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RESEARCH ARTICLE

A Systematic Review of Economic Sustainability of Vertical Greenery Systems in Buildings

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Abstract

Urban areas have been significantly affected by climate change, leading to an increase in global temperatures. Nature-based solutions, including Vertical Greenery Systems (VGSs), are gaining increasing importance as means of mitigating the effects of climate change. Despite showing significant benefits, the adoption of VGS has been limited, primarily because of the high costs associated with it. This study assessed the economic feasibility of using VGSs to reduce the effects of climate change and enhance urban sustainability. 17 studies were evaluated in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to determine various costs, benefits, and economic indicators associated with VGS. Additionally, the net present value, internal rate of return, and payback period were thoroughly evaluated to gain insight into their long-term economic sustainability. The results show that, although the initial cost of VGS may be high, it can provide long-term financial benefits to building owners and operators through energy savings, increased property values, and reduced operational expenses. Nevertheless, the extended payback period and negative net present values for certain VGS types make them economically unsustainable. This review provides evidence-based guidelines and suggestions for the successful implementation of sustainable VGS.

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Keywords

Vertical Greenery System; Living Walls; Green Facades; VGS Benefits; Economic Sustainability; Economic Performance

Introduction

Urbanization is a critical issue for cities today and is expected to continue to grow. By 2050, two-thirds of the world's population will live in urban areas (Khor, et al., 2022). Rapid urbanization is increasing people's vulnerability to adverse effects of climate change. Urban areas are more susceptible to extreme weather events, such as heatwaves, due to climate change (Seneviratne, et al., 2021). Human-caused emissions have already increased the global temperature by 1.1°C compared to pre-industrial levels, and it is predicted to reach 1.5°C in the coming decades (IPCC, 2021). This can have a significant impact on health and cities, thereby posing economic risks.

Existing efforts to combat climate change have been inadequate. Research has shown that proven climate actions can address this issue (Project Drawdown, 2020). It is crucial to identify areas for improvement and implement stringent measures to reduce emissions, as buildings are a major source of energy consumption and emissions that cause climate change (IEA, 2022; Lucon, et al., 2014). However, buildings also offer an opportunity to reduce the impacts of climate change (United Nations Environment Programme, 2021). Nature-based solutions, including vertical greenery systems, are being investigated as potential solutions to address climate change issues in cities, as they can reduce carbon emissions, store carbon, and have positive indirect and behavioural impacts (Pan, et al., 2023).

Vertical greenery systems (VGSs) are building facades that are covered by vegetation, either partially or completely. These systems integrate living plants into building envelopes and can take a variety of forms. The terminology used for each type varies across studies, primarily because of the contexts and systems employed (Radić, Dodig and Auer, 2019). Although their ability to mitigate climate change-related issues may vary across VGS types, they have been proven to contribute significantly to climate change mitigation (Andric, Kamal and Al-Ghamdi, 2020). Therefore, a holistic analysis of the VGSs is required.

The Intergovernmental Panel on Climate Change (IPCC) recognizes VGS in buildings as a potential climate mitigation measure but marks them as "controversial" due to a lack of literature on their long-term performance in different climates and regions (Cabeza, et al., 2022). This indicates a research gap in the economic sustainability of VGS despite the rising interest in vertical greenery in buildings as a sustainable urban development approach. Substantial literature exists on the environmental advantages of VGS (Pan and Chu, 2016; Perini, et al., 2021; Qurraie and Kıraç, 2023; Zhang, et al., 2019). However, the economic benefits and challenges of VGS remain unclear. The lack of clarity regarding the economic implications of VGS hinders its successful adoption and sustainability.

VGS requires a large initial investment but can offer long-term economic advantages. For instance, Haggag, Hassan and Elmasry (2014) found that VGS led to up to 20.5% annual energy savings in hot, arid climates. VGS can also filter greywater, reducing costs for activities requiring low-quality water (e.g., WC flushing and irrigation) in areas with increasing water demand (Masi, et al., 2016). VGS may also raise property value and reduce building maintenance costs (Perini and Rosasco, 2013). Sustainable infrastructure incentives or regulations can further encourage the implementation of VGS (Shazmin, et al., 2017). IEA (2023) reported that VGS are a "high-priority measure" to reduce air-conditioning demands, but affordability must be addressed before wider adoption. The economic viability of VGS is often questioned because of the installation and maintenance costs.

The aim of this review is to examine the viability of VGS as a solution to climate-related challenges faced by buildings, with a focus on their economic sustainability. This study aimed to identify the factors that influence the adoption of VGS and address the knowledge gaps in the literature. The findings of this review will contribute to the development of evidence-based guidelines for the successful implementation of VGS in buildings and will promote their long-term sustainability.

Methods

The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic literature reviews, which are widely recognized standards for such reviews (Moher, et al., 2009).

SEARCH STRATEGY

To identify relevant articles, a comprehensive search was conducted between November 2022 and March 2023 using major academic databases including Scopus, Web of Science, and Science Direct. These databases screened and searched the titles, abstracts, and keywords of indexed studies. The search used a combination of keywords and controlled vocabulary terms related to VGS and economic sustainability. The keywords were refined after the initial searches of these databases and the process was repeated multiple times to improve the search results. A keyword search was independently performed by both authors to eliminate bias and to expand the search results. The final keyword strings used were: ((“vertical greenery*” OR “green wall” OR “green facade” OR “building-integrated vegetation” OR “living wall” OR “living facade”) AND (“economic sustainability” OR “financial feasibility” OR “cost-benefit analysis” OR “return on investment” OR “life cycle cost*” OR “economic analysis”)).

ELIGIBILITY CRITERIA

The study selection process involved screening the titles and abstracts of retrieved articles according to the inclusion and exclusion criteria. The inclusion criteria were peer-reviewed empirical studies that evaluated the economic performance of VGS and reported quantitative data. Only studies reporting the financial costs associated with VGS were included.

Studies that evaluated green roofs or reported only qualitative data were excluded. Reviews, editorials, opinion papers, grey literature, and articles published in languages other than English were also excluded.

DATA EXTRACTION AND ANALYSIS

A standardized data extraction form was used to collect the title, author(s), year of publication, methodology, type of vertical greenery system, economic sustainability indicators, and main findings from the selected articles. Narrative synthesis was used to summarize the main findings and compile them in MS Excel. Patterns and themes related to the economic sustainability of VGS were identified.

To conduct a comprehensive cost analysis, this review converts the costs from the original articles into inflation-adjusted US$ values to compare the lifecycle costs across studies. These inflation-adjusted costs (as of 1 January 2023) were calculated for the values reported in the reviewed studies using Eq. (1). This accounts for annual inflation based on the overall consumer price index (CPI) for the base year 2010 for different countries, as in the reviewed literature (IMF, 2023). Although this value may not truly reflect current prices, given the nuanced nature of inflation, it helps in comparing the present value of reported lifecycle costs.

$$C_{i,2023} = C_b * (CPI_{2023} / CPI_b) \quad \text{Eq. (1)}$$

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where $C_{i,2023}$ is the inflation-adjusted cost as of 1 January 2023, C_b is the cost in base year as reported in literature, CPI_{2023} is the consumer price index for the particular country as on January 01, 2023, and CPI_b is the consumer price index for the base year.

The calculated inflation-adjusted costs in the base currency are then converted to US$ values, using the conversion rates (for instance, 1 EUR = 1.0727 USD) as of 1 January 2023 available from Google Finance (Google, n.d.). This approach accurately and comparably evaluates VGS costs by providing decision makers with valuable information for VGS implementation.

QUALITY ASSESSMENT

The quality of the selected articles was assessed using a critical appraisal approach to evaluate their internal and external validity and reporting quality. Both authors independently screened articles based on the inclusion and exclusion criteria. Discrepancies during the selection process, data extraction, and quality assessment were resolved through discussions and consensus.

LIMITATIONS

This systematic literature review has language limitations and excludes unpublished studies, grey literature, and non-peer-reviewed articles. These limitations may have led to the exclusion of relevant studies from the analysis. However, we believe that the selection criteria used in this review resulted in a thorough and high-quality analysis of the available literature on the economic feasibility of using VGS in buildings.

Results

STUDY SELECTION

An initial database search returned 179 articles. After removing duplicates (n=25) and screening titles and abstracts, 67 articles were sought for retrieval. Six articles could not be retrieved and were excluded. 61 studies were evaluated for inclusion after full-text review. 23 of these studies focused on green roofs or other nature-based solutions; therefore, they were excluded. 21 articles discussed VGS but did not assess their economics. The review excluded studies that did not report VGS costs and those that only reported 'willingness to pay' (WTP), as WTP is not a measure of economic performance and is based on user perceptions. Duplicate studies from the same research group were excluded from this review. The database search used language filters (English); however, one non-English article still remained and was therefore removed. After screening the results for inclusion/exclusion criteria by all the authors, 15 articles from the search results and two from the reference lists (17 in total) were included in the review. Figure 1 shows the study selection process (PRISMA flow diagram).

