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From Stone to Green: Engineering Innovations in Retrofitting Buildings with Vertical Greenery Systems

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Abstract

Increasing demand for sustainable architecture has created a need to retrofit Vertical Greenery Systems (VGS) in existing buildings. Green façades and living walls, which form part of the VGS, contribute significantly to improved energy efficiency, air quality, and aesthetics. However, VGS implementation on existing buildings, particularly stone façades, poses some unique engineering challenges, the majority of which are associated with preserving the existing facade of the building. This research considers the implications of retrofitting stone façades with VGS. Through an examination of different models of VGS—panel systems, Textile bag systems, and planter/pot systems, the paper addresses their technical, material, and compatibility with stone surfaces. Considering load management and material choice, the paper offers valuable guidelines to architects and engineers with a view to overcoming retrofitting challenges and improving building performance. Moreover, the article is a guide to retrofitting stone facades with VGS, and step-by-step procedures are given for the successful integration of such green systems. The paper emphasizes how integrating VGS will help retrofit existing buildings and act as a spur to sustainable development.

Keywords: *Green Facades, Retrofitting, Living Wall, Structural Integrity, Engineering Solutions, Sustainability.*

Introduction

Retrofitting existing vertical Greenery, Systems is, nevertheless, faced with specific challenges, especially structural strength and installation.

While there is extensive literature on the environmental benefits of vertical Greenery Systems, not much work has been directed towards engineering problems that need to be addressed by retrofitting such systems to existing buildings. The research answers the following question: What is the retrofitting roadmap for existing stone facades with Vertical Greenery Systems?

The study introduces a road map to architects, engineers, and policymakers working on building retrofitting projects.

Green Façades, Vertical Greenery Systems, and Living Walls

Although terms such as green façades, vertical greenery systems (VGS) and living walls are

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often used interchangeably (Cuce et al., 2021; Aria et al., 2015; Radić et al., 2019; Farrokhirad et al., 2024; Arenghi et al., 2021; Martinez et al., 2015; Younis et al, 2024), there are important distinctions among them. A green façade is a side of a building that is covered with vegetation, climbing up along the outer side of buildings - usually with the use of climbers or vine plants, and typically without the use of engineered systems to support the plants. In contrast, a vertical greenery system is a technological approach equipped with modular panels, underpinning, and irrigation systems that facilitate more control over the health of the plant and building performance. Realized through pre-planted and irrigated panels, (also known as "green walls") one specific type of vertical greenery system applies irrigation and automatic feeding of the nutrient solution to achieve maximum sustainability and aesthetic value. They vary from low-tech on the far left, such as green façades, to more complex technologies that increase biodiversity in urban areas, such as living walls.

The exhaustive literature review on green façades also indicated that various other synonyms, rather than specific definitions, are used by most studies to define “green façade”, such as “Living Wall” and “Vertical Greenery System” . There were, however, terms like "green façade" and "living wall," which were repeatedly used in describing systems of vertical greenery, suggesting a broad and all-embracing approach in the use of terminology. Based on this observation, the words were considered together as a cluster in the study.

To counter this diversity, a broad search was conducted in the Scopus database to collect all relevant researches, using the keywords "Vertical Greenery System," "Living Wall," and "Green Façade." The studies were selected through an extensive keyword search and thorough review of the neighboring literature. Eventually, 35 studies were selected and processed by Bibliometrix software. This tool allowed for a systematic analysis of novel trends, innovations, and engineering breakthroughs within green façades—offering valuable insight into the trends and innovations that are distinguishing this sector. Figure (1)

