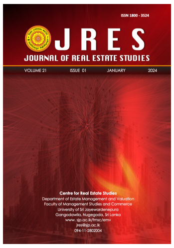

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Vertical Greenery Systems in Tropical Climate - A Review

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ABSTRACT

In burgeoning tropical urban areas, impermeable surfaces exacerbate urban heat stress, creating Urban Heat Islands (UHI). Mitigating this requires the adaptation of Vertical Greenery Systems (VGS) in the built environment. While studies explore VGS, few address their environmental impact in tropical contexts, where adverse weather challenges the design and management. Guided by 'Green wall,' this study categorizes literature on VGS into systems, technical properties, and tropical challenges. Scrutinizing climate, maintenance, and cost as barriers, the study aims to identify factors influencing successful VGS deployment in the tropics. Objectives include exploring typologies, designs, performances, irrigation, maintenance challenges, and climatic factors. Insights seek to offer a nuanced understanding of their efficacy across climates. Recommendations stress the need for targeted tropical research, a multidisciplinary maintenance approach, meticulous material selection, and ongoing technological adaptation for sustainable VGS in tropical urban landscapes.

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1. INTRODUCTION

Urbanization is predominantly observed in developing and third-world nations, particularly within tropical and subtropical zones (Jamei et al., 2020). These climatic regions span between 23.5°N and 23.5°S latitudes, encompassing numerous rapidly developing countries in South America, Africa, South Asia, East Asia, and Southeast Asia. These areas experience intense sunlight and maintain average temperatures of 18°C or higher throughout the year. The annual precipitation in these regions is typically high and exhibits a rhythmic pattern to varying degrees (Marcotullio et al., 2021). Regarding the Urban Heat Island (UHI) effect, canopy temperature differences are generally in the range of 3–4°C (Voogt, 2002; Oke et al., 2017). However, these values can fluctuate significantly, spanning from 0.4 to 12°C, and can even peak at 17°C in specific inner-city hotspots (Santamouris, 2015; Makrogiannis et al., 1998). This variability underscores the intricate dynamics of urban heat within these regions.

Like the rest of the world, tropical regions shown in figure 1 show a continuous

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growth in cities for the last decades (UN, 2018) and life loses its quality day by day, adversely affecting the inhabitants of the city (Baran & Gultekin, 2017). According to the United Nations, cities situated in the tropical zone occupy only 36% of the Earth's surface yet account for ⅓ of the entire global population (Jamei et al., 2020). This rapid growth of compact dense cities in the tropics has also been accompanied by increased urban temperature and studies have been conducted on urban heating effects as urban environments are generally hotter than rural contexts (Marcotullio et al., 2021).

British Petroleum (BP) specifies that due to higher energy consumption, global oil consumption will be increased by 30% within another decade and a half (Berardi, 2017). According to the International Energy Agency (IEA), cities consume 73% of the world's total energy with emissions of 70% CO_2. As a result, the quality of the city's environment, microclimate, and ecosystems has a negative impact causing relatively rapid changes in the global climate and having other catastrophic effects on the whole environment, sources the development of carbon footprints and greenhouse gasses, increasing the urban heat island effect (El Menshawy et al., 2021).

Taking into consideration, the International Energy Outlook report emphasizes that the building sector will play an outstanding role in the world's total energy use in the future (Berardi, 2017). Responding to this phenomenon pressing upon climate change challenges, Architects and Urban planners have been proposing sustainable building designs to reduce the energy demand, minimize environmental impacts and alleviate the heat island effect (Radic et al., 2019). The most important part of the building is the skin or the façade of the building when approaching a bioclimatic design (Othman & Sahidin, 2016). Contributing to the problem's solution, the application of green facades and living walls are used as sustainable building design elements that are steadily gaining importance and are increasingly widely used (Radic et al., 2019).

In-depth knowledge is necessary to promote green facades and living wall adoption in cities. Many research studies have been conducted across the globe, nevertheless, information and knowledge on the adaptation of green wall systems in tropical cities are incomplete and piecemeal in the scientific literature (Jim C, 2015). The number of articles found in the tropical context is mentioned in Figure 1. This insufficient knowledge contributed to design failures, improper management, and outright failure.

Research studies have been comprehensively mapping out: Different types of Vertical green facades (Baran & Gultekin, 2017) (Manso & Castro-Gomes, 2015), their benefits on health and comfort (Radic, Dodig, & Auer, 2019) (Manso et al., 2021), carbon emission and thermal comfort of the users (Charoenkit & Yiemwattana, 2016) (Koch et al., 2020), evaluation of the thermal performance of the green facade or the living walls (Koc et al., 2018) (Hunter et al., 2014), state of art of new technologies used (Medl et al, 2017), economical and maintenance challenges (Teotonio et al., 2021) (Liberalesso et al., 2020; Gunawardena & Steemers, 2020), are widely studied around the world. As some review studies on vertical green systems are already available, this paper focused on vertical greenery systems around the tropical context, addressing,

- The typologies, design, and performances of the vertical green wall systems in the tropics
- Extended discussion on different irrigation systems used in VGS.
- Maintenance and challenges faced by VGS in tropical climates.

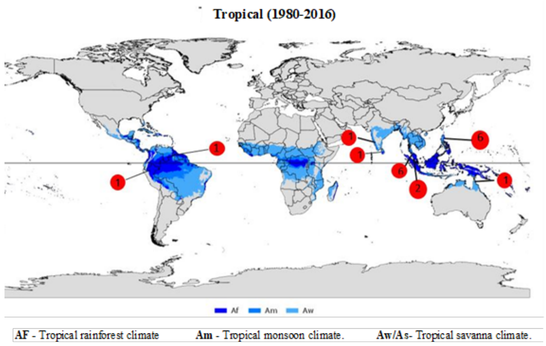
- Discussion on climatic factors affecting VGS in tropical settings and a comparison of the same in different climates.

2. METHODOLOGY

The study conducted a comprehensive review and analysis of past and recent literature on vertical greenery systems (VGS), covering both green facades and living walls. The systematic literature review involved searching academic databases such as Science Direct, Scopus, ResearchGate, and Google Scholar, using the main keyword "Vertical greenery systems." This search yielded 98 relevant papers and articles. The study also consulted websites and manufacturers' catalogues to gather information on construction methods and plant types.