CHARACTERISTICS OF INCLUDED STUDIES

A summary of the characteristics of the included studies is shown in Table 1. All reviewed studies were published in the last decade (2012-2021) and most of these were published recently (2019-2021). This helps establish a state-of-the-art review. Of the 17 articles reviewed, 16 were journal articles and one was a book chapter. Most of the reviewed studies were conducted in temperate climates (according to the Köppen Geiger classification) in Italy (n=4), Portugal (n=3), Austria (n=1), France (n=1), Spain (n=1), and Sweden (n=1). The research designs employed in these studies include case studies, life cycle cost analysis, and cost-benefit analysis. The studies varied in terms of the type and scale of VGS evaluated, covering a diverse range of systems such as direct and indirect green facades, living walls (indoor and outdoor), and felt-based green walls. This aids in the holistic appraisal of the diverse types of VGS suited to different contexts and climates.

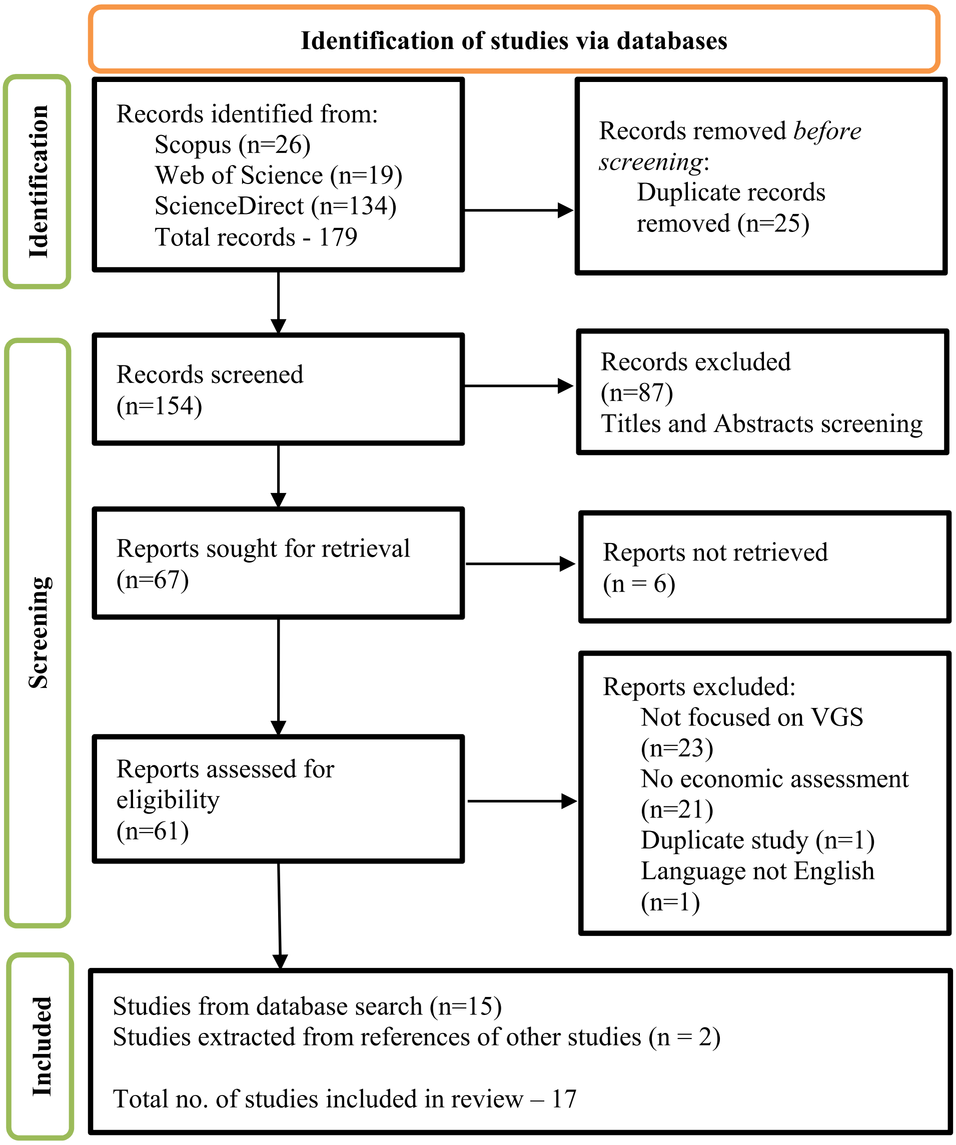

Figure 1. PRISMA flow-diagram for selection of studies from databases

ECONOMIC COSTS OF VERTICAL GREENERY SYSTEMS

Most studies evaluated in this review assessed the economic costs associated with VGS throughout their lifespan. These costs are divided into three life cycle stages: (i) initial costs, (ii) maintenance costs, and (iii) disposal and/or replacement costs. The costs reported in the articles are based on the literature, including case studies, bills of quantities, and manufacturers' technical reports. Among the 17 studies reviewed, only four reported cost data from live projects (Haggag and Hassan, 2015; Hollands and Korjenic, 2021; Huang, et al., 2019; Rosasco and Perini, 2018). Additionally, two studies (Akinwolemiwa, et al., 2018; Riley, et al., 2019) presented findings from prototype testing projects aimed at reducing the cost of VGS in buildings.

The literature indicates that VGS life cycles range from 10-15 years to 50 years, with variations likely stemming from distinct materials, designs, and maintenance approaches. Direct green facades feature plants growing directly on a building surface, whereas indirect green facades employ separate supporting structures, such as steel or high-density polyethylene (HDPE). Perini and Rosasco (2013) and Matos Silva, et al. (2019) demonstrated that both direct and indirect green facades can exhibit lifecycles of up to 50 years.

Table 1. Overview of characteristics of reviewed articles

Source	Region, Climate Type[1]	VGS Type	Methods[2]	Reported costs[3]			Reported Benefits
				I	M	D	
Veisten, et al. (2012)	Unspecified	Living wall	CBA	✓	✓		Acoustic comfort, aesthetic improvement
Perini and Rosasco (2013)	Genoa, Italy, Csb	Green facade, living wall	CBA	✓	✓	✓	Energy Savings, rental income, cladding longevity,
Haggag and Hassan (2015)	Al-Ain, UAE, BWh	Living wall	CS	✓	✓		Energy Savings, rental income
Perini and Rosasco (2016)	Genoa, Italy, Csb	Green façade	CBA	✓	✓	✓	Energy Savings, rental income, cladding longevity
Serrano-Jimenez, Barrios-Padura and Molina-Huelva (2017)	Seville, Spain, Csa	Green facade	CS	✓	✓		Energy Savings
Shazmin, et al. (2017)	Kulai, Johor, Malaysia, Af	Living wall	CBA	✓			Energy Savings
Akinwolemiwa, et al. (2018)	Lagos, Nigeria, Aw	Green fa cade	CS	✓	✓		Job creation, thermal comfort, income from plants
Rosasco and Perini (2018)	Genoa, Italy, Csb	Green facade	CBA	✓	✓	✓	Energy Savings, rental income, cladding longevity, tax reduction, biomass production
Huang, et al. (2019)	Singapore, Af	Green facade, living wall	LCCA	✓	✓	✓	Energy Savings, water savings
Matos Silva, et al. (2019)	Lisbon, Portugal, Csa	Green facade, living wall	CBA	✓	✓	✓	Improved aesthetics, air quality, acoustic comfort, job creation, user satisfaction
Riley, et al. (2019)	Lyon, France, Cfb	Living concrete	CS	✓			
Santi, et al. (2019)	Italy, unspecified	Green facade, living wall	CS	✓	✓		Energy savings

Table 1. continued

Source	Region, Climate Type[1]	VGS Type	Methods[2]	Reported costs[3]			Reported Benefits
				I	M	D	
Melo, et al. (2020)	Lisbon, Portugal, Csa	Green facade, living wall	CBA	✓	✓	✓	Cladding longevity, improved aesthetics, air quality, acoustic comfort
Almeida, et al. (2021)	Lisbon, Portugal, Csa	Green facade, living wall	CBA	✓	✓	✓	Cladding longevity, improved aesthetics, air quality, acoustic comfort
Dong and Huang (2021)	China, unspecified	Green facade, living wall	LCCA	✓	✓		
Hollands and Korjenic (2021)	Vienna, Austria, Cfb	Living wall	CBA	✓	✓		Improved hygrothermal comfort
Huang, et al. (2021)	Singapore, Af	Green facade, living wall	LCCA	✓	✓	✓	

[1] Köppen-Geiger Classification – Af: Rainforest, Aw: Tropical savanna, BWh: Hot desert, Cfb: Temperate oceanic, Csa: Hot-summer Mediterranean, Csb: Warm-summer Mediterranean

[2] CBA – Cost-Benefit Analysis, CS – Case Study, LCCA – Lifecycle cost analysis

[3] I – Initial costs, M – Maintenance costs, D – disposal costs

In contrast, Huang, et al. (2019) reported shorter life cycles of 10-15 years for indirect green facades. The extended life cycles observed for some direct green facades could be due to a reduced need for maintenance and component replacement compared to the more intricate support structures of indirect green facades. The costs associated with the three stages of VGS lifespan are discussed in detail below.