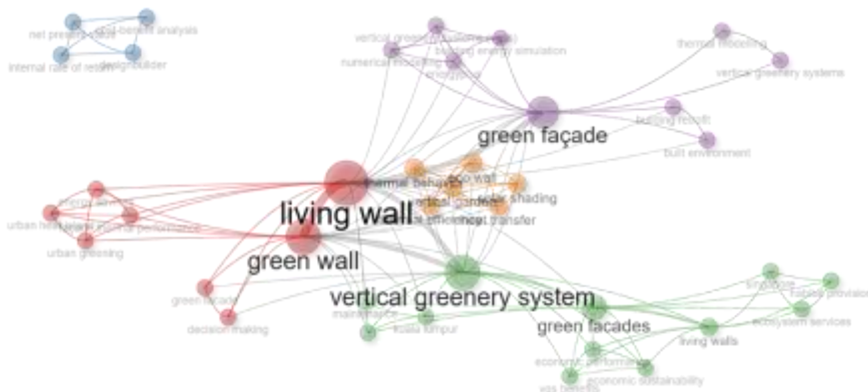


Figure 1. Keywords most frequently used in the articles reviewed.

Types of Vertical Greenery Systems

Vertical Greenery Systems (VGS) are broadly classified into the two main types: extensive (green façades) and intensive (living walls) (Fernández-Cañero et al., 2018). Green facades use climbing plants, while living walls use hydroponic systems or substrates that can support various different plant species, Figure (2) Living wall systems are typically modular systems and allow for complex designs through vertical, inclined or horizontal planting interface. In comparison with traditional green façade systems that are usually made up of creeping or climbing plants, living wall systems are also believed to have more plant species sorts that are suitable for their growth.(Alnsour et al, 2024), (Seah & Kim, 2016) (Akinwolemiwa et al, 2018), They are usually made up of pre-vegetated panels, planted blankets, or vertical modules, which are mounted vertically on structural walls or frameworks (Kontoleon and Eumorfopoulou, 2009; 2010), (Albtoosh et al, 2024).

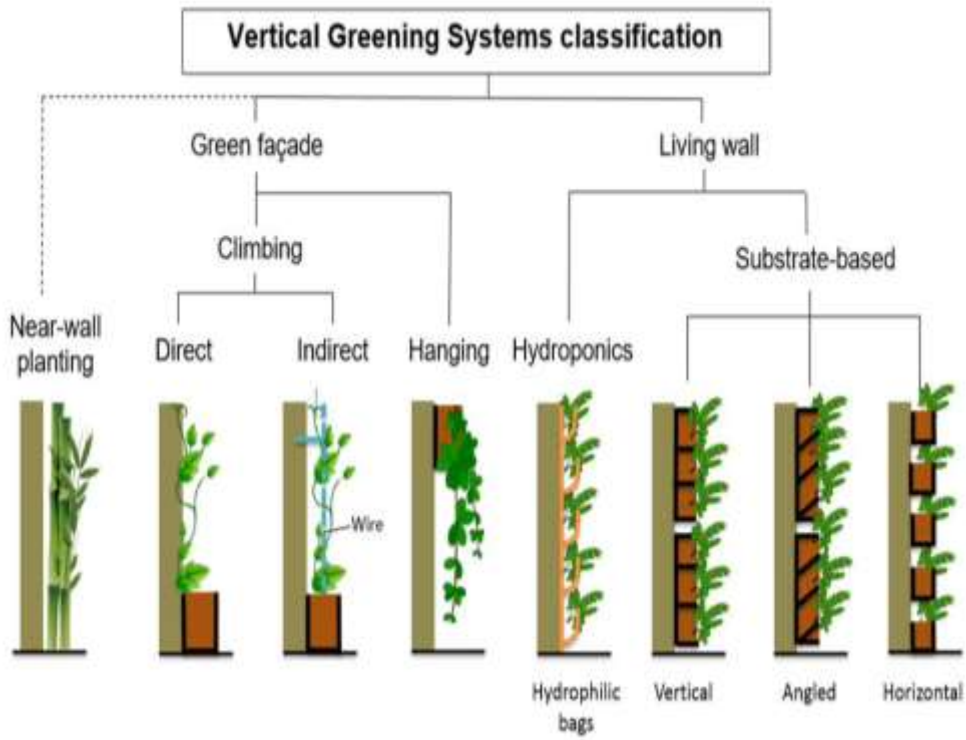


Figure 2; Classification of vertical greening systems (Fernández-Cañero et al., 2018).