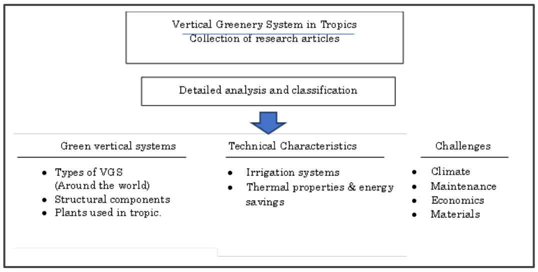
The challenge of precise categorization arose due to diverse naming conventions for similar VGS construction types. Mina Radic's study (Radic et al., 2019) emphasized the lack of precise naming, noting the term "hydroponic system" used interchangeably with VGS construction types. The paper classified various names found in literature, articles, and catalogues under green facades and living walls based on construction types, acknowledging differences in design and materials. Conclusively, a compilation of various names associated with green facades and living walls has been organized according to their construction types. Notably, these names may signify distinctions in both design and the materials utilized, as depicted in Figure 3.

Figure 1: Number of publications related to VGS around the tropics. Locations and color-coded by Koppen-Geiger classification



Source: Beck et al. (2018)

Figure 2: Flow diagram of the methodology.



The review focused on plant types, climatic factors influencing plant growth in tropical settings, and briefly discussed thermal performance. The primary emphasis was on technical challenges related to maintenance in tropical installations. Technical characteristics such as weight, dimensions, recyclability, and economic aspects, as well as specific architectural typologies and computer-simulated studies, were excluded from the scope. The study also excluded cantilevered vegetated balconies and green stepped terraces in buildings due to their classification as non-facade structures. Overall, the research provided insights into VGS construction, plant considerations, and addressed challenges related to maintenance in tropical environments.

Within the comprehensive collection, 20

articles are allocated to typology, while 10 articles are dedicated to elucidating the benefits of Vertical Greenery Systems (VGS). Additionally, 35 articles focus on technical characteristics and thermal properties, addressing their role in climate change mitigation and as a method for carbon sequestration. Notably, a subset of 22 articles specifically investigates VGS in tropical regions, based on the Köppen-Geiger climate classification.

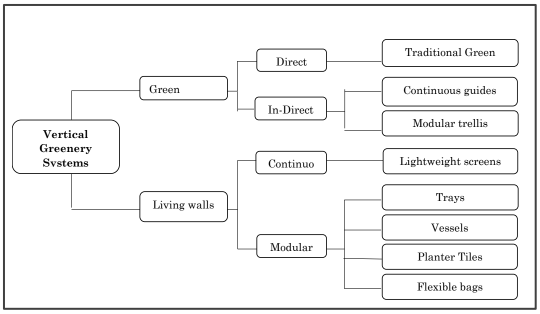
3. VERTICAL GREENERY SYSTEMS

The history of Vertical Greenery Systems (VGS) dates to the 7th century with the Hanging Gardens of Babylon, featuring terraces covered in vegetation (Wang et al., 2016). Modern systems were introduced by Stanley Hart White in 1938, presenting the concept of Vegetation Bearing Architectonic Structure and System (Hindle, 2012). VGS gained popularity in the 1980s when botanist Dr. Patrick Blanc integrated plants on building facades, addressing environmental concerns (Abu Bakar et al., 2013). Since then, the VGS model has been globally modified and adopted, particularly in tropical regions like North, South, and Central America, the Caribbean, and Asia (Abu Bakar et al., 2013).

3.1 Types of Vertical Greenery Systems

Vertical greenery or commonly referred to as a "vertical garden" has different systems which can be categorized according to the growing method (Perini et al., 2011). It can be a plant rooted into the ground or on the wall material itself or in modular panels attached to a building façade which can be grouped as green facades and living walls (see figure 3) (Perini et al., 2011). Each system can be further categorized into different types and systems according to design, installation and maintenance (El Menshawy et al., 2021).

Figure 3: Types of vertical greenery systems



Source : Cuce (2016); El Menshawy et al. (2021)

3.1.1 Green Facades

The green facades are the types of vertical greening systems that climbing plants have been using to cover building facades (Othman & Sahidin, 2016). This system further can be categorized as direct and in-direct systems which consist of climbing or hanging plants that can grow directly attaching to the building facade or supported by cables or trellis (Cuce, 2016).

The direct greening façade system

Plants are directly attached to the wall without any structural support. This is called the Traditional green facade system where climbing plants and creepers' roots are either placed in the ground or planter boxes (El Menshawy et al., 2021). These plant species have the adhesive property to attach to a wall without any additional support to grip. This method takes about 3-5 years for the plants to fully grow and cover the whole façade (Othman & Sahidin, 2016). Mostly common seen on fences or columns, embedded in existing walls (Baran & Gultekin, 2017).

The in-direct greening façade system

Certain plants lacking adhesive properties require additional support structures for growth (El Menshawy et al., 2021). Various materials like cables, meshes, ropes, wood, plastic, or aluminum can serve as support for climbing plants (Baran & Gultekin, 2017; Perini et al., 2011; Susorova, 2015). Rooting space may be in the ground or planter boxes, positioned at the bottom or on different levels of the facade for optimal coverage (El Menshawy et al., 2021). Creating an air gap between the vegetation and facade forms a "Double skin facade" (Manso & Castro-Gomes, 2015). Indirect systems include the Modular trellis panel, continuous guides (grid system), and wire-rope net system. The latter promotes rapid plant growth, suitable for fast-growing plants, while slower-growing plants benefit from smaller intervals in the wire-rope net system (Baran & Gultekin, 2017). Modular trellis panels, made of powder-coated galvanized steel wire, serve as building blocks, influencing aesthetics and functionality based on factors like weight, profile thickness, durability, and cost (Baran & Gultekin, 2017).