The initialization stage includes the acquisition and preparation of different components of the VGS that are performed off-site, whereas installation involves on-site processes, such as transportation costs for materials, labour, and workforce, among others (Huang, et al. 2019). However, segregation of costs and processes into two stages has been reported in only two studies (Huang, et al. 2021; 2019). Most of the articles reviewed herein reported these costs together under one head, such as initial costs (Perini and Rosasco, 2013) or production/installation costs (Melo, et al. 2020; Almeida, et al. 2021). For comparison, all costs were clubbed together under the 'initial costs' in this review. An overview of the components accounting for the initial costs of VGS in the reviewed studies is presented in Table 2.

The initial costs for direct green facades vary between €30/m^2 and €45/m^2 (Perini and Rosasco, 2013; Santi, et al., 2019), whereas indirect green facade costs are in the range of €38.58/m^2 (¥290/m^2, Dong and Huang, 2021) up to €335.48/m^2 (Rosasco and Perini, 2018). The cost of indirect green facades depends on the material of the support structure; €218.72/m^2 for HDPE with planter boxes and €293.93/m^2 for steel with planter boxes (Perini and Rosasco, 2013). In all the studies, initial costs were the second highest contributor to life cycle costs, except in the case of indirect green facades reported by Rosasco and Perini (2018) and Santi, et al. (2019), owing to the reduced life span of 25 and 15 years, respectively (see Table 3).

Table 2. Overview of initial cost components of VGS in reviewed studies

Cost Component	Description	Sources
Manpower costs	Salary of workers in nursery, for transportation, preparation and installation of the system	Shazmin, et al. (2017), Akinwolemiwa, et al. (2018), Huang, et al. (2019, 2021), Riley, et al. (2019)
Design costs	Fees for designers, architects, service providers, horticulturists	Perini and Rosasco (2016), Akinwolemiwa, et al. (2018)
Material costs	Structure, plant species, digging, pots, panels, planter boxes, growing media, waterproofing, irrigation system, drainage system, fertilizers	Perini and Rosasco (2013, 2016), Haggag and Hassan (2015), Shazmin, et al. (2017), Akinwolemiwa, et al. (2018), Rosasco and Perini (2018), Huang, et al. (2019, 2021), Riley, et al. (2019), Santi, et al. (2019), Melo, et al. (2020), Dong and Huang (2021)
Utilities cost	Electricity, water, equipment	Haggag and Hassan (2015), Huang, et al. (2019, 2021)
Transportation Cost	Transportation of materials	Perini and Rosasco (2013, 2016) Akinwolemiwa, et al. (2018), Rosasco and Perini (2018), Huang, et al. (2019, 2021)
Production costs	Atmospheric emissions	Melo, et al. (2020)

Living wall systems exhibited a wider range of initial costs, as shown in Table 4. Santi, et al. (2019) reported a wide range of initial costs (€100 – 1,200/m^2), accounting for up to 84.21% of the total lifecycle costs, constituting a considerable portion of the overall expenses. In contrast, Perini and Rosasco (2013) reported an outdoor living wall system with an initial cost of €314.83/m^2, representing only 13.28% of the total lifecycle costs. This could be attributed to the fact that Perini and Rosasco (2013) reported a detailed analysis of life cycle costs, whereas Santi, et al. (2019) did not account for all the components and only reported lumpsum costs and an assumed life cycle of 15 years, which led to a reduced component of costs across the life span of the system.

The costs of living walls also vary according to their use (indoors or outdoors). For instance, Matos Silva, et al. (2019) presented a living wall system for both indoor and outdoor use with an initial cost of €600/m^2, or 16.21% of the total lifecycle costs. In contrast, for the same climate type and location, Melo, et al. (2020) compared two living wall systems: an outdoor system with initial costs of €100.10/m^2 (4.21% of total lifecycle costs) and an indoor system at €615.10/m^2 (23.52% of total lifecycle costs). Additionally, Hollands and Korjenic (2021) investigated two indoor living wall systems, the trough system and fleece system, with initial costs in the range of €1,033 – 1,265/m^2 (29.24 – 33.87% of total lifecycle costs) and €1,262 – 2,589/m^2 (24.26 – 39.29% of total lifecycle costs), respectively. The substantial difference in the initial costs between indoor and outdoor systems highlights the importance of considering the intended application of living wall systems when selecting the most appropriate option.

In contrast to the studies in Tables 3 and 4, Akinwolemiwa et al. (2018) and Riley, et al. (2019) reported the costs of VGS prototypes, particularly focusing on cost-effectiveness, whereas Shazmin, et al. (2017) reported VGS costs in the context of tax incentives for these systems. Akinwolemiwa, et al. (2018) presented multiple VGS prototypes in a study conducted in Nigeria. The initial costs (including material, transportation, labour, and plants) reported were – ₦10,328.40/m^2 (inflation-adjusted US$ equivalent - $39.84/m^2) for the HDPE prototype, and ₦3,540/m^2 ($13.66/m^2) for the bamboo prototype. Riley, et al. (2019) reported a unique prototype created by integrating greenery within the concrete that could be used for the building envelope. The living concrete's cost was €120/m^2 ($138.33/m^2). These values were substantially lower than those of conventional VGS reported in other studies. The initial costs of VGS are influenced by numerous factors, including system type, location, and context. As demonstrated by the reviewed studies, costs can vary significantly even within the same type of system.

Although initial investment in VGS is often a key focus, maintenance costs significantly affect the long-term sustainability and cost-effectiveness of VGS. These costs include regular upkeep activities such as watering, fertilizing, pruning, pest control, and repair or replacement of damaged or malfunctioning components or plant species. In addition, the costs associated with ongoing monitoring and inspection, including labour and materials, also contribute to the overall maintenance expenses (Huang, et al. 2019). As shown in Tables 3 and 4, maintenance costs accounted for a substantial portion of the total lifecycle costs, underscoring the importance of considering these expenses when evaluating the economic sustainability of VGS.

Maintenance costs for direct green facades are relatively lower compared to other VGS types because the only expenditure is the cost of regular pruning of the plants. The higher maintenance costs of €1,353.61/m^2 (94.88% of total lifecycle costs) reported by Perini and Rosasco (2013) are due to the one-time cladding renovation costs included in the maintenance costs. If cladding renovation costs were excluded, the effective maintenance costs for direct green facades would be €129.26/m^2 (68% of the total lifecycle costs), which is much lower than the maintenance costs for other VGS types reported in this review. Only two studies (from the same research group) accounted for the costs incurred in renovating a building facade owing to the impact of VGS (Perini and Rosasco, 2013, 2016), resulting in increased maintenance costs.

The costs of indirect green facades are more commonly reported and are found to be slightly higher than those for direct green facades but comparatively lower than those for living walls. Perini and Rosasco (2013) reported a variation in the maintenance costs of indirect green facades owing to different support structures. For HDPE and steel, these costs were similar (€884.65/m^2); for HDPE with planter box systems, they were approximately €1,243.67/m^2 (74.69%of the lifecycle costs). Considerably lower maintenance costs of €45/m^2 (Santi, et al., 2019) and ¥30 – 50/m^2/yr. (Dong and Huang, 2021) were reported for indirect green facades, whereas Matos Silva, et al. (2019) reported maintenance costs of €650/m^2 (79.75% of the total lifecycle costs) for similar indirect green facades. This not only highlights the difference in costs due to different contexts but also a clear lack of standardization in cost reporting.

For community-driven vertical greenery prototypes, Akinwolemiwa, et al. (2018) reported maintenance costs, including irrigation, water, security, weeding, cropping, and replacing/replanting, of ₦37,037/m^2/yr. (inflation-adjusted US$ value: $142.87/m^2/yr.). Two of the reviewed studies did not report the maintenance costs (Shazmin, et al. 2017; Riley, et al. 2019) however, they acknowledged that maintenance costs account for a considerable portion of the total life cycle costs. Maintenance costs generally constitute a sizeable portion of total lifecycle costs, highlighting the importance of considering long-term maintenance expenses when evaluating the economic feasibility of green facades and living walls.