(Sun et al , 2024) ,(Dominici et al , 2022), (Younis et al, 2024) presents various Vertical Green Systems (VGS; the Modular Panel System, uses pre-vegetated panels with waterproof insulation, offering thermal and noise benefits but requiring maintenance. the Textile Bag System, is lightweight and flexible, using fabric pockets to hold plants, though it limits root space. the Planter/Pot System, is versatile and adaptable, suitable for various plants but requires careful irrigation and drainage management. the Guttering System, repurposes old gutters for planting, offering a cost-effective solution but limited by shallow root space. the Piping System, uses PVC pipes to hold plants, allowing creative designs with a drip irrigation system. Finally, the Freestanding Wood-Based System, uses stacked wooden crates for larger root space and plant variety, though it requires maintenance to prevent wood damage. Table (1)

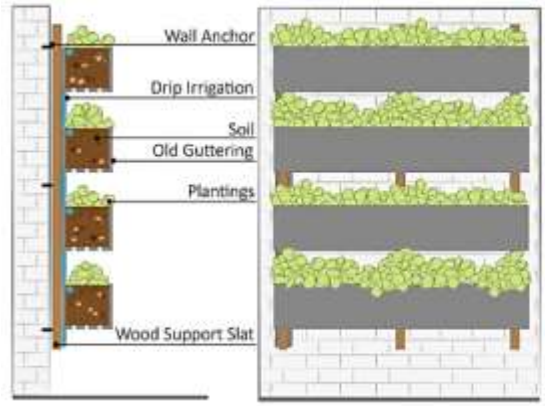
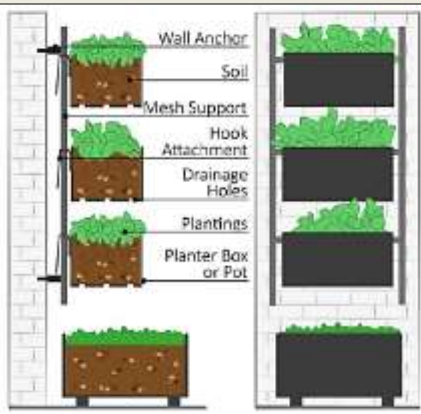
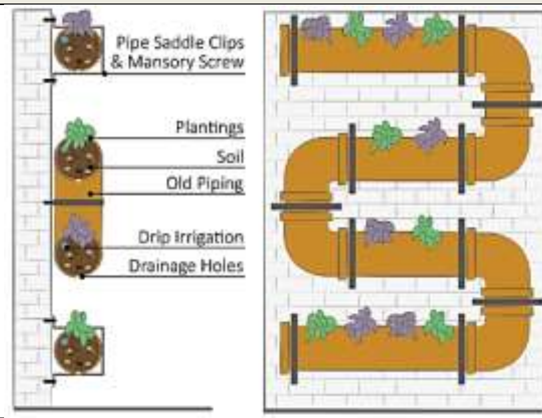
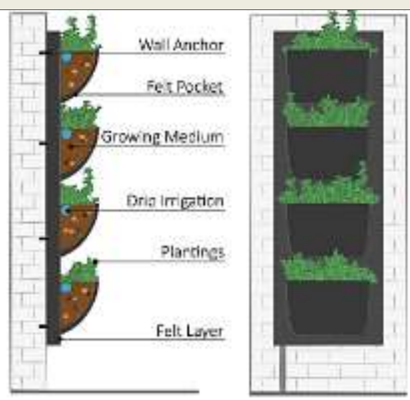
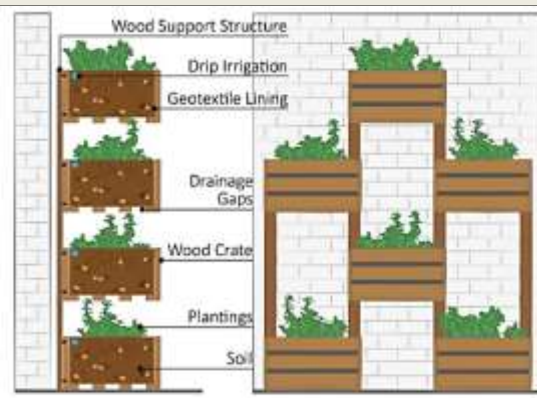
Modular Panel System	Guttering System
	