3.1.2 Living Walls

Living walls also referred to as green walls and vertical gardens, consist of more than one type of plant. Ground cover plants or evergreen plants (such as small shrubs, grasses, perennial plants, and succulents (Palemo & Turco, 2020)) are possible to grow vertically by using this method (Othman & Sahidin, 2016) (Susorova, 2015). Living walls are constructed from modular panels which contain soil or other artificial growing mediums, where both plant and the planting medium are placed on the vertical surface (Perini et al, 2011). For example, the use of foam, perlite, and mineral wool, and based on hydroponic culture, all parts of the plant's food and water requirements are provided along with balanced nutrient solutions (Perini et al, 2011). This type of vertical greenery system needs more maintenance compared to other types, as it contains a wide variety of plant species (Othman & Sahidin, 2016). To protect the façade surface, commonly the living wall has been separated from a layer of waterproofing membrane (Susorova, 2015). Some living walls' substrate needs improvements with nutrients for plant growth. For example, the use of a mixture of organic and inorganic fertilizers, metal chelates, minerals, nutrients and hormones for plants or other additives can be used as upgrades (Manso & Castro-Gomes, 2015).

Over the years living wall system has been developed into a wide variety of types with different characteristics. They can be classified as continuous or modular, according to their growing medium and application method (Perini et al., 2011).

Continuous Living wall

The Hydroponic system, as described by Palemo and Turco (2020), eliminates the need for soil substrate, utilizing fabric or felt layers cut into pocket-like forms for plant growth. These lightweight, absorbent screens, attached to layers, are root-proof, flexible, and permeable, supported by a base panel. Indirectly connected to the building façade, a void space is created, preventing wall humidity (Manso & Castro-Gomes, 2015). Following the Hydroponic technique, pre-grown plants are individually inserted into panels, applicable in both indoor and outdoor settings (Editors, 2020). Irrigation pipes behind fabric layers ensure water and nutrient distribution via gravity (Susorova, 2015), supported by a waterproof PVC sheet (Perini et al., 2011).

Modular Living wall

Out of the types of living wall systems, the modular living wall system differs in weight, composition, and assembly (Perini et al., 2011). These pre-vegetated panels can be in the form of different supporting elements, such as vessels, trays, flexible bags, or planter tiles. In this system, plants' growing medium can be both organic and/or inorganic substrate with a good retention capacity where root growth is propagated. Typically, the irrigation system is installed between the panels according to the configuration of the supporting elements (Palemo & Turco, 2020). This system is usually comprised of several interlocking parts, made from lightweight materials like plastic (polypropylene or polyethene) or metal sheets (aluminium, stainless steel, or galvanized steel) (Manso & Castro-Gomes, 2015).

a) Trays are sturdy containers, typically plastic or metal, designed with specific dimensions for holding plants and substrate weight (Palemo & Turco, 2020). They come in various shapes, such as framed boxes or wire cages, with precut holes. Some have hooks or brackets on the back surface for vertical facade connection (Manso & Castro-Gomes, 2015).

b) Vessels - This system can be attached vertically to each other and easily fastened to a vertical structure (Perini et al., 2011). Moreover, this system allows the installation of several plants in each vessel along the same row. Commonly made from polymeric materials and the form creates a pleasing image on the building surface (Manso & Castro-Gomes et al., 2015).

c) Planter tiles - The system acts as modular cladding for both exterior and interior walls, functioning beyond a vegetative layer (Perini et al., 2011). Tiles connect by juxtaposition, featuring a flat back for surface attachment and areas for individual plant insertion. Constructed from lightweight materials like plastic or ceramic, they can be glued or mechanically fastened to vertical surfaces (Manso & Castro-Gomes, 2015).

d) Flexible bags- Also termed as hanging pocket living walls (Susorova, 2015) are lightweight fabric containers (felt, capillary mat) attached to a rigid support (waterproof plywood board). These living walls are shaped like pocket modules containing soil or other growing media such as pumice and compost (Urrestarazu et al., 2019). Application of vegetation on surfaces with different forms, for example, curved or sloped surfaces (Perini et al., 2011).

Peter et al. (Pérez et al., 2011) was classified these construction systems into 'extensive and intensive systems,' with Green Facades as extensive and Living Walls as intensive. Lee and Jim (Lee & Jim, 2017) classify green walls as "climber green wall" and "Herb-shrub green wall" based on veneer and substrate systems. Safikhani et al. (2014) detail living wall modules like G-sky, green wall containers, woolly pockets, Verti-Garden, Philly Green Wall, and Fytowall. Woolly pockets are pouches with stacked plants, while Verti-Gardens, produced by a British company, use plastic panels in zinc-plated steel frames.

Interior Living walls

Susan Loh (Loh S., 2008) introduces 'Interior living walls,' utilizing panel, felt, or container/trellis systems integrated into a building's mechanical system. Plants cleanse and humidify the air, with growing medium supplied indoors. Othman Ahmad (Othman & Sahidin, 2016) labels these as "Bio-Filtration" systems providing thermal regulation and purifying air using fans, akin to Hydroponics. Recycled water and nutrients from a tank irrigate the wall. Synthetic fabric layers on the gutter, with microbes, prevent volatile organic compounds (VOC) from entering. Termed 'Smart and Active' green walls in catalogues, they boast purification efficiency (Mustonen, 2017).

3.2 Irrigation

Both Green Facades and living walls need an amount of regular irrigation and fertilization throughout the life cycle. Water and nutrients can be treated either by pumping and distributed mechanically, or irrigated naturally by rain, manually or automatically (Susorova, 2015). Green façade systems can be easily irrigated while living walls should be monitored periodically to ensure the functioning of the irrigation systems and plant health. Specifically, the need for irrigation depends on the type of vertical greenery system, the plants used, and the climatic conditions, which matter (Manso & Castro-Gomes, 2015). Two different types of Irrigation systems can be found in research articles so far. VGS types have been summarized with specified irrigation and drainage systems in table 01.

