiversity enhancement based on the limited plant species choice and thus diversity possibilities, and air pollution mitigation performance is also lower [36]. Environmental amenity and aesthetic values are comparatively low, as plant species choice is limited to what can be planted at ground level and will effectively climb the vertical surface. Nonetheless, under certain circumstances, these systems can produce attractive and effective urban greening features, especially along long, low walls.

The Indirect Greening Façade design utilises a planter box at the base of the external wall in which the plants are grown. A trellis structure is secured to the external wall and provides a framework for the plants to climb, resulting in less likelihood of plant root damage occurring to the building external surfaces. Watering of the planter box will be required when rainfall is insufficient, especially if the planter boxes are small relative to the size of the plant root systems (e.g., with well-developed systems). Space at the base of the building is needed for the planter box, as is access to a water supply for plant watering. In most cases, the trellis structure will be lightweight and can be easily and securely fixed to the wall structure, although periodic maintenance inspections will be needed to ensure connections are secure. Noise abatement, stormwater use potential, biodiversity enhancement, air pollution mitigation, environmental amenity, and aesthetic value are all lower with this design.

The Modular Panel System comprises a series of planted modular panels fixed to an external wall with incorporated drip feed irrigation. The growing medium volume is greater in this design, providing more options for planting. This design, whilst heavier and more complex than the two previous designs, provides greater services. The modular panel provides very high potential for noise abatement. Stormwater use potential is medium, with a limited capacity and complex diversion plumbing required. Air pollutant mitigation is quite high, with significant research having been performed on these systems [37]. Environmental amenity and aesthetic value are also high due to the large and flexible vegetation surface coverage offered by this design. Whilst moisture damage to walls will not occur due to the incorporation of an air gap between modules and the supporting walls, thermal expansion of the building envelope has been associated with modular panels becoming unstable [25]. In some instances, wall maintenance costs may be reduced, as the wall is protected from external exposure to the elements by the modular panels, and there is considerable potential for energy savings through improved insulation with this design as more of the building external surface is covered [38].

The Textile Bag System comprises a collection of "potted" plants, and the soil-cells are subject to the challenges facing the majority of potted plants: soil compaction, climatic stress, and soil nutrient replenishment [25]. This system also has the potential problem of soil loss due to wind and water erosion [25]. The system is fixed directly to the external wall, leading to the same moisture ingress problems as the Direct Greening Façade, although in this system, the problems are likely to be magnified due to constant contact between wet substrate and wall surface, requiring high performance wall waterproofing. The varying thickness of these systems means that noise abatement potential is low in most practical applications, as is stormwater use potential. The potential to plant a variety of species is a valuable characteristic of textile bag green walls, which can facilitate good biodiversity

enhancements. Environmental amenity is usually high, and aesthetic value is affected by the quality of the textile bag and is deemed medium unless very high plant coverage can be obtained. Maintenance costs associated with these systems are typically high.

A summary of the VGS design models' characteristics is provided in Table 1. We have identified the modular system as the most complex of these VGSs. Due to this complexity, several companies sell pre-made components for this design model, which makes designing and installing it much easier. The same can be said for textile bag designs. Commercially available products are durable and stable, and are recommended for situations that require high levels of security, a large coverage area, and an immediate aesthetic appeal.

Table 1. Comparison of VGS design models based on six criteria.

	Noise Abatement	Stormwater Use Potential	Biodiversity	Air Pollution Mitigation	Environmental Amenity	Aesthetic Value
Direct Façade	Very low	Medium	Low	Low	Low	Low: non-homogeneous surface coverage
Indirect Façade	Low	Low	Low	Low	Low	Low
Modular Panel	Very High	Medium	Medium	High	High	High: large and flexible vegetation surface coverage
Textile Bag	Low	Low	Medium	Medium	High	Medium: dependent on the quality of textile bag used

This work has showcased four design models of VGS, with varying degrees of complexity in design, maintenance, and performance dependent on design type. Some VGSs are simple in both design and capabilities, such as the two façade models, and thus offer more limited environmental benefits, while others require specific materials and technical skills to construct them, such as the modular systems. These differences notwithstanding, all of the described systems have several, common inherent limitations:

Poor longevity due to the limited plant species suited to the systems—Plants in these VGSs will not reseed, and many species will not spread vegetatively. The absence of effective recruitment results in additional maintenance and a requirement for regular replanting.