Table 3. Summary of costs associated with green facades as reported in articles reviewed

Source	Life cycle (years)	Type of VGS	Initial[1]	Maintenance	Disposal	Total lifecycle costs[2]	Adjusted lifecycle costs[3] (US$/m^2)
Perini and Rosasco (2013)	50	Direct Green Façade	€41.96/m^2 (2.94%)	€1,353.61/m^2 (94.88%)	€31.10/m^2 (2.18%)	€1,426.66/m^2 (100 %)	1,738.43
		HDPE indirect green facade	€176.02/m^2 (13.99%)	€884.65/m^2 (70.32%)	€197.40/m^2 (15.69%)	€1,258.07/m^2 (100%)	1,532.99
		Steel indirect green facade	€215.08/m^2 (16.44%)	€884.65/m^2 (68.08%)	€199.74/m^2 (15.37%)	€1,299.47/m^2 (100%)	1,583.43
		HDPE indirect green facade with planter boxes	€218.72/m^2 (13.14%)	€1,243.67/m^2 (74.69%)	€202.69/m^2 (12.17%)	€1,665.08/m^2 (100%)	2,028.94
		Steel indirect green facade with planter boxes	€293.93/m^2 (17.63%)	€1,167.17/m^2 (70%)	€206.20/m^2 (12.37%)	€1,667.3/m^2 (100%)	2,031.64
Perini and Rosasco (2016)	50	Indirect Green Façade	€212.15/m^2 (33.36%)	€373.83/m^2 (58.78%)	€50.04/m^2 (7.87%)	€636.02/m^2 (100%)	773.57
		Indirect Green Façade with planter box	€252.05/m^2 (26.52%)	€638.75/m^2 (67.22%)	€59.45/m^2 (6.26%)	€950.25/m^2 (100%)	1,155.75
Serrano-Jimenez, Barrios-Padura and Molina-Huelva (2017)	30	Green Façade - unspecified	€350/m^2 (9.74%)	€3,243.6/m^2 (90.26%)	Not reported	€3,593.60/m^2 (100%)	4,396.09
Rosasco and Perini (2018)	25	Indirect Green Façade	€335.48/m^2 (43.22%)	€307.28/m^2 (39.59%)	€133.4/m^2 (17.19%)	€776.16/m^2 (100%)	922.09
	50	Indirect Green Façade	€335.48/m^2 (28.55%)	€641.28/m^2 (54.57%)	€198.39/m^2 (16.88%)	€1,175.15/m^2 (100%)	1,396.09
Huang, et al. (2019)	30	Indirect Green Facade	S$220/m^2 (24.86%)	S$652/m^2 (73.67%)	S$13/m^2 (1.47%)	S$885/m^2 (100%)	715.37

Table 3. continued

Source	Life cycle (years)	Type of VGS	Initial[1]	Maintenance	Disposal	Total lifecycle costs[2]	Adjusted lifecycle costs[3] (US$/m^2)
Matos Silva, et al. (2019)	50	Indirect Green Facade	€90/m^2 (11.04%)	€650/m^2 (79.75%)	€75/m^2 (9.20%)	€815/m^2 (100%)	954.54
Santi, et al. (2019)	15 (assumed)	Direct Green Facade	€30 – 40/m^2 (38.36 – 47.05%)	€45/m^2 (52.94 – 60%)	Not reported	€75 – 85/m^2 (100%)	88.56 – 100.37
		Indirect Green Facade	€40 – 75/m^2 (47.05 – 62.5%)	€45/m^2 (37.5 – 52.94%)	Not reported	€85 – 120/m^2 (100%)	100.37 – 141.70
Melo, et al. (2020)	50	Indirect Green Facade	€100.06/m^2 (13.34%)[4]	€530/m^2 (70.66%)	€120/m^2 (16%)	€750.06/m^2 (100%)	878.59
Dong and Huang (2021)	40	Climbing Vertical Green Wall	¥122 - 290/m^2 (9.23 – 12.67%)	¥30 – 50/m^2/yr. (87.33 – 90.77%)	Not reported	¥1,322 – 2,290/m^2 (100%)	195.47 – 338.60
Almeida, et al. (2021)	50	Indirect Green Facade	€100/m^2 (11.76%)	€600/m^2 (70.59%)	€150/m^2 (17.65%)	€850/m^2 (100%)	983.21
Huang, et al. (2021)	10-15	Indirect Green Facade	S$14.45/m^2/yr. S$180.62/m^2 (30.65%)	S$30.97/m^2/yr. S$387.12/m^2 (65.70%)	S$1.72/m^2 S$21.5/m^2 (3.65%)	S$47.15/m^2/yr. (100%) LCC – S$589.38/m^2	466.52

[1] Some of the articles reported separate costs for initialization and installation whereas some articles did not report a clear division between costs. Therefore, all the costs reported whether under initialization, installation or initial costs are reported together here.

[2] Total life cycle costs are extracted from the data reported by the studies. The costs are as reported in the year of publication and have not been adjusted for inflation.

[3] Adjusted life cycle costs have been calculated by first adjusting the reported costs for inflation as on January 01, 2023, and then conversion to US dollar as per international market exchange rates on January 01, 2023. The adjusted costs help in a direct comparison of VGS costs around the globe.

[4] Melo, et al. (2020) reported pollutant emission costs involved in the production of VGS and are therefore included in the initial costs.

Disposal costs refer to the various expenses associated with the removal, dismantling, and discarding of VGS at the end of its life. cycle. These costs include expenses incurred on labour and equipment, transportation, and/or recycling of components (Huang, et al. 2019). At the end of the life cycle, some components can either be demolished or recycled/replaced (Almeida, et al. 2021). Three reviewed studies reported replacement costs in addition to disposal costs (Almeida, et al. 2021; Melo, et al. 2020; Matos Silva, et al. 2019). However, demolition and disposal are the most common ends of a VGS, as reported in other studies. Therefore, for comparison, only the disposal costs are analysed in Tables 3 and 4.

Disposal costs constitute only a small percentage of total lifecycle costs, ranging from 1.47% to 17.65%. For example, Perini and Rosasco (2013) found disposal costs for direct green facades to be 1.88% (€31.10/m^2) of the total costs. In contrast, the disposal costs for the HDPE indirect green facade system were higher at 4.59% (€197.40/m^2) of the total life cycle costs. On the other hand, Almeida, et al. (2021) reported that the disposal costs for indirect green facades were 17.65% of the total cost (€150/m^2).

Table 4. Summary of costs associated with living walls as reported in articles reviewed

Source	Life cycle (years)	Type of Green Facade	Initial[1]	Maintenance	Disposal	Total lifecycle costs[2]	Adjusted lifecycle costs[3] (US$/m²)
Veisten, et al. (2012)	10	Unspecified outdoor green wall	€56.91/m² (18.54%)	€250/m² (81.46%)	Not reported	€306.91/m² (100%)	389.70
Perini and Rosasco (2013)	50	Outdoor Living Wall	€314.83/m² (13.28%)	€1,837.96/m² (77.51%)	218.56 €/m² (9.22%)	€2,371.35/m² (100%)	2889.54
Haggag and Hassan (2015)	15 (assumed)	Outdoor Living Wall	$250/m² (86.81%)	$13.5/m² (13.19%)	Not reported	$288/m² (100%)	309.58
Huang, et al. (2019)	30	Living Wall – Planter System	S$699/m² (18.46%)	S$3,058/m² (80.77%)	S$29/m² (0.77%)	S$3,786/m² (100%)	3,060.33
		Living Wall – Carrier System	S$758/m² (15.41%)	S$4,125/m² (83.88%)	S$35/m² (0.71%)	S$4,918/m² (100%)	3,975.36
Matos Silva, et al. (2019)	50	Living Wall – Indoor & Outdoor	€600/m² (16.21%)	€2,900/m² (78.38%)	€200/m² (5.41%)	€3,700/m² (100%)	4,333.50
Santi, et al. (2019)	15 (assumed)	Living wall with planters	€100 – 800/m² (40 – 84.21%)	€150/m² (15.78 – 60%)	Not reported	€250 – 950/m² (100%)	295.20 – 1,121.76
		Living wall with panels	€400 – 1,200/m² (51.61-76.19%)	€375/m² (23.80 – 48.39%)	Not reported	€775 – 1,575/m² (100%)	915.12 – 1,859.75
Melo, et al. (2020)	50	Living Wall –Outdoor	€100.10/m² (4.19%)[4]	€2,090/m² (87.44%)	€200/m² (8.37%)	€2,390.10/m² (100%)	2,799.67
		Living Wall –Indoor	€615.10/m² (13.34%)[4]	2090 €/m² (71.94%)	€200/m² (6.88%)	€2,905.10/m² (100%)	3,402.92
Hollands and Korjenic (2021)	10 (assumed)	Indoor Living Wall – Trough System	€1,033 – 1,265/m² (29.24 – 33.87%)	€2,470 – 2,500/m² (66.13 – 70.76%)	Not reported	€3,533 – 3,754/m² (100%)	4,113.76 – 4,371.09
		Indoor Living Wall – Fleece System	€1,262 – 2,589/m² (24.26 – 39.29%)	€3,940 – 4,000/m² (60.71 – 75.74%)	Not reported	€5,202 – 6,589/m² (100%)	6,057.12 – 7,672.11
Dong and Huang (2021)	40	Blanket Vertical Green Wall	¥645 – 4,220/m² (9.15 – 9.54%)	¥160 – 1,000/m²/yr. (90.46 – 90.85%)	Not reported	¥7,045 – 44,220/m² (100%)	1,041.69 – 6,538.44