Table 1: VGSs with Irrigation systems

VGS	Category	Sub-category	Irrigation system	Drainage system	Ref.
Green Facades	Direct	Traditional Green Facades	Sprinkler system/ manually		(Jim C. , 2015)
	In-Direct	Continuous Guides	Sprinkler system/ manually		(Jim C. , 2015)
		Modular trellis	Dip Irrigation system	Vessels with inferior holes	(Manso & Castro-Gomes, 2015) (Baran & Gultekin, 2017),
Living Walls	Continuous	Felt pockets Vertical gardens	Dip Irrigation system	Lateral and inferior holes	(Manso & Castro-Gomes, 2015)
	Modular systems	Trays	Dip/ Sprinkler Irrigation system	Lateral and inferior holes	(Baran & Gultekin, 2017)
		Planter tiles	Dip Irrigation system	Lateral and inferior holes	(Manso & Castro-Gomes, 2015)
		Flexible bags	Dip Irrigation system		(Manso & Castro-Gomes, 2015)

Jim (2015) conducted a field experiment using low-pressure, low-flow rate sprinklers with a flexible buried pipe on direct and indirect green facades. Yasemin Baran (Baran & Gultekin, 2017) discussed 'Metal Fence System Vegetation,' utilizing drip irrigation for climber plants. Modular system vegetation allows liquid manure and nutrient application through a sprinkler system (İpekçi & Yüksel, 2012). Manso and Castro-Gomes (Manso & Castro-Gomes, 2015) emphasized proper irrigation for modular green facades, suggesting continuous tubes at the top for uniform water distribution.

Continuous living wall systems with permeable screens ensure consistent water and nutrient distribution (Manso & Castro-Gomes, 2015). Modular living walls like trays use top-inserted irrigation tubes for gravity-fed watering, with drainage holes for excess water flow (Sabin, 2011; Sichello, 2010; Urriola, 2011; Yap et al., 2011). Various irrigation materials, including rubber, plastic, thermoplastic piping, and silicone connectors, offer outputs like drip, sprinkler, holes, or pipes with different distribution patterns. The equipment, housed in a mechanical room, includes manure and water tanks, pumps, crushers, and electric boards (Baran & Gultekin, 2017; Erdoğan & Khabbazi, 2013).

To conserve water, Manso and Castro-Gomes (Manso & Castro-Gomes, 2015) recommend placing plants with lower water needs at the top and those with higher demands at the bottom, utilizing gravity-fed vertical irrigation. Martensson et al. suggest high water retention substrates for irrigating larger volumes without runoff risk (Mårtensson et al., 2014). Regular maintenance is crucial for irrigation systems, addressing leaks, inspecting controllers and sensors, clearing debris from injectors, replacing electronic devices if needed, and verifying proper water flow and pressure (Ascione et al., 2020; Wood et al., 2014).

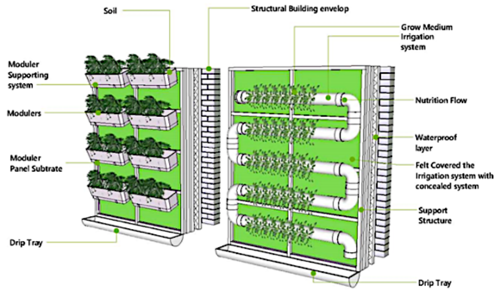
3.3 Drainage

In green wall types, geotextile materials facilitate gravity-driven excess drainage, particularly in Continuous and modular living walls. The permeable membrane in these systems allows water to pass through, enhancing drainage and nutrient access in modular trays (Manso & Castro-Gomes, 2015). Some modular systems feature concave, inclined, or perforated bottoms, made from porous or absorbent materials, improving drainage (Laurence & Sabin, 2011). Channels or holes in modular systems aid surplus water removal. Vessel-type living walls use filter materials, like inoculated sand, to purify rainwater and remove toxins, while inert fillers like expanded clay promote drainage and root development (Blanc, 1996).

3.4 Drip Trays

The excess irrigated water dripping from the growing medium and foliage is captured from drip trays. The size of the drip tray may vary with the volume of the vertical greenery system which should be sufficient to hold the entire irrigation cycle. If runoff is allocated below the irrigated vegetation, then a drip tray may not be necessary for the system. The tray should have a drainage pipe of sufficient diameter in size to capture the excess water without overflowing. Facia treatments can be added to conceal the edges. Moreover, the irrigated water collected at the drip tray can be pumped back to the top of the irrigation system for re-use (Growing Green Guide, 2014).

Figure 4: : Detail of the drip tray in both modular and hydroponic system

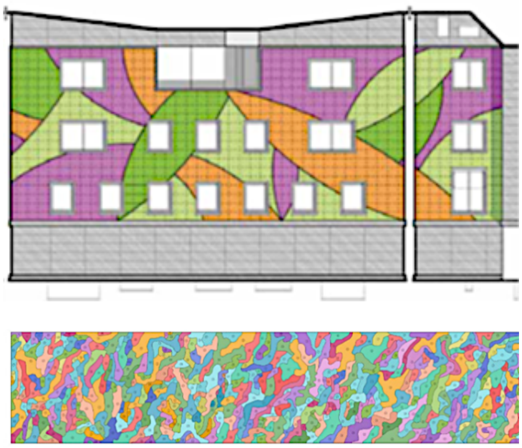


Source: Growing Green Guide (2014)

3.5 Tropical Vegetation on VGS

Beecham et al. (Beecham et al., 2019) was discussed the critical role of vegetation in any green wall system. Compared with the non-vegetative building cladding, vegetated facades provide shading to the façade which helps to regulate the temperature and the microclimate of the building. The selection of plants relies totally on the building orientation and climatic conditions along with local weather patterns.

Figure 5: Living wall plant pattern layout designs from manufactures' catalogues



Source: Knauf Insulation (2023); Horticulture (2023)

In tropical climates, characterized by persistently high temperatures and humidity, the design and durability of vertical greenery systems face significant challenges (Nedhal et al., 2013; Othman & Sahidin, 2016). This study addresses these issues by concentrating on vertical greenery systems tailored to tropical contexts. Baran and Gultekin (2017) underscore the importance of selecting suitable plant species that can easily adapt to prevailing climatic conditions for the maintenance of green walls. Jim (2015) contributes to this by developing a matrix guiding the selection of climber plants based on biological and horticultural traits.