Planter/Pot System	**Piping System**
	
Textile Bag System	**Freestanding Wood-based System**
	

Table 1. Types of vertical green systems

Technical Considerations

The VGS systems, namely Modular Panel, Textile Bag, Planter/Pot, Guttering, Piping, and Freestanding Wood-Based Systems, all have some unique technical issues. (Su et al., 2024)

(Abdeen et al., 2024) (Wu et al., 2023) These issues are irrigation and drainage control, provision for structural stability, and maintenance of root space and water retention that is favorable for plant growth. Models such as Modular Panels and Textile Bags need careful positioning and water management, whereas Planter/Pot and Guttering systems need weight support and root space. Piping systems need secure fastening and maintenance, whereas Freestanding Wood-Based systems need appropriate wood treatment to avoid rotting and attain durability. Maintenance needs to be done on all models at all times to maintain functionality and aesthetics. Table (2).

VGS systems	Technical Considerations
Modular Panel System	Must be incorporated into irrigation systems for the plants to grow. Panels must be aligned with accuracy so as not to cause structural compromise. Waterproof insulation must be maintained for thermal and noise insulation. Maintenance is required to ensure panel and plant integrity.
Textile Bag System	Constricted root space owing to fabric pocket structure. Requires to be precisely controlled for water holding, via wicking or surface drip irrigation. Drain holes should be located at the bottom of every pocket to prevent waterlogging.
Planter/Pot System	The design must adequately support the weight of planters, particularly when accommodating larger vegetation. Continuous monitoring of irrigation is necessary to maintain uniformity.
Guttering System	Limited root space restricts the use of plants to shallow-rooted plants. Careful design must be employed to permit satisfactory water flow. The gutters need to be properly secured to prevent movement.
Piping System	Requires pipes to be securely connected to prevent displacement. Drip irrigation is used extensively to distribute water evenly. The system has to be such that it facilitates easy access to maintain and replace plants.
Freestanding Wood-Based System	Need a strong base not to collapse under the weight of the structure. Wood is liable to decay if it gets in contact with water thus it has to be treated. It needs some routine care for the duration of the wood to last as long as possible. It is necessary to have good drainage and aeration so as not to stand in water.

Table 2. VGS systems technical considerations

Structural Support System

One of the most important considerations in retrofitting vertical green systems (VGS) is ensuring the structural integrity of the existing buildings. Most studies (Hong et al., 2019) have addressed the issue of weight-bearing capacity, particularly for buildings that were not originally designed to support heavy green systems. A robust frame with strength and capability to carry vegetation is vital in Vertical Green Systems (VGSs). VGS weight ranges from 60 to 500 kg/m² based on the foliage intensity and vegetation level (Cuce 2017). (Pérez et al, 2015). An in-depth analysis of the building's structural stability and capacity to bear load during critical conditions is vital in order to ascertain that the VGS will not compromise the building's structural stability. This forms a critical consideration in maintaining the safety and efficiency of the VGS installation.

Incorporating (VGS) into existing buildings requires keen attention to building structure. The ideal design considerations include several aspects such as load management, and material, , which ensure VGS maximizes building function and form. For the living wall system, manufacturers of products must be consulted particularly for weights of modular panel and fabric mats. Modular, gabion, mortared, and cast-in-place retaining walls have high potential and can be used as green walls through the incorporation of vegetation. Durability issues along with an insight into the dynamics of the roots of plants need to be considered.