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Table 4. continued

Source	Life cycle (years)	Type of Green Facade	Initial[1]	Maintenance	Disposal	Total lifecycle costs[2]	Adjusted lifecycle costs[3] (US$/m²)
		Pocket-Style Vertical Green Wall	¥310 – 2,390/m² (7.20 – 10.67%)	¥100 – 500/m²/yr. (89.32 – 92.80%)		¥4,310 – 22,390/m² (100%)	637.28 – 3,310.62
		Hanging Containers Vertical Green Wall	¥345 – 2,570/m² (7.94 – 17.64%)	¥100 - 300/m²/yr. (82.36 – 92.05%)		¥4,345 – 14,570/m² (100%)	642.46 – 2,154.34
		Modular Containers Vertical Green Wall	¥360 – 2,740/m² (5.32 – 12.05%)	¥160 – 500/m²/yr. (87.95 – 94.67%)		¥6,760 – 22,740/m² (100%)	999.54 – 3,362.37
Almeida, et al. (2021)	50	Living Wall – Indoor & Outdoor	€550/m² (19.30%)	€2,175/m² (76.32%)	€125/m² (4.39%)	€2,850/m² (100%)	3,296.66
Huang, et al. (2021)	10-15	Living Wall – Planter System	S$38.45/m²/yr. S$480.62/m² (21.19%)	S$140.23/m²/yr. S$1,752.86/m² (77.29%)	S$2.765/m² S$34.56/m² (1.52%)	S$181.44/m²/yr. (100%) LCC – S$2,268/m²	1,795.25
		Living Wall – Carrier System	S$47.89/m²/yr. S$598.62/m² (26.20%)	S$132.83/m²/yr. S$1,660.38/m² (72.67%)	S$2.065/m² S$25.81/m² (1.13%)	S$182.79/m²/yr. (100%) LCC – S$2,284.88/m²	1,808.61

[1] Some of the articles reported separate costs for initialization and installation whereas some articles did not report a clear division between costs. Therefore, all the costs reported whether under initialization, installation or initial costs are reported together here.

[2] Total life cycle costs are extracted from the data reported by the studies. The costs are as reported in the year of publication and have not been adjusted for inflation.

[3] Adjusted life cycle costs have been calculated by first adjusting the reported costs for inflation as on January 01, 2023, and then conversion to US dollar as per international market exchange rates on January 01, 2023. The adjusted costs help in a direct comparison of VGS costs around the globe.

[4] Melo, et al. (2020) reported pollutant emission costs involved in the production of VGS and are therefore included in the initial costs.

Similar to green facades, the disposal costs for living walls are a small percentage of the total lifecycle costs, ranging from 0.71% to 9.22%. Huang, et al. (2019) found that the disposal costs for living walls with planter systems were 0.77% (S$29/m²) and 0.71% (S$35/m²) for carrier systems. On the higher end, Perini and Rosasco (2013) reported that the disposal cost for outdoor living walls was 9.22% (€218.56/m²) of the total lifecycle costs. Matos Silva, et al. (2019) reported similar costs (€200/m²) for both indoor and outdoor living walls, accounting for 5.41% of the total lifecycle costs.

The disposal costs for different VGS types vary, with living walls generally incurring higher disposal costs than their counterparts. Understanding and considering these disposal costs are crucial for evaluating the economic viability and sustainability of VGS implementation. It is important to note that only eight of the 17 reviewed articles reported disposal costs. Further research in this area can contribute to optimizing disposal strategies and minimizing the environmental impact of VGS at the end of its life cycle.

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ECONOMIC BENEFITS OF VERTICAL GREENERY SYSTEMS

A balanced understanding of both the costs and benefits is essential for evaluating the economic feasibility and long-term sustainability of VGS in urban settings (Ghazalli, et al., 2019). VGS offers several benefits, such as energy savings, increased property value, cost savings through stormwater management, and enhanced productivity due to health benefits (Pérez, et al. 2014). However, there are other benefits that cannot be easily quantified and, thus, are not included in most cost-benefit analyses (Melo, et al. 2020). This review included only studies that reported quantifiable benefits and equivalent cost values. Table 1 presents an overview of the numerous benefits reported in the reviewed studies. This section discusses relevant studies that quantify the economic benefits of VGSs and the factors that may affect their realization in different contexts to help policymakers, urban planners, and other stakeholders understand their potential role in promoting sustainable urban development and informing decision-making.

Table 5 presents a summary of the cost savings owing to economic benefits of VGS, as reported in the literature. The potential of VGS to regulate the thermal performance of a building envelope is among the most documented benefits of VGS. The articles reviewed here emphasize the potential for energy savings in buildings because of the insulating properties of VGS, which can lead to reduced heating and cooling costs. Perini and Rosasco (2013) compared VGS types, reporting the highest energy savings in living walls (€2,036.17/yr.), followed by direct green facades (€1,337.41/yr.), and indirect green facades (€1,160.41/yr.). Indirect green facades with planters demonstrated slightly lower savings of €1,045.67/year. Haggag and Hassan (2015) assessed living walls and reported savings between $88 and $133.32 per year. Shazmin, et al. (2017) reported modest savings of $37/year for outdoor living walls; however, their study did not include a detailed analysis of the costs or other co-benefits. It is clear that VGS shows significant potential for energy savings in buildings, leading to cost reductions and emphasizing the benefits of incorporating them for sustainable design.

Studies have also shown that incorporating VGS into buildings can augment their market value, thereby affecting the rental income of building owners (Table 5). Living walls can add to the annual rent by up to €2,036 (Perini and Rosasco (2013)) while for green facades, this could go up to €1,951 (Rosasco and Perini (2018)). For commercial properties (offices), the rental market is more significant than the sales market; therefore, attention to aesthetic and functional qualities due to VGS may increase rental income (Perini and Rosasco, 2013). This increase in rental income can offset the initial investment in VGS and lead to higher profits for property owners in the long run.

Although VGS cannot extend the life of a building envelope, it can reduce the annual maintenance and repair costs of building facades by providing an additional layer of protection (Perini and Rosasco, 2013). Cladding longevity cost savings refers to the expenses that building owners typically allocate for facade maintenance and repair, which can be reduced or avoided through the incorporation of VGS. The reviewed literature suggests that these systems can contribute to significant cost savings across the lifespan (see Table 5). Rosasco and Perini (2018) demonstrated that the benefits of VGS in terms of cladding longevity become more pronounced over time. Melo, et al. (2020) reported higher cladding longevity cost savings for indoor VGS types (€20,760) than for outdoor applications (€13,500). In contrast, Almeida, et al. (2021) reported lower cladding longevity cost savings for outdoor indirect green facades and living walls compared with other studies. This suggests that variations in installation methods, location, or VGS design might influence the extent of cladding longevity cost savings.