Figure 6: Plant Selection Matrix

Multiple climbers- plant characteristics for Vertical Greenery System design and management			
Biological	**Provenance**	**Life- cycle**	**Growth-form**
	Native Naturalized Exotic	Perennial Biennial Annual	Stout-woody Slender-woody Herbaceos
Ecological	**Seasonality**	**Light-preference**	**Moisture-preference**
	Evergreen Semi-deciduous deciduous	Full-sun Semi-shade Shade-tolerant	Hydric Mesic Xeric
Growth-Habit	**Growth-rate**	**Attainable-height**	**Green-coverage**
	Fast Medium Slow	Tall>20m Medium 10-20 m Short 3-10 m Dwarf < 3m	High > 75% Medium 50-75% Low 25-50% Sparse < 25%
Foliage	**Leaf-size**	**3D-foliage**	**Seasonal-colour**
	Large> 8 cm Medium 4-8 cm Small <4 cm	Cantilever Normal Veneer	Vivid Change Moderate change Little change
Flower	**Showy-flower**	**Flower-size**	**Bloom duration**
	Conspicuous Moderate Non-showy	Large> 8 cm Medium 4-8 cm Small <4 cm	Long > 4 week Medium 2-4 weeks Short < 2 week
Climbing	**Attachment-mode**	**Training-system**	**Climbing-surface**
	Sticking[a] Gripping[b] Twining[c]	Bare wall Mesh (trellis) Netting (web) Cable (wire rope)	Wall Wall-like frame Pergola (arbour) Post-pole

[a] Direct attachment to the bare wall surface with sticky pads or sticky aerial roots.

[b] Attaching to wires of a training system of mesh or netting by tendrils, hooks, thorns, etc.

[c] Spiral twining around the cable (wire-rope) of the cable training system.

Source: Jim (2015)

Living walls offer a diverse array of growing methods and plants compared to the more limited green facades. Green facades primarily feature climbing plants, restricted to evergreen and deciduous foliage. Evergreen plants, with leaves year-round, suit continuous cooling in hot climates, while deciduous ones provide cooling in summer and heating in winter (Susorova, 2015). Climbing plants are classified as self-supporting or supported by structures varying in height and growth patterns (Yap et al., 2011).

In contrast, living walls present a wider range of plant types, encompassing shrubs, grasses, and perennials, facilitating artistic patterns and diverse aesthetics on building facades (Manso et al., 2015). This design concept is gaining popularity among designers and residents, providing a visually appealing option (Beecham et al., 2019). Before implementing creative intentions on building exteriors or interiors, it is crucial to analyse plant development, colour patterns, blooming, foliage, and composition.

Emphasizing sustainability, Manso and Castro-Gomes (2015) advocate for living walls with vegetation adapted to local weather conditions and possessing low irrigation needs. Modular living walls, featuring succulent plants, emerge as a low-maintenance alternative that reduces system weight. While extensive living walls may not be suitable for succulents, they can be integrated into smaller facades. Additionally, incorporating urban agriculture into green walls addresses food production challenges in densely populated areas.

3.6 Benefits from VGSs'

Green walls, supported by Manso et al. (2021), offer extensive benefits spanning micro to macro environments, addressing environmental and climate concerns. Through processes like photosynthesis, transpiration, and respiration, they absorb solar radiation, contributing to evaporative cooling and mitigating the Urban Heat Island (UHI) effect, particularly in warmer climates (Ascione et al., 2020; Radic et al., 2019). Green facades positively impact air quality and reduce pollution in urban areas (Radic et al., 2019), while elevated CO2 concentrations aid UHI mitigation (Zaid et al., 2018). Vertical greenery systems (VGS) act as sound buffers, reducing outside noises by up to 40 dB, and protect building facades, extending their lifespan (Timur & Karaca, 2013; Zaid et al., 2018).

Hydrologically, VGS contributes to the water cycle by absorbing evaporating water, reducing strain on rainwater drainage systems (Loh & Stav, 2008). Some living walls use greywater or rainwater for irrigation, incorporating renewable energy for sustainability (Radic et al., 2011). Qualitatively, VGS enhances well-being, offering psychological benefits, stress alleviation, and improved urban connectivity (Manso et al., 2021; Radic et al., 2019). Economic benefits include increased real estate values, potentially rising by 7 to 15%, making VGS a holistic and sustainable solution with long-term paybacks and tax incentives (Jialin, 2013; Perini & Rosasco, 2013). In summary, green walls and VGS significantly contribute to multifaceted environmental, social, and economic improvements in urban settings.

3.7 Thermal Performances and Energy Savings

Vertical Greenery Systems (VGS) provide heat insulation in buildings (Wang, Er, & Rahman, 2016). They enhance thermal performance by absorbing solar energy and converting it into latent heat through evapotranspiration (Zaid et al., 2018; Wang et al., 2016). The shadow effect on the façade reduces energy consumption and costs (Demuzere et al., 2014). Pérez et al. (2011) emphasize mechanisms like solar radiation interception, thermal insulation, evapotranspiration, and wind obstruction for energy savings. Beecham et al. (2019) highlight factors influencing VGS cooling, including canopy cover, thickness, and plant morphology. Lee and Jim (2017) identify weather, season, wall orientation, plant species, and growth as factors affecting thermal benefits. Research on VGS in tropical regions is limited, despite its significance in mitigating thermal stress and Urban Heat Island effects (Jamei et al., 2020). Wong et al. (2010) conducted an experimental study revealing that high foliage density and stable diurnal temperature reduce temperatures in VGS. Factors like substrate type, structure insulation, moisture content, and plant coverage influence thermal performance. Notably, the color of plants, such as red-leaved species, can impact temperature reduction (Wong et al., 2010). Overall, understanding these factors contributes to energy savings and efficient VGS implementation.