Structural Load Management

Static and Dynamic Loads: VGS must account for both dead loads (weight of the system) and live loads (occupants, maintenance) to prevent structural failure (Gartner, 2008).

Dead Load Calculation (Weight of VGS System): Dead load is used when expressing the weight of the Vertical Green System, all the components like modular panels, fabric mats, growing medium, plants, and irrigation systems. Weight per unit area must be procured from manufacturers, who usually have specifications like kilograms per square meter (kg/m²). (Murkute et al, 2019). For each component of the system, use the following formula:

$$\textbf{Dead Load (kg/m}^2\textbf{)} = \sum \textbf{(Weight of each VGS component} \times \textbf{Area of coverage)}$$

Where:

- Weight of each VGS component includes the weight of the panel system, soil, plants, water, and any irrigation infrastructure.
- Area of coverage is the area on the wall or surface where the VGS will be applied.

Live Load Calculation (Occupant and Maintenance Loads):

Live loads are the loads due to occupants, maintenance operations, or equipment that could affect the VGS system. This would typically be determined from local building regulations or engineering design guidelines . ASCE,. (2010). For a VGS, this could also include other aspects such as cleaning or maintenance of an irrigation system. The general formula is:

$$\textbf{Live Load (kg/m}^2\textbf{)} = \textbf{Occupant Load} + \textbf{Maintenance Load}$$

Seismic and Wind Effects: Proper design and anchorage must eliminate the risks of wind forces, especially in high-rise structures (Gartner, 2008). (Bielawski et al, 2024) Dynamic Loads (Wind, Seismic Forces): Wind load on the VGS system equation is determinable as:

$$\mathbf{F(wind) = q(z) \times Cd \times A}$$

where:

- F = wind load per unit length (kN/m or lb/ft),
- q(z) = velocity pressure at height zzz,
- Cd = drag coefficient,
- A = projected area per unit length.

Material Considerations

The use of lightweight, durable materials can decrease the load on the building while maximizing insulation and energy efficiency (Manouchehri et al., 2024). The conventional living wall systems are heavy because of the plants, the soil, and irrigation systems. The load can be lessened considerably by using lightweight materials while retaining the advantages of greenery. According to Rahiminejad et al. (2022), some of the materials utilized in modular green wall systems are lightweight concrete panels, aluminum frameworks, and composite materials. The materials selected encourage the preservation of structural integrity while simultaneously reducing the effect on the building's overall load-carrying capacity.

Retrofitting Stone Facades with Vertical Greenery System

This offers a unique opportunity to combine the aesthetic and historical significance of traditional stone construction with the energy efficiency and environmental sustainability benefits of vertical greenery systems. Stone facades, being long-lasting, with thermal mass properties and enduring beauty, offer a suitable substrate for vertical greenery system installation (VGS). Retrofitting must be well planned, particularly in conjunction with the existing stone building, to be structurally sound, compatible, and sustainable.

Assessment of Structural Integrity

Prior to retrofitting a stone facade with a VGS, the structural integrity of the building must be evaluated. Stone facades are heavy, so it is required to look carefully into whether or not the existing structure will have the capacity to carry the extra dead load that the green facade system will entail, such as the weight of the plants, growing media, irrigation systems, and the structure of the green wall itself. In certain instances, it may be crucial to add support to the current stone facade or incorporate structural changes to offset the additional load. The viability of such an installation is dependent on the load-carrying capacity of the stone walls and their capacity to support static loads (dead load) as well as dynamic forces (wind and seismic loads) of the green wall system. (Ogut et al, 2022)