Vegetation can also improve urban acoustics through three key mechanisms, namely sound absorption, diffusion, and reflection (Veisten, et al. 2012). The acoustic comfort-related benefits of VGS are quantified based on the comfort of the building occupants as well as the expenses saved on interventions used for noise reduction (Melo, et al., 2020). Table 5 shows that the reviewed literature reports benefits related to acoustic comfort of up to €1,652,216/yr. for transportation infrastructure (Melo, et al., 2020), €476,429

Table 5. Economic Benefits of VGS as reported in literature

Source	VGS Type	Annual Energy Savings	Annual Rental Income	Cladding longevity	Aesthetics	Acoustic comfort	Job Creation
Perini and Rosasco (2013)	Direct green facades	€1,337.41	€1,264	€61,164	-	-	-
	Indirect green facades	€1,160.41	€1,264	€107,354	-	-	-
	Indirect green facade with planters	€1,045.67	€1,281	€113,236	-	-	-
	Living walls	€2,036.17	€2,036	€133,793	-	-	-
Haggag and Hassan (2015)	Living walls	$88 – 133.32	-	-	-	-	-
Perini and Rosasco (2016)	Indirect green facades	€908.94	€843.40	€14,196.06	-	-	-
	Indirect green facades with planters		€1,180.87	€20,826.25	-	-	-
Shazmin, et al. (2017)	Outdoor living wall	$37	-	-	-	-	-
Rosasco and Perini (2018)	Indirect green facades (25 yr.)	€1,873	€1,951	€20,686	-	-	-
	Indirect green facades (50 yr.)			€22,919	-	-	-
Huang, et al. (2019)	Indirect green facades	S$93.20 -230	-	-	-	-	-
	Living wall – planter system		-	-	-	-	-
	Living wall - carrier system		-	-	-	-	-
Santi, et al. (2019)	Direct green facades	€1,163.43/ m2	-	-	-	-	-
	Indirect green facades		-	-	-	-	-
	Living wall with planters	€979.25/m^2	-	-	-	-	-
	Living wall with panels	€1,868.60/m^2	-	-	-	-	-
Veisten, et al. (2012)	Living wall	-	-	-	€423,852.5	€184,650	

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Table 4. continued

Source	VGS Type	Annual Energy Savings	Annual Rental Income	Cladding longevity	Aesthetics	Acoustic comfort	Job Creation
Akinwolemiwa, et al. (2018)	Indirect green facade - HDPE	-	-	-	-	-	₦14,000
	Indirect green facade - bamboo	-	-	-	-	-	₦72,000
	Indirect green facade – timber	-	-	-	-	-	₦52,500
Matos Silva, et al. (2019)	Outdoor indirect green facade	-	-	-	€50,700/yr.	-	€6363.50 /yr.
	Outdoor living wall	-	-	-	€72,429/yr.	-	€1897.88/yr.
	Indoor indirect green facade	-	-	-	€76,124.70/yr.	€437,940	€6363.50/yr.
	Indoor living wall	-	-	-	€110,199/yr.	€109,110	€1,897.88/yr.
Melo, et al. (2020)	Outdoor indirect green facade	-	-	€13,500	€6,6150	€1,405,660/ yr.	-
	Outdoor living wall	-	-	€13,500	€6,6150	-	-
	Indoor indirect green facade	-	-	€20,760	-	€1,652,216/ yr.	-
	Indoor living wall	-	-	€20,760	-	€140,035/yr.	-
Almeida, et al. (2021)	Outdoor indirect green facade	-	-	€6,142.50	€268,894	€190,787	-
	Outdoor living wall	-	-	6,142.50 €	€312,565	€476,429	-
	Indoor indirect green facade	-	-	-	€196,247	-	-
	Indoor living wall	-	-	-	€266,334	-	-

for an outdoor living wall for primary school case studies reported by Almeida, et al. (2021), and €184,650 for residential towers (Veisten, et al. 2012). Studies have shown that the acoustic benefits of implementing a VGS can be significant for user comfort, particularly in spaces with a high influx of people, such as train stations and transport systems.

VGSs are known to remove pollutants and filter air, thereby improving air quality (Matos Silva, et al., 2019). To compute monetary benefits, studies used the equivalent carbon dioxide price found in the European Union Emissions Trading Scheme (Melo, et al. 2020; Almeida, et al. 2021; Matos Silva, et al. 2019). While several studies have reported the direct benefits of VGS in improving air quality, only three of the reviewed studies quantified the benefits and their monetary equivalents (see Table 5). Matos Silva, et al. (2019) reported that outdoor indirect green facades contributed benefits equivalent to €136.80/yr. for air quality improvement, whereas indoor indirect green facades provided a slightly higher improvement of €273.60/yr. Melo, et al. (2020) reported minimal air quality improvement for indoor indirect green facades, amounting to just €0.06/yr. Both studies reported data on transport infrastructure. Similarly, for school buildings, Almeida, et al. (2021) compared both outdoor and indoor VGS, revealing that outdoor indirect green facades and outdoor living walls each contributed €9.912/yr. to improve air quality. For indoor systems, the study found that indirect green facades and living walls offered similar benefits, with both systems improving air quality by €6.804/yr. The available data highlight the potential of various VGS types to improve air quality, with differences in the extent of improvement depending on the specific system and its indoor or outdoor application.

Living walls are often complex systems that require specialized professionals and labour. This helps to create employment opportunities for skilled workers. Only two of the reviewed studies reported data on job creation resulting from VGS installation. Hiring skilled labourers adds to installation and maintenance costs, but also offers indirect benefits to those employed in these jobs (Matos Silva, et al. 2019). It can be observed from Table 5 that the job creation benefits of VGS can reach up to €6,363.50/yr. for VGS installed in rail stations (Matos Silva, et al., 2019) depending on the scale and type of vertical greenery. On the other hand, Akinwolemiwa, et al. (2018) reported data from their case study on installing affordable VGS, which led to the creation of jobs benefiting the local community. They include carpenters, horticulturists, welders, and plumbers. The prototypes resulted in job creation benefits of ₦14,000 for HDPE indirect green facades, ₦72,000 for bamboo indirect green facades, and ₦52,500 for precast timber green facades. These are significant for low-income communities and help with the adoption of VGS on a larger scale (Akinwolemiwa, et al. 2018).

OTHER CO-BENEFITS OF VERTICAL GREENERY SYSTEMS

Some studies have also reported the indirect benefits of VGS, which can be utilized for a more comprehensive cost-benefit analysis of these systems. These studies employ various methodologies to quantify these benefits and ascribe them monetary value.

Certain countries across the globe provide tax benefits for installing green systems in buildings, such as green roofs, photovoltaics, and vertical greenery (Shazmin, et al. 2017). These benefits can be provided either in the form of tax reduction, in which beneficiaries can pay a reduced tax to install these systems, or in the form of tax exemptions, where the amount spent on green systems can be exempted (partially or fully). Rosasco and Perini (2018) reported that although there are currently no tax benefits for vertical greenery in Italy, such benefits exist for green roofs. The study reported a tax reduction of up to €2,647/yr. equivalent to 50% of the installation costs for green facades. Similarly, Shazmin, et al. (2017) reported that installing living walls could lead to tax exemptions of $8/yr. for a typical residence (900 sq. ft. area) in Malaysia. This study also reports that similar property tax assessment incentives can help in the adoption of green systems to ensure sustainability.

VGS can also filter grey water to an acceptable quality for irrigation. This translates into cost savings for the water used for irrigation. Depending on the type of VGS and filtration mechanism, water saving benefits up to S$27-200/yr. (indirect green facade), S$446-894/yr. (living wall – planter systems) and S$224-620/yr. (living wall – carrier system) has been achieved (Huang, et al. 2019).

Evaluating the impact of VGS installation in a train station, Matos Silva, et al. (2019) highlighted that user satisfaction, and new spaces result in higher returns owing to the users' appreciation of the infrastructure. The study reported a monetary benefit of €6,996/yr. on account of the user satisfaction. Benefits equivalent to €75,710.40/yr. are attributed to rental income from the creation of new spaces because of indirect green facades in the indoor environment of a train station. On the other hand, Akinwolemiwa, et al. (2018) developed VGS prototypes using both medicinal and edible plants. Therefore, these systems can generate revenue from selling these plants, thereby creating steady income for building owners. An income of ₦40200 – 251400/yr. for bamboo-type indirect green facades and ₦37800– 146600/yr. for precast timber green facades was reported in their study. This is significant for low-income economies like Nigeria.

Hollands and Korjenic (2021) reported that VGS installation improves hygrothermal comfort, thereby reducing the number of sick leaves consumed by office employees. The study reported a cost savings of €440.43/person/yr. for the trough-type indoor living wall and €349.93/person/yr. for the fleece system. Furthermore, Rosasco and Perini (2018) also accounted for the biomass produced (700 kg) due to the pruning of plants over the VGS lifecycle. The monetary benefits are computed based on 'the repurchase price of energy produced from renewable resources' in Italy. However, these benefits are exceptionally low (€2.09/yr.) compared to the lifecycle costs of these systems, and therefore have a negligible impact on the overall costs. These co-benefits add to the value of VGSs and advocate their sustainable use.