Low foliage volume capabilities—Shallow green wall containers/systems have insufficient soil volume to support sufficient root mass to deliver high foliage volumes.

Lack of permeability—Modular and Textile bag designs compartmentalize substrate within discrete containers that isolate root balls, constraining growth and reducing plant health. This effect may also apply to the façade systems if small ground-level planter boxes are used or ground-level plantings have limited soil volume for root spreading.

4. A Proposed New System: The Tessellated Double Green Perforated Façade System

A new VGS typology that hybridizes Green Façades and Living Walls (LWs) is proposed to overcome the limitations present in the aforementioned systems: the Tessellated Double Green Perforated Façade system. Conceptually, the novel design fragments the modular substrate panels of the LWs to form façade elements. These elements are rotated perpendicular to the host building's façade, spacing the façade elements to create a 'porous' façade system. These façade elements are suspended between structural elements to create geometric forms. The top and bottom of the façade elements converge together to form apertures (Figure 3).

The apertures allow the plants to be maintained from inside through window openings or from maintenance access gantries suspended between the host building's façade and the façade system, reducing operating costs. This porosity allows for the creation of habitat corridors facilitating the movement of birds, flying insects, and climbing terrestrial animals between and through the apertures of the façade elements. Habitat infrastructure such as nesting hollows, insect hives, and multispecies water stations (bird baths) can be integrated into the structural elements to further support the formation of functional habitat. The size of the apertures can be varied to generate more complex interconnected voids essential

for habitat corridors [39]. This spatial complexity could replicate some of the functions of multilayer canopy ecosystems, by mimicking the canopy stratification found in forests. The multiscale apertures create defensive spaces for smaller birds and animals from predators, such as predatory birds, rodents, and cats, which are essential in providing the trophic cascades necessary to enable a multi-layered ecosystem.

Figure 3. Top and bottom of the façade elements converge together to form apertures.

The convergence of the plant-growing substrate of the façade elements allows for root system integration and the consistent flow of water throughout the façade system. The resultant interconnectivity generates a monolithic root structure that could grow throughout the façade system to potentially improve resilience. Further, the multiscale apertures would result in different solar exposure conditions across the plant-growing substrates, producing a high density of diverse microclimatic conditions. This feature improves the variety of plant selection possible, increasing aesthetic qualities and supporting a greater diversity of flora and its accompanying fauna. The design of the structural elements incorporates 'micro awnings' that provide shading, further enhancing the formation of microclimates. The geographic location and orientation of the host buildings will, however, necessitate that micro-awnings are bespoke designed to suit the conditions. Such tailored designs would maximize the environmental performance of the building, maximize microenvironment diversity, and protect the vegetation, further increasing resilience in harsh environments and reducing the maintenance burden.

A cross section showing the system design and how it is attached, suspended away from the host building and maintenance access gantry is shown in Figure 4. The proposed system exploits the façade articulation zone within planning instruments. The system is suspended away from the host building with steel structural supports allowing for a maintenance access gantry. The structural members of the system connect to its adjacent member to form a module. The plant-growing substrate is connected to the system's structural members within each module. At each building storey level, the irrigation reservoirs connect to the underside of the steel structure. Excess water and water harvested from rain events is distributed to these reservoirs, where it is measured before being used to irrigate the level below. Awnings and gutters are located at the bottom of the design to collect excess irrigation water and water harvested from rain events and drained to a treatment tank for reuse in the system.