Table 2: Different selection of plants from data available in scientific literature around the Tropics

Ref	Characteristics	Country/ Context	Species	Plant type	category	VGS Type
(Jim C. , 2015)	Moderate growth rate with Ornamental flowers	Hong Kong, China	*Campsis grandiflor*	Surface Climber	Direct	Green Facades
(Jim C. , 2015)	Very poor growth rate	Hong Kong, China	*Epipremnum aureum*			
(Jim C. , 2015)	Poor growth rate. Moderate growth rate at the lower part but the upper level has a slow growth rate	Hong Kong, China	*Ficus pumila*			
(Jim C. , 2015)	Very poor growth rate and climber performance index	Hong Kong, China	*Ficus pumila cv variegata*			
(Jim C. , 2015)	Very poor growth rate with moderate flower score	Hong Kong, China	*Hedera helix*			
(Jim C. , 2015)	Very poor growth rate	Hong Kong, China	*Hedera nepalensis var. sinensis*			
(Jim C. , 2015)	Very good growth rate with a better climber performance index	Hong Kong, China	*Parthenocissus dalzielii*			
(Jim C. , 2015)	Poor growth rate. Moderate growth density at the lower level than upper levels.	Hong Kong, China	*Philodendron scandens*			
(Jim C. , 2015)	Poor growth rate. High growth density at the lower level while showing a moderate density at upper levels.	Hong Kong, China	*Syngonium podophyllum*			
(Jim C. , 2015)	Very poor growth rate	Hong Kong, China	*Trachelospermum jasminoides*			
(Jim C. , 2015)	Very good growth rate with moderate flower score	Hong Kong, China	*Antigonon leptopus*	Mesh/ supported	In-direct	Green Facades
(Jim C. , 2015)	Very good growth rate. Low growth density at the lower level & high density at the upper level.	Hong Kong, China	*Bauhinia corymbosa*			
(Jim C. , 2015)	Very good performance growth rate and density at all levels	Hong Kong, China	*Bougainvillea sp.*			
(Jim C. , 2015)	Very good performance growth rate and density at all levels.	Hong Kong, China	*Lonicera japonica*			

Ref	Characteristics	Country/ Context	Species	Plant type	category	VGS type
(Jim C. , 2015)	High growth rate with moderate density growth at all levels.	Hong Kong, China	*Podranea ricasoliana*		Indirect	Green Facades
(Jim C. , 2015)	Moderate growth rate and moderate flower score.	Hong Kong, China	*Pseudocalymma alliaceum*			
(Jim C. , 2015)	Fair growth rate and high flower score	Hong Kong, China	*Pyrostegia venusta*			
(Jim C. , 2015)	High growth performance at all levels with high flower score	Hong Kong, China	*Quisqualis indica*			
(Jim C. , 2015)	Moderate growth rate. Low-density growth at the upper level.	Hong Kong, China	*Vitis vinifera*			
(Jim C. , 2015)	Very good growth performance and moderate climber deficiency index	Hong Kong, China	*Wisteria sinensis*			
(Zaid et al., 2018)	Moderate growth rate and better flower score	Jawa, Indonesia (Native)	Bread flower *(Vallaris glabra)*			
(Zaid el al. 2018)	Fast growing with better flower score. Grows up to 15m	Indian sub-continent, southern China and Myanmar	White sky vine (*Thunbergia grandiflora alba)*			
(Zaid et al. 2018)	High growth rate, slow density growth at a lower level, requires a lot of water.	East Africa, Papua New Guinea, India	Winged bean (*Psophocarpus tetragonolobus)*			
(Zaid et al., 2018) (Pandey et al., 2015) (NParks, 2013)	High growth rate. Traditional medicinal plant and fast-food colouring agent. Air pollution tolerance index- 12.26–14.14.	Africa and the Indian Ocean	Bluebell vine (*Clitoria ternatea*)			
(Zaid et al., 2018)	High growth rate. The colour of the flower changes from white to pink at the latter stage	Indian sub-continent, China (Yunnan), Indochina	Shower orchid (Congea tomentosa)			

Ref	Characteristics	Country/ Context	Species	Plant type	category	VGS type
(NParks, 2013)	High growth rate. Air pollution tolerance index- 13.03–15.13	India	Elephant creeper (*Argyreia nervosa)*		Indirect	Green Facades
(Zaid et al., 2018) (Pandey et al., 2015						
(Zaid et al., 2018) (Pandey et al., 2015	High growth rate, grows up to 10m	Taiwan, Southeast Asia to Australia &	Australian gold vine (*Tristellateia australasiae*)			
(NParks, 2013)		Western-Pacific				
(NParks, 2013)	Medium growth rate with a good flower score. Air pollution tolerance index: 16.69–19.21	Tropical America	Sandpaper vine (*Petrea volubilis*)			
(NParks, 2013)	Moderate growth rate. Leaves give a garlic-like smell and have medicinal values	Tropical America	Garlic vine (*Pseudocalymma alliaceum*)			
(NParks, 2013)	High growth rate, with a good flower score	India and Malaysia	Blue trumpet vine (*Thunbergia laurifolia*)			
(Zaid et al., 2018) (Pandey et al., 2015	High growth rate. Air pollution tolerance index: 21.07–23.98	Mexico	Honolulu creeper (*Antigonon leptopus*)			
(NParks, 2013)						
(Zaid et al., 2018) (Pandey et al., 2015	High growth rate. Air pollution tolerance index: 18.20–20.15	Philippines, India, and Malaysia	Rangoon creeper (*Quisqualis indica*)			
(NParks, 2013)						
(Louis & Jim, 2019)	High Growth rate. Leaf Area Index-0.69	Hong Kong	Japanese Honeysuckle			
			(*Lonicera japonica*)			
(Boby et al., 2020)	Takes about 3 months to get its full-grown stage	Singapore, Asia	Thunbergia Grandiflora			