ECONOMIC INDICATORS OF VERTICAL GREENERY SYSTEMS

The evaluation of the economic sustainability of VGS is based on economic indicators from the reviewed literature. Some studies have reported data on the internal rate of return (IRR), net present value (NPV), and payback period. While the benefit-cost (BC) ratio has not been reported in most studies, it has been calculated based on reported costs and benefits. The reviewed literature indicates that the economic sustainability of VGS is highly dependent on the specific VGS type, materials used, and the context in which they are implemented.

Benefit – cost (BC) ratios are useful for comparing the economic feasibility of these systems, with higher values indicating greater benefits relative to costs. Figure 2 presents an overview of the cost-benefit analysis based on the literature. Most reported cases of VGS are profitable in the long term because the BC ratio is greater than 1.

The BC ratios calculated for VGS reported by Perini and Rosasco (2013) for both green facades and living walls were less than one, indicating that these systems are not economically viable in the long run. In contrast, Huang, et al. (2019) reported BC ratios in the range of 4.07 - 14.57 for indirect green facades and up to 8.90 for living walls. Santi, et al. (2019) reported much higher BC ratios than those reported in other studies (205.311 and 145.429 for direct and indirect green facades, respectively). However, this is primarily due to the non-reporting of all the associated maintenance and disposal costs. Green facades have higher BC ratios than living walls, as the benefits provided by green facades outweigh the costs when compared to living walls.

Shazmin, et al. (2017) only accounted for energy savings and tax exemption benefits for living wall systems in Malaysia, resulting in the lowest BC ratio of 0.14. This could be attributed to the non-reporting of other co-benefits of VGS; however, this also indicates that these systems are expensive and may not be economically feasible. Similarly, Haggag and Hassan (2015) reported a BC ratio of 0.875 to 1.111 for outdoor living wall systems when including only energy savings and rental benefits. BC ratios were calculated from the costs and benefits reported in the literature. It is important to note that these may vary when discount rate and NPV are considered. For example, Almeida, et al. (2021) reported BC ratios of up to 34.99 for indirect green facades and up to 7.75 for living walls, considering a discount rate of 6.67%.

The net present value (NPV) helps determine whether an investment will generate positive returns over time. A positive NPV indicates that the investment is expected to create value, whereas a negative NPV suggests that the investment will result in a net loss (Perini and Rosasco, 2013). Only 3 of the reviewed studies reported NPV data for VGS.

In their studies conducted for an office building in Genoa, Italy, an NPV of 49.68 €/m^2 for indirect green facades and 17.02 €/m^2 for indirect green facades with planters was reported by Perini and Rosasco (2016), while another study conducted in 2018 by the same research group reported an NPV of –43.94 €/m^2 for indirect green facades with a life of 25 years when economic incentives (tax reduction) were not factored in, and 202.93 €/m^2 for indirect green facades with 50 years lifecycle and considering economic incentives (Rosasco and Perini, 2018). Perini and Rosasco (2013) also reported a negative NPV for living walls

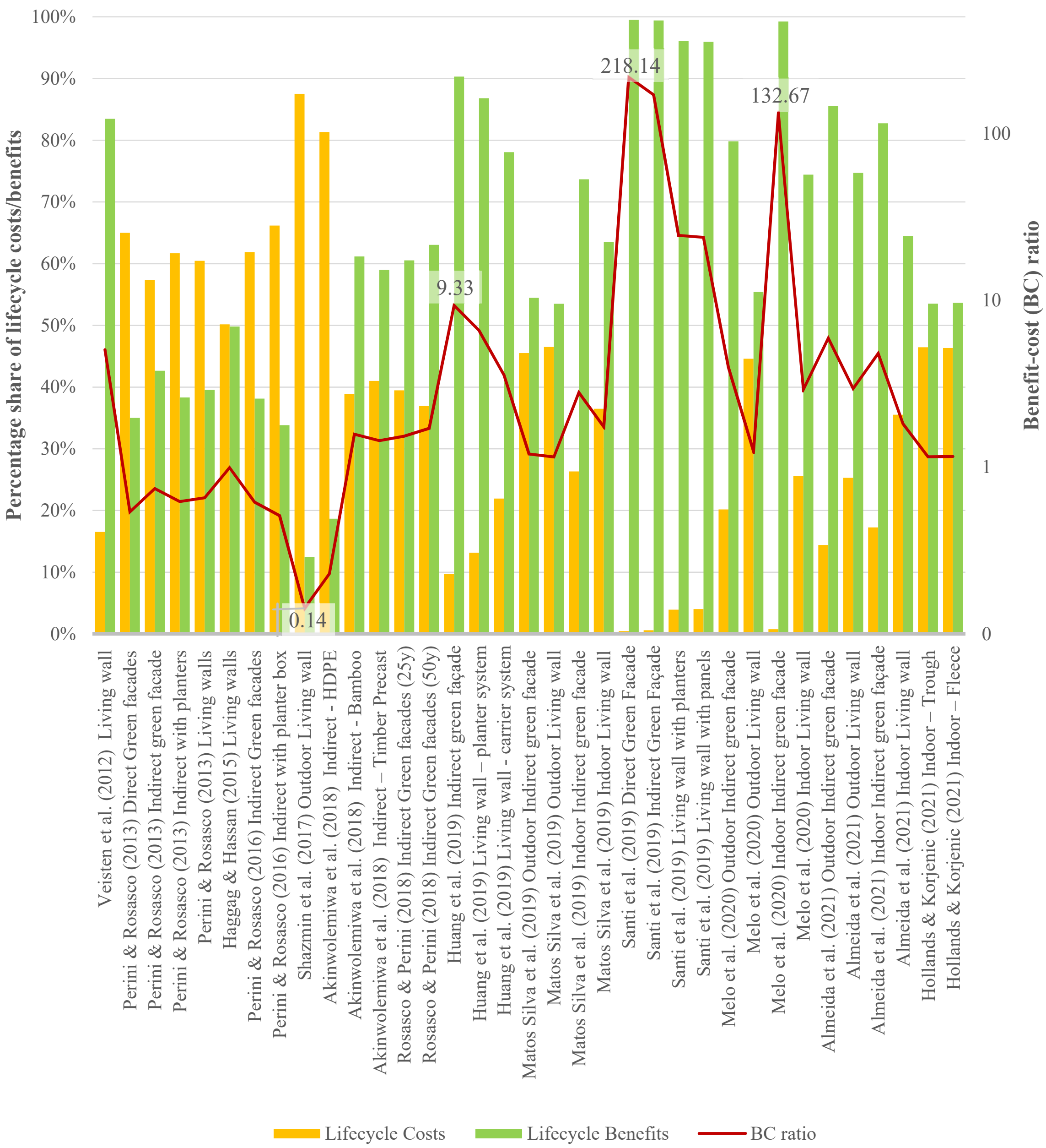

Figure 2. Cost-Benefit Analysis of VGSs reported in literature reviewed

(-271.231 €/m²) and indirect green facades with steel support and planter boxes (-101.653 €/m²), whereas a high NPV for direct green facades (133.951 €/m²) and HDPE indirect green facades (65.391 €/m²) was reported. In all scenarios, the living walls were reported to have a negative NPV, indicating that these systems are economically unsustainable.

On the other hand, an investment is deemed sustainable when its internal rate of return (IRR) is at least as high as the minimum acceptable value. This ensures that the project's returns cover the financing costs (Rosasco and Perini, 2018). Perini and Rosasco (2013) reported IRR of 10.7%, 5.8%, and 4.5% for direct green facades, HDPE indirect green facades, and indirect green facades with planter boxes, respectively. The same study found that steel indirect green facades with planter boxes and living walls were economically unsustainable, as they reported a negative NPV and, thereby, 0% IRR. In another study by the same group, it was reported that indirect green facades with a lifespan of 25 years had an acceptable IRR (>5%, 8.5 - 12/6%) when economic incentives (tax reduction) were considered, whereas when lifespan of 50 years was considered, the IRR was in the range of 5.8-11.1%.

The payback period is the time required to recover the cost of an investment or reach the break-even point (Perini and Rosasco, 2016). Only five studies in the reviewed literature reported the payback period. The review found that the costs of direct green facades can be paid back within 16-24 years, whereas indirect green facades can have a payback period ranging from 16 to 50 years, depending on the material of the support structure and VGS type. The payback period for living walls can exceed 50 years (Perini and Rosasco, 2013). Another study reported a payback period of 8-21 years for indirect facades when the lifespan of the VGS was 25 years and 9-23 years when it was 50 years (Rosasco and Perini, 2018). Payback periods of 17 and 27 years for indirect green facades and indirect green facades with planter boxes, respectively, were reported by Perini and Rosasco (2016). Although Haggag and Hassan (2015) reported a payback period of 13-17 years for living walls, they noted that this was a lengthy period; therefore, these systems could not be economically sustainable. Huang, et al. (2019) reiterates that the VGS costs for both indirect green facades and living walls cannot be repaid within the lifecycle of the systems.