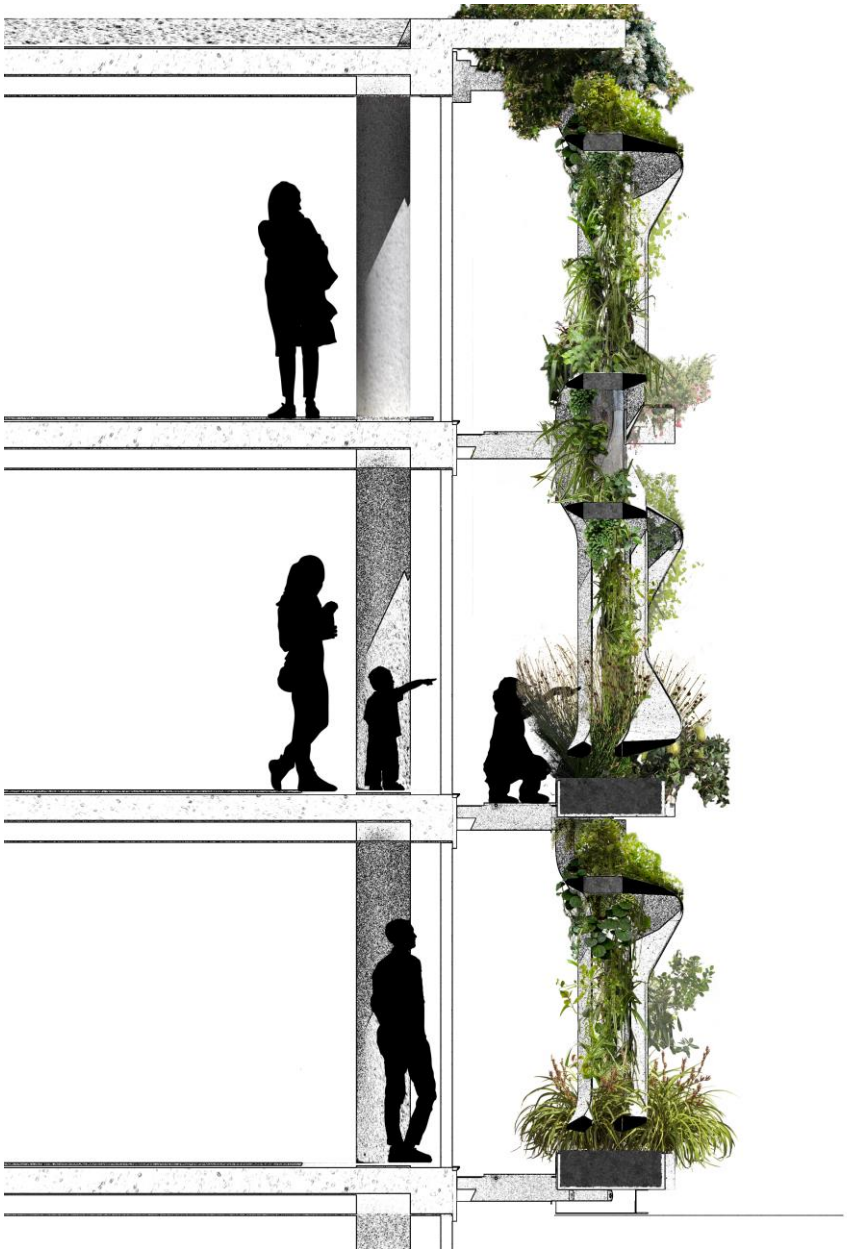

Figure 4. Host building and new design cross section showing system suspended away from host building and maintenance access gantry between.

The proposed configuration allows plants to grow on both faces of the plant-growing substrate ('façade elements'). Consequently, this doubles the vegetative volume for the same volume of plant-growing substrate compared to modular designs, which are universally single-sided. The porous design encourages airflow through the façade by creating a stack effect. This increases air movement and encourages airflow over the substrate, which would be expected to improve the air pollution removal performance of the system [14]. The resultant design thus creates new opportunities for VGS environmental amenity increasing its scope of applications and improving the environmental performance of the host building. The resultant design transforms the VGS beyond its conventional functions of aesthetic greening to create novel ecosystems, which enhances the formation of habitats for a more diverse range of flora and fauna.