Compatibility with Green Wall Systems

When installing a VGS on a stone façade, material compatibility becomes a very important factor to consider. The chosen VGS system must be able to be attached to the stone in a safe manner without compromising the integrity of the stone surface or damaging itself in the long term. Various attachment means can be utilized, including anchors, brackets, and fasteners, which must be carefully selected to be compatible with the stone surface. (Di Nunzio, 2021) For instance, in a modular panel system, pre-vegetated panels may be installed on a frame that is anchored into the stone wall using the right fasteners that do not damage the stone or the masonry. Figure (3) (4) Additionally, systems for supplying moisture drainage are of highly important value. Stone facades are prone to water penetration; thus, there should be sufficient drainage in the design to avoid water collection behind the green facade since this would lead to the deterioration of the stone in the long term. Textile bag or planter pot systems can be utilized in combination with other moisture control layers to avoid water accumulation and protect the stone facade.

Design Considerations for Aesthetic and Functionality

The design of the green facade, along with enhancing the building's aesthetic value, should complement the architectural theme of the stone facade. Stone facades, through their complex textures and natural hues, offer the ideal background for the rich colors of foliage, which can create a captivating contrast between the traditional and modern themes. (Magliocco, 2018) The design should also consider the plant species to be incorporated, ensuring that the vegetation selected is resilient to the existing environmental conditions of the building, such as sunlight exposure, direction of wind, and humidity. Climatically native low-maintenance plants will guarantee the sustainability of the green facade and minimal maintenance expenses. Aesthetic harmony must also exist between the stone components and the green facade. While a modular panel system can provide a more contemporary look, a textile bag system or planter pot system can provide a more natural, earthy look that will blend with the earth tones of the stone. This design flexibility allows architects to be able to create a facade that is sensitive to the building's history but includes a modern, green touch.

Discussion

Modular Panel System Utilizing composite light materials (e.g., HDPE, polystyrene) which provide thermal insulation and allow for effective removal of moisture, the modular panel system can help reduce a building's dead load. The dead load comprises the weight of the panels, growing medium, plants, water, and weight of irrigation system all of which need to be quantified per unit area. Live loads, e.g., maintenance, shall also be included. Design should include wind load calculation and proper anchoring to prevent moving into high winds. Including the Textile Bag System (made from burlap or geotextile) provides an even lighter dead load, in addition to the capacity for plant growth and thermal control.

Similar to the Modular Panel System, wind load calculation and anchorage are essential because of the fabric material's flexibility. The dielectric strength and permissible voltage stress are also affected by the surface roughness and the type of gap between the insulation and the metal. By using a tape, the surface roughness is eliminated, and both systems provide adequate voltage stress. Plastic planters and PVC pipes lessen the weight, while materials such as ceramic or wood add weight to it. Live loads should consider maintenance activities, and all the systems need to be anchored to avoid being displaced by strong winds. The Guttering System's thin profile is less vulnerable to wind forces but still needs to be anchored, particularly in high-rise structures. The Freestanding Wood-Based System, being heavier in mass, needs to be well treated for durability and also handled with care for wind loading. Static and dynamic loads in both systems need to be properly addressed. The static load, as the total weight of all system elements (i.e., panels, soil, vegetation, water, and irrigation systems), needs to be determined in terms of manufacturer-defined weight per unit area. Similarly, the dynamic load, as occupant use and maintenance activities, needs to be determined in compliance with local building codes and engineering practices. Anchoring is required by all structures to prevent wind and seismic-caused structural failure, especially on tall buildings or areas prone to the same. Wind load calculations are important, especially for systems that possess large surface areas that are exposed to the elements.

Installation Process

The installation process involves several key steps:

- **Preparation of the Stone Surface**

The existing stone façade must be thoroughly cleaned and inspected for structural imperfections that must be rectified before installing the green façade system. Cracks, deteriorations, or loose portions of stone be repaired before installing the green façade system (Mas et al., 2011). In order to guarantee effective water resistance in stone façades without compromising their visual appearance, there are different sprayable waterproofing materials that can be used. Water is absorbed in the micro-pores of a sealing material at accelerated rate by using a sealant either among silicone, acrylic, polyurethane, fluoropolymer sealants or lithium silicate- and nano-coating-based sealants. Poster products act as an invisible barriers to allows moisture to pass in and out of the stone, without retaining moisture in the stone and also not adding any sheen nor altering the natural appearance of the stone. Qattan et al. According to (2018), a space should be provided between the VGS system and the stone wall for the airflow and for the flow of water so that the chance of water accumulation at the back of the VGS is minimal. Treatment application involves surface cleaning, spraying with a solution, and allowing sufficient drying time, which ensures durability in water resistance without altering the stone's aesthetic value.