Ref	Characteristics	Country/ Context	Species	Plant type	category	VGS type
(Perera et al., 2021) (Rahman & Hassan, 2012)	Shallow root system with a woody taproot. Up to 50cm stems are strongly branched. A Perennial plant	Tropical and warm subtropical environments	*Desmodium triflorum*	Shrubs/ perennial		Living wall Modular
			(Fabaceae)			
(Perera et al., 2021) (Gilman, 1999)	Evergreen. Grow up to 30-40cm approx. Linear blades, sharp-tipped & stiff form. Dense ground cover.	Tropical context. Drought tolerant	*Roheo spathacea*			
(Rahman & Hassan, 2012) (Percy et al., 2000)(Perera et al., 2021)	Shallow rooted. Forms a dense mat with 15-30cm tall foliage. Slender culms and stolon,	Drought tolerant	*Axonopus fissifoliu*			
(Perera et al., 2021) (Liu, et al., 2008)	A medicinal plant, Maximum height of 0.2m and plant spread/crown width of 1m. shallow root system		*Centella asiatica*			
(Perera et al., 2021) (Shouliang & Phillips, 2006) (Arunbabu et al., 2015)	A shallow root system, Maximum 15-20cm tall creates a dense mat with foliage. A Perennial plant	Withstand dry weather	*Axonopus compressus*			
(Perera et al., 2021)	Shallow fibrous root system. High growth rate. Grow up to 0.5m	Tropical/ Subtropical regions	*Elusine indica*			
(Perera et al., 2021)	Dumb cane plant. Purify air.	Tropical plant	*Dieffenbachiae spp*			
(Perera et al., 2021)	Fibrous, tuberous, or rhizomatous roots. Size ranges from a few inches to over 12 feet in height.	Tropical/ Subtropical regions	*Bigonia spp*			
(Perera, Jayasinghe , Halwathura, & Rupasinghe, 2021)	Shallow root System. Fern species, non-flowering vascular plants with complex leaves	Indian sub-continent	*Tectaria spp*			

Table 3: Major findings from different experimental studies on thermal evaluation around tropics

Ref.	Experimental outputs/ major findings	Study Year	Plant species/ size	VGS type & Orientation	Country
(Cheng et al., 2010) (Lee & Jim, 2017)	Living wall reduced surface temperatures by 16°C and 13°C during day and night, respectively.	2008	Zoysia Japonica	Modular Living wall-Southwest	Hong-Kong
(Jim C. Y, 2015) (Lee & Jim, 2017)	Pyrostegia Venusta raised east-facing building surface temperature by 5°C. Climbing wall's air gap showed 2.5°C difference from bare wall ambient air.	2012	*Bauhinia corymbosa, Ficus pumila* & *Pyrostegia venusta*	Climbing - all directions	Hong-Kong
(Pan & Chu, 2016)	Maximum external wall surface temperature was reduced by 8°C, 5°C and 3°C on sunny, cloudy & rainy days respectively.	2013-2014	*Peperomia claviformis*	Modular Living wall-Southwest	Hong-Kong
(Tan et al., 2014) (Lee & Jim, 2017)	Removal of modular living walls increased the surface temperature by 6.7°C outdoor and 3.8°C indoor.	2011-2012	• *Piper armentosum, Hemigraphis alternate,*	Modular Living wall-West	Singapore
			• *Portulaca grandiflora, Cordyline terminalis,*		
			• *Nephrolepis acutifolia, Philodendron,Schefflera*		
(Wong, et al., 2010)	1. The surface temperature difference average of 10.03°C compared with the control wall. Stable diurnal temperature fluctuation.	2008	Small to medium	1. Modular Living Wall (MLW)- plug-in system	Singapore
	2. 4.36°C Average temperature reduction.				
	3. Surface temperature varies from 4-12°C & 4°C during day and night, respectively.			2. Modular trellis GF	
	4. During the day max. reduction: 10.94°C.		Climber plants	3. MLW-continuous	
	5. The surface temperature of the control wall reduces max. 10.03°C & 4°C, day & night.		*Hemigraphis repanda*		
	6. Surface temperature varies with different plant species during the day and night. The maximum average reduction of the substrate surface compared to the control wall is 6.11°C.			4. MLW- peat moss	
	7. Average temperature reduction 3°C & 6°C, during night & day respectively.		Small in size	5. MLW-planting	

Ref.	Experimental outputs/ major findings	Study Year	Plant species/ size	VGS type & Orientation	Country
(Wong, et al., 2010)	8. Wall surface reduces to 2°C at night & 9°C during the day.	2008	*Phyllanthus myrtifolius*	Bays	Singapore
(Wong, et al., 2010)		2008	*Tradescantia spathacea* ‘ Compacta’	6. MLW- Framed mini planters	Singapore
			P. myrtifolius	7. MLW- Moss tiles & Flexible mats tapestry	
			T. spathacea Compacta.	8. MLW- Plant cassette	
			Small, custom- grown on tiles & medium.	All South oriented	
			Small to medium-large		
(Pérez et al., 2014)	*Parthenocissus Tricuspidata* external wall surface temperature reduction 13°C and *Dishcloth gourd,* in between 1-3°C.	1988	*Parthenocissus*	GF support system-West &	Hoyano-Japan
			Tricuspidata	Southwest	
			Dishcloth gourd		
(Sunakom & Yimprayoon, 2011)	Surface temperature variation of 9.9°C	2011			Bangkok-Thailand
(Widiastuti et al., 2018)	External wall surface temperature was reduced up to 9°C avg. Total heat transfer through the building envelops was reduced by 60-97%.	2018			Hong-Kong
(Safikhani et al., 2014)	The surface temperature of Living walls & green facades shows a difference of 0.5°C-1.5°C.	2014		Living wall	Malaysia

Table 4: Climbing vegetable plants in the tropical area

Species	Plant type	Country/ Context	Characteristics
Common bean (*Phaseolus vulgaris*)	Supported Climbing	Native to Peru	• High growth rate. • Height: up to 3m. • Fibrous roots, thin and twining stems, long and wide, dark green leaves. • Requires full sun exposure with moderate water.
Long bean (*Vigna unguiculata sesquipedalis*)	Supported climbing	Africa and Asia	• Fast growth rate, • grows up to 4m, • Long and wide leaves, thin and twining stem • Requires full sun exposure with regular watering.
Pea (*Pisum sativum*)	Supported climbing	Native to Asia or Southwest Asia	• Fast growth rate, • Height: up to 3.7m. • Small broad leaves and tap root. • Requires full sun exposure with moderate water.
Cucumber (*Cucumis sativus*)	Supported climbing	Southern Asia	• Fast growth rate, • Height: up to 2m. • Wide and broad leaves and tap root. • Requires full sun exposure with regular watering.
Chayote (*Sechium edule*)	Supported climbing	Mexico, Guatemala	• Fast growth rate, • Height: up to 15m. • Wide & broad leaves & Tuberous root • Requires full/ partial sun exposure with average water.