The support structure has been designed to be constructed from fibre-reinforced pre-cast concrete. This would reduce the heat load on the host building's mass, while also functioning to self-shade to reduce the storage of solar heat in the structure through the

optimized, minimized cross-sectional profile. When implemented at scale, the combined effects of the shaded host building mass and the cooling effects of evapotranspiration are predicted to assist in mitigating the impact of the UHI effect. This reduced heat load could lower the demand for artificial building cooling and the associated operational carbon footprint [40], which is a significant contributor to global carbon emissions.

Unlike intensive street tree planting, the retrofit potential of the Tessellated Double Green Perforated Façade system opens opportunities for rapid urban greening (compared with the relatively slow growth of trees) without the requirement for extensive ground infrastructure and services. Collectively this could, theoretically, further reduce building cooling demand.

The configuration of the façade and the closed irrigation system guides water directly through the growing substrate, which is shaded by the micro awnings and structure (Figure 5). This design reduces evaporative loss, and consequently water consumption. The structure has been specifically designed to harvest water from rain with the growing substrate rotated perpendicular to the host building, allowing water from vegetation driplines to fall onto the growing substrate below. The micro awnings protrude to capture additional rainwater and are shaped to funnel the water back to the growing substrate. The micro awnings incorporated into the structure reduce the heat load on plants and provide shelter from damaging winds. The resultant façade texture also mitigates the effects of downdrafts from buildings into the public space at the podium or ground level.

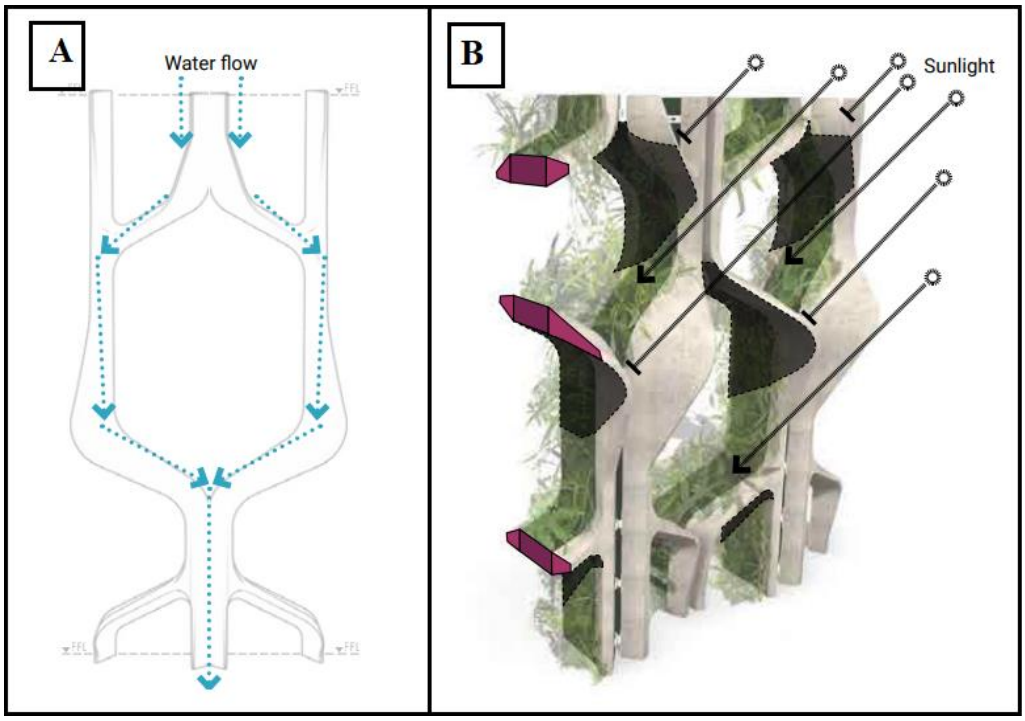

Figure 5. Configuration of the façade allows for a closed irrigation system guiding water directly through the growing substrate (**A**). The design additionally allows for different solar exposure conditions across the plant-growing substrates through the multiscale apertures (**B**).