- **Attachment of the Green Facade System**

It depends on the kind of Vertical Greenery System (VGS) model, i.e., pre-vegetated panels, textile bags, or planters. Such a system has to be spaced and attached carefully to give even load distribution to the stone facade. Aluminum uprights, aluminum frame, FOREX panels, multilayer felt (3-4 layers), aluminum support brackets, hook attachments for fixing panels are used for Modular Panel System installation. For the Textile Bag System, there are 26 to 65 mm adjustable anchor brackets in combination with 60 mm aluminum uprights. Rigid pot supports, pot support fixing clips, and hook attachment modular pots also play a role in overall stability. These types of attachment offer secure integration without affecting the structural integrity of the wall. Figure (3) (4)

- **Integration of the Irrigation System**

It is required to retrofit a Vertical Greenery System (VGS) in such a manner that the plants are properly watered without causing any possible water damage to the stone façade (Wang et al., 2016). In the Modular Panel System, the irrigation system is composed of tubes fixed to an aluminum water collection tank. Within the Textile Bag System, a horizontal micro- irrigation system is coupled with raceway water channels and granular surface to ensure maximum watering distribution. The systems are specifically designed to supply even moisture to the plants while safeguarding the underlying structure from water intrusion. Figure (3)(4)

Figure 3. Attachment of the (GVS) modular panel system

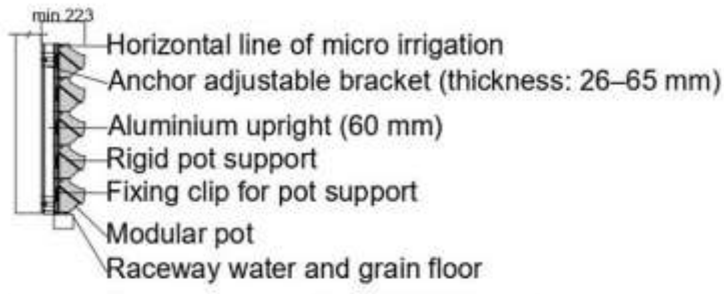


Figure 4. Attachment of the (GVS) textile bag system

Conclusion

Retrofitting a stone facade with a green facade system provides an opportunity to keep the building's historic value while modernizing it with eco-friendly technologies. It contributes to sustainability through improved energy efficiency, better air quality, and stormwater management, as well as offering aesthetic enhancement and increased property value.

Figure (5) illustrates the step-by-step process for retrofitting stone facades with VGS. The roadmap begins with the assessment of the existing facade, where the building's structural integrity is evaluated. If the structure passes this assessment, the next step is to choose a suitable type of VGS based on the building’s requirements. Next, material considerations on the structural support system are made, as well as static, dynamic, and dead load analysis, ensuring the building is capable of holding the extra weight. The structural load management phase, on the other hand, will ensure its right spread and reinforcement. After that, world aesthetic and functionality design concept is determined by balancing synthesizing visual of the stone and greenery once the stone facade is prepared, it needs to be waterproofed and structurally secure before moving forward. Next is the VGS which is attached to the wall through well-crafted installation methods used to avoid infiltration or damage to the facade. All these are then concluded into the successful retrofitting of the building with the Vertical Greenery System (VGS) on it which adds to the sustainability aspect of the building along with the aesthetic value.