Source: Zaid et al. (2018)

3.8 Challenges faced by VGSs around Tropics

Terblanche (Terblanche, 2019) emphasized major factors affecting the implementation of green walls. According to the study, the climate is the most difficult barrier to overcome. Following, the maintenance and cost are the next major factors hindering the green wall installations.

Climate

In tropical climates, design considerations are dynamic due to year-round high temperatures and humidity, impacting summertime comfort (Nedhal et al., 2013; Othman & Sahidin, 2016). Façade design in hot and humid tropics faces challenges during rainy days, as high humidity levels impede natural ventilation as a cooling energy source (Louis & Jim, 2021). Implementing Vertical Greening Systems (VGS) requires considering temperature, humidity, orientation, and wind (Hopkins & Goodwin, 2011).

Jim's experimental study (Jim C. Y, 2015) revealed challenges faced by green facades in strong winds, leading to stem detachment and plant failure. Louis and Jim (Louis & Jim, 2021) emphasized the importance of shading-induced cooling in tropical countries with longer hot seasons. Climber plants with high leaf area index and extended growing periods are effective for shading, particularly in low-altitude regions with constant lengthy days. However, Jim's study also noted failures, such as Campsis grandiflora unable to attach properly in strong winds (Jim C. Y, 2015).

Geographical location and diurnal solar radiation distribution influence climber plant success. Summer temperatures in the tropics often exceed comfort thresholds, making VGS crucial for temperature reduction indoors and outdoors (Pan & Chu, 2016). Understanding these complexities is vital for effective VGS integration in tropical building designs.

Maintenance on VGS

Susorova (Susorova, 2015) highlighted challenges in long-term maintenance for both green facades and living walls. Green facades' plant choices impact aesthetics and functionality, posing implications for damage and visual aspects. Living walls' diverse plant options and functional complexity, involving multiple layers, supporting materials, and water and nutrient control, make maintenance difficult and expensive (Jim C, 2015). Shrubs in living walls demand strong gravity support due to heavy components, limiting VGS suitability.

Tray systems, with greater seeding depth, are more manageable for restoring plant species than continuous living walls (Palemo & Turco, 2020). Louis et al.'s study emphasized potential issues with metallic trellis or wire ropes, causing temperature increases and damage to climber plants' fresh tissues. Wire rope distortion, complex entanglement with adjoining climbers, and immense forces exerted by some stems on wires and bolts were observed. Nutrient supply for active growth could attract micro-organisms and insects (Louis & Jim, 2021). Understanding these challenges is crucial for effective VGS maintenance and selection in building designs.

Cost

Installation and maintenance costs for Vertical Greening Systems (VGSs) are significant (Beecham et al., 2019). Perini et al. have considered yearly maintenance costs, requiring approximately four years for greening facade pruning. VGS costs depend on type, plant species, and space (Boby et al., 2020). Allocating an additional 5% of the budget helps manage unforeseen maintenance issues (Growing Green Guide, 2014). Boby et al. (2020) have detailed costs of plant species, structural components, and irrigation systems separately, with green facade vegetation costing less than some living wall plants. Green facade structural elements cost approximately US$42.11 per piece, and drip irrigation systems range from US$12.98 to US$21. Living wall structural components cost around US$200 per sq. ft, with drip irrigation at US$275 per month.

A life cycle environmental impact study (Pan & Chu, 2016) estimated over 50 years of service life for polyethylene panels and plant baskets in tray systems. Low-density material watering systems and drip lines have a life expectancy of 7.5 years with regular replacements. Ottelé et al.'s research (Otteléa et al., 2011) found direct green facades to be more economical and sustainable than modular living wall systems (Beecham et al., 2019). Eco-efficient VGS outcomes involve proper material selection and recycling. Reducing materials used, employing environmentally friendly and durable options, and incorporating drip irrigation and water-retaining planter boxes support economic benefits and environmental sustainability for living walls (Pan & Chu, 2016).

4. DISCUSSION

Numerous global studies have explored Vertical Greening Systems (VGS) types and thermal performances. In tropical contexts, where challenges are pronounced, further research is crucial for effective implementation (Othman & Sahidin, 2016). Terblanche (2019) identified climate, maintenance, and cost as key challenges in VGS, emphasizing the need for a comprehensive understanding. Radic et al. (2019) stressed multidisciplinary research on maintenance, while the use of diverse materials impacting maintenance, economy, and environmental sustainability requires thorough examination.

Design considerations by El Menshawy et al. (2021) outlined crucial steps, emphasizing site analysis, existing structures, and local vegetation study.

Critical decisions during design and planning, considering objectives, irrigation, drainage, and skilled involvement, lead to successful implementation. Installation components, such as plant species selection, substrate, water supply, and supporting structures, play a pivotal role (El Menshawy et al., 2021). Maintenance, an integral part of the design process, ensures durability and livability, demanding performance targets and resource availability.

Othman et al. (2016) suggested factors for VGS selection in office buildings, including scale, space, concept, and thermal comfort. VGS, vital for urban sustainable development, includes diverse types like green facades and living walls. Irrigation and drainage systems are crucial for VGS on building facades, while plant species selection varies between systems.

Despite the significance of VGS, adaptation in tropical contexts faces challenges in climate, maintenance, and cost. The lack of scientific analysis impedes successful implementation. New trends and technologies must align with sustainability goals to overcome constraints and establish effective VGS in tropical climates. The role of VGS in sustainable urban development remains prominent, requiring ongoing research and innovative approaches for tropical implementation.

5. CONCLUSION

In conclusion, implementing Vertical Greening Systems (VGS) in tropical climates requires a nuanced approach to overcome challenges. The dynamic tropical climate, characterized by high temperatures and humidity, presents design obstacles impacting comfort and natural ventilation. Maintenance proves critical, with the intricate structures of green facades and living walls posing challenges and expenses. Tray systems offer a more manageable solution for plant restoration. Installation and maintenance costs vary, demanding careful planning. Life cycle studies stress material selection and eco-efficient outcomes for sustainability. Despite challenges, VGS are vital for sustainable urban development. Key design considerations, ongoing research, and innovative technologies aligned with sustainability goals are essential. Adaptation of new trends must be guided by scientific analysis for continued prominence in fostering sustainable urban environments, requiring collaboration, innovation, and a commitment to addressing complexities.

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