The current paper thus proposes a new design to overcome the disadvantages of existing systems, whilst incorporating all of their advantages, with the aim to develop a vertical greening system that can provide the maximum diversity and depth of ecosystem services possible with this type of planted system as can be seen in Figure 6. As a free-standing system, the proposed design incorporates the advantages of other systems of this type whilst further extending the potential for different plant forms due to the horizontal growing alignment, such as woody bushes and grasses that cannot be grown vertically due to the compromises such an alignment forces on the aesthetic of their growth forms.

The proposed system would also allow more traditional VGS plants to grow, such as climbers and vines, potentially facilitating the development of complex plant communities, allowing the proposed design to provide more complex ecological patterns than other designs. The potential for deeper, longer-lasting substrate and the more robust containment system than other designs such as textile bags could also facilitate the incorporation of slower-growing woody plant species whilst extending maintenance intervals. Further, the structural elements of the proposed system are a design element on their own, negating the requirement to choose species with dense foliage cover to obscure an unappealing structure from view, as is the case in many modular systems.

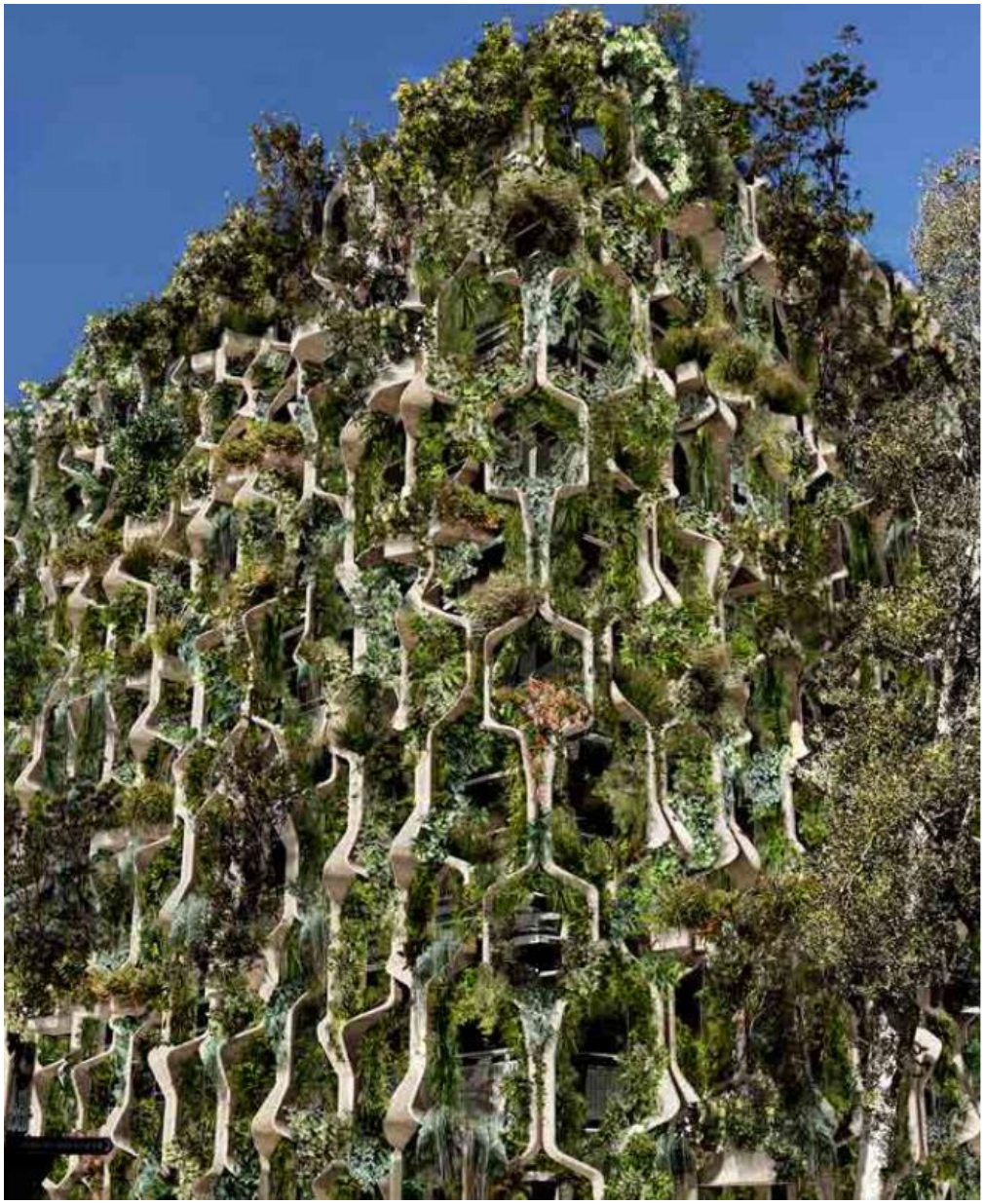

Figure 6. Idealized tessellated double green perforated façade covering a multistory building.

However, the proposed system will require substantial testing and modification before its full capacity can be realized. We propose initial laboratory and small-scale trials before field assessment to isolate the discrete functions of the wall into a series of manageable testable hypotheses. Noise and air pollution mitigation along with stormwater management can effectively be tested on scaled-down systems, along with the capacity of the system to

contain novel plant forms such as woody plants and grasses and the aesthetic results such mixed floristic systems might provide. Many of the services provided by existing systems have been tested by similar methods, allowing comparisons of their performance to be made. Longer-term field trials following laboratory proof-of-concept trials will then be required to assess the development of biodiversity provision, such as insects and especially interspecific plant interactions, along with the other aspects of amenity provision.

5. Conclusions