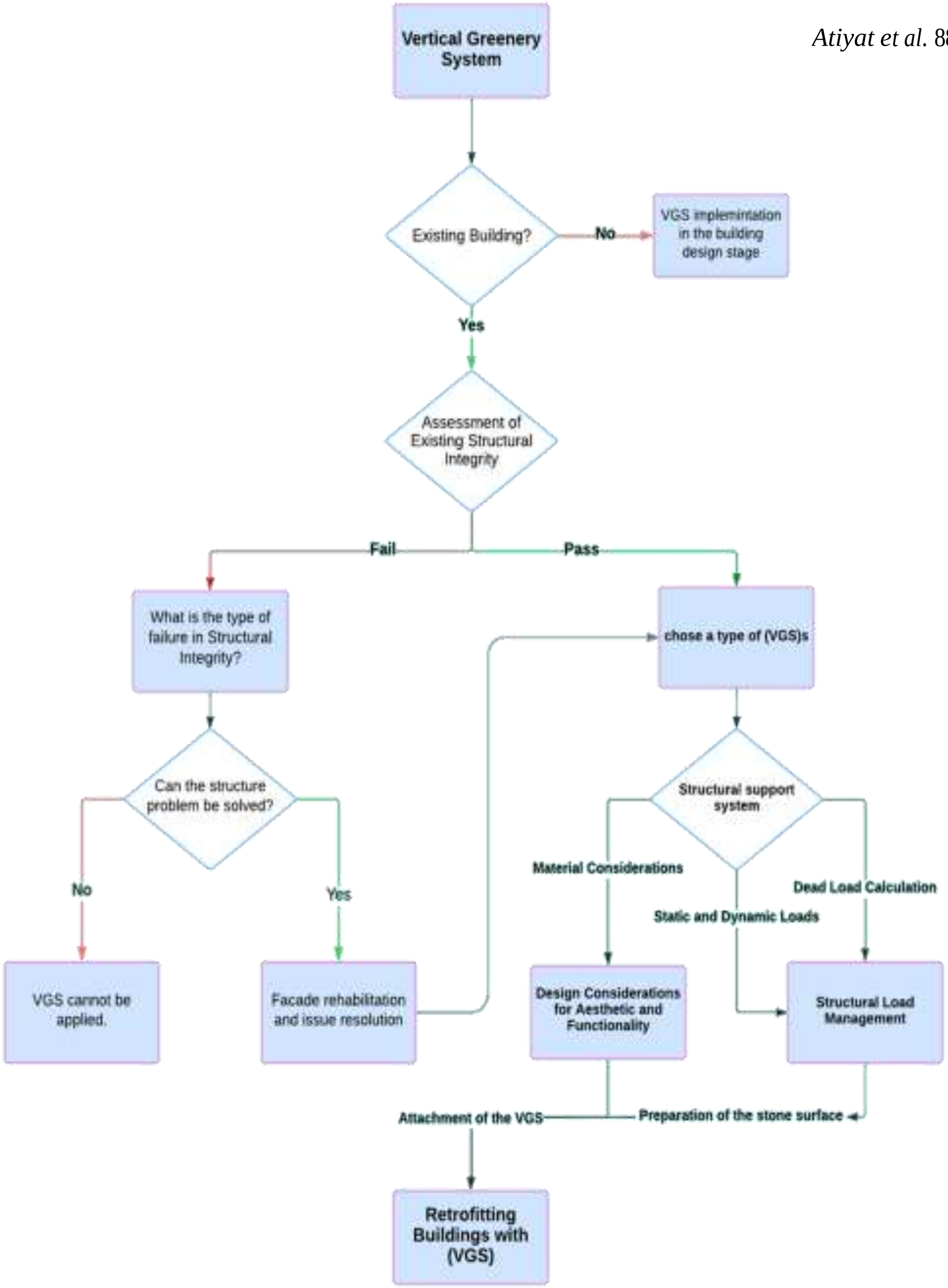


Figure 5. Road map for retrofitting stone facades to VGS facades

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