The increasing densification of the world's growing urban population creates the need to reconsider the structure and design of cities, particularly to improve public health and wellbeing. Urban green areas can support human health and welfare and provide a host of valuable ecosystem services. However, the need to provide structural density in the urban environment, thereby reducing energy and transport requirements, and to meet resident demands competes with public green areas. This has led to increasing interest in innovative, space-minimalist GI technologies such as green walls and roofs including VGSs, which facilitate new, space-effective vegetated surfaces in otherwise unavailable, or inaccessible, urban areas. VGSs are the most achievable and promising forms of GI in buildings within compact cities. However, the existing VGS designs have created differing solutions that vary in how effectively they achieve these eco-sustainability development goals.

This paper has reviewed existing vertical greening system technologies in the field of building-integrated horticulture and assessed their implementation impacts on the provision of services. Based on an appraisal of existing VGS systems, the limitations apparent in all current designs have led to a proposal for a new VGS design that theoretically achieves the best possible outcomes in all aspects, namely the Tessellated Double Green Perforated Façade.

This proposed porous façade system has thus been explicitly designed to incorporate the advantages of all existing systems whilst minimizing their disadvantages:

- It facilitates easier plant maintenance and safe maintenance access through an easily accessible structure.
- It supports greater diversity of flora and fauna and thus enables creation of habitat corridors for biodiversity.
- It enables root system integration and consistent water flow.
- It accommodates greater plant numbers and vegetative volume than other designs.
- It has excellent visual amenity due to the incorporation of structural design elements that do not need to be covered with foliage, thus providing flexibility in plant choice and possibly reduced maintenance.
- It optimizes efficient water usage and protects plants from wind and solar damage.
- It provides the combined effects of a well-shaded host building mass and cooling effects derived from evapotranspiration to help mitigate the UHI effect. This reduced heat load could lower the demand for artificial building cooling and the associated carbon footprint, a significant contributor to global carbon emissions.
- The system has a high retrofit potential.

The primary predicted disadvantage of the proposed system is its likely cost, although the use of pre-cast concrete and economies of scale should reduce this.

The current perspective paper has been provided to help generate progress in the VGS field and to encourage the design of new and improved systems by outlining the clear potential that VGSs have for the provision of an exceptionally broad range of ecosystem services. As such, the design proposed here has not been constructed or tested, and further, it is likely that the design will undergo some modification during initial prototype manufacture.

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D.G.; funding acquisition, D.G. All authors have read and agreed to the published version of the manuscript.

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