Discussion and Conclusion

The comprehensive analysis conducted in this review offers valuable insights into the economic feasibility of using VGS in buildings. In general, the reviewed studies provide a compelling case for VGS, owing to its numerous benefits. However, despite the numerous environmental, economic, and social benefits of VGS, high initial and maintenance costs discourage decision makers (Huang, et al., 2021). The literature quantifies several economic benefits of VGS, which, when considered over the lifetime of these systems, can compensate for their high initial costs and assist users in adopting VGS in buildings.

Green facades cost less than living walls because of the complexity and presence of additional components in living wall systems as the primary contributors to higher costs. Maintenance costs contributed the most to lifecycle costs, followed by initial and disposal costs, for both green facades (Figure 3) and living walls (Figure 4). This is because maintenance costs are recurring expenses incurred throughout the VGS lifetime, whereas the initial and disposal costs are one-time expenditures. The replacement and pruning of plants are primary contributors to maintenance costs (Huang, et al., 2019).

Analysing and comprehending the elements of each phase of the VGS lifecycle are essential for making informed decisions. This could also help optimize systems for greater economic efficiency. Existing literature on VGS suggests that the economic sustainability of these systems is largely dependent on the typology, climate, and location. In general, VGS that are more complex and require more maintenance are less likely to be economically sustainable. However, a VGS, which is simple to install and maintain, can be economically sustainable in a variety of climates and locations. The success and potential economic returns of VGS are highly context-dependent and require careful consideration of design, installation, operation, and maintenance costs. Economic analysis revealed that the BC ratios for various VGS types varied, but green facades generally exhibited higher BC ratios. Most VGS cases were profitable because the BC ratio was greater than 1, however, a realistic analysis is only possible when both costs and benefits are reported in depth, which was lacking in most of the studies reviewed.

When co-benefits and tax incentives are considered, the VGS's payback period can be as low as eight years (Rosasco and Perini, 2018), but it usually exceeds the lifespan of the system (Huang, et al., 2019; Perini and Rosasco, 2013). The VGS design, implementation, and optimization capacity affect the payback period. Living wall systems have higher costs, and the realization of their benefits takes a long time, resulting in an unfavourable NPV and IRR. This, combined with the higher payback periods, indicates that these systems are economically unsustainable. However, the higher efficiency of living wall systems to capture pollution

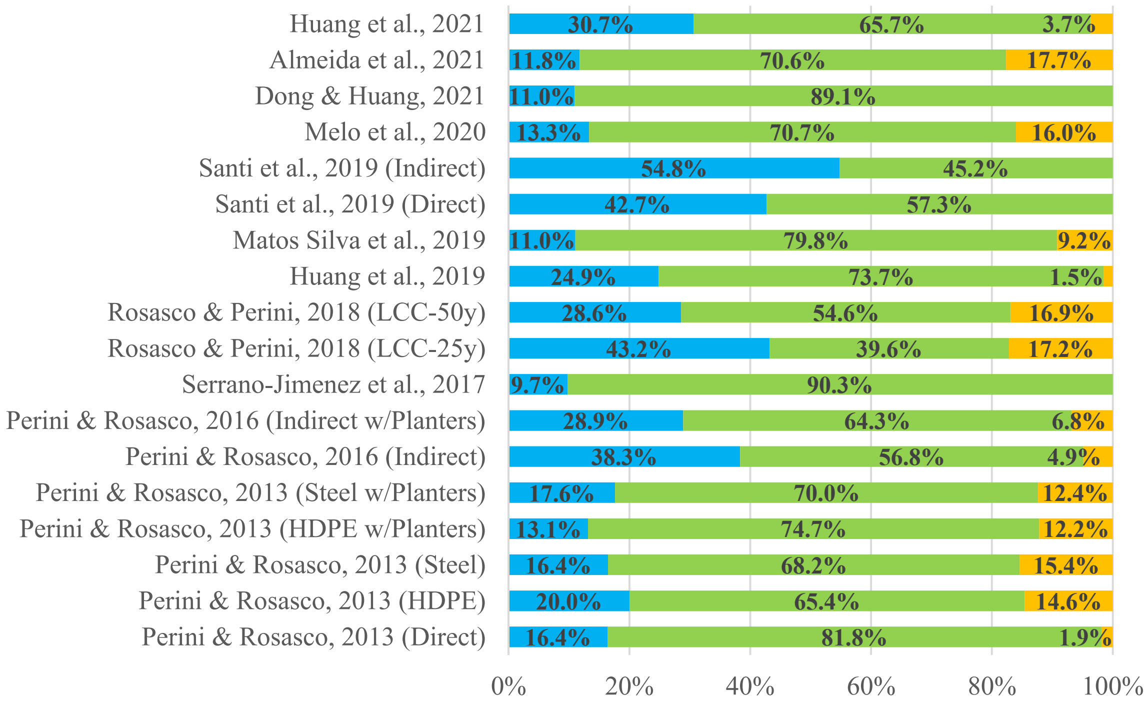

Figure 3. Distribution of initial, maintenance and disposal costs of green facades

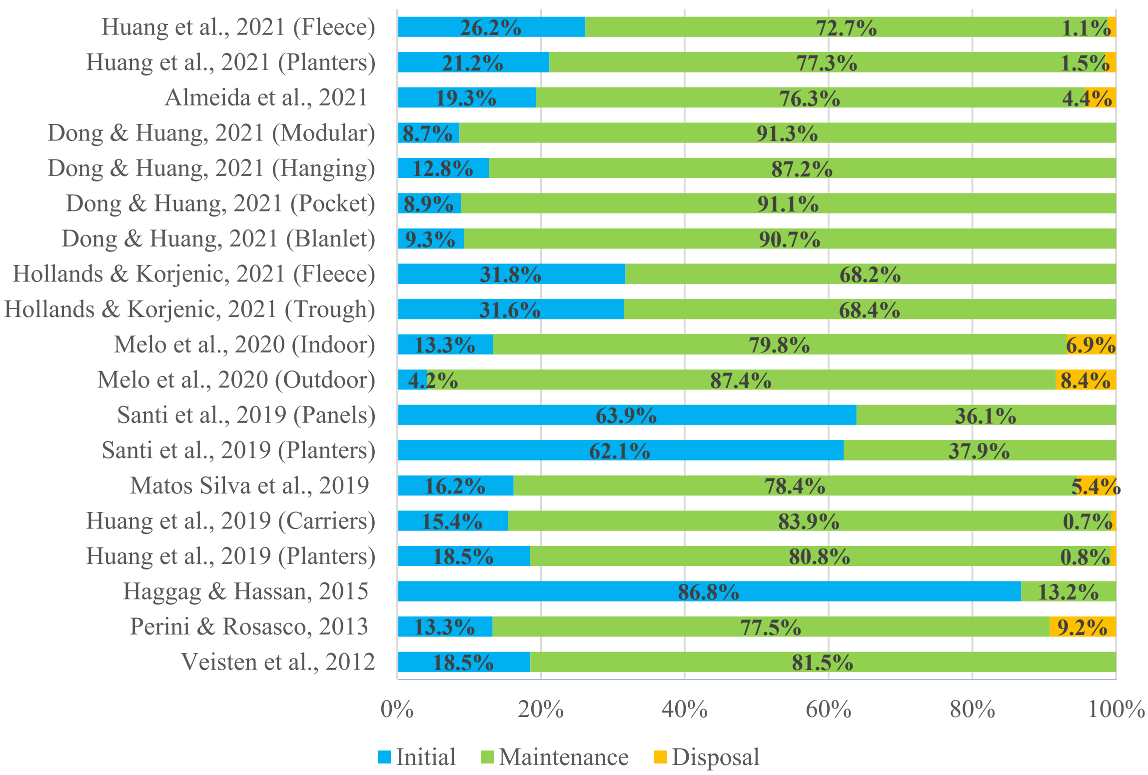

Figure 4. Distribution of initial, maintenance and disposal costs of living walls

and reduce emissions compared to green facades could make them a viable option to address climate change-related issues in buildings. Therefore, it is important to weigh and analyse economic sustainability and its potential to mitigate climate change.

This review also establishes the need for precise and standardized financial data to provide clarity. Studies often omit costs, making economic data comparisons challenging. For instance, the maintenance costs reported by Santi, et al. (2019) are lower because of assumptions rather than actual project data, and details of life cycle costs are not provided. Similarly, Haggag and Hassan (2015) only considered irrigation and electricity costs, neglecting regular maintenance expenses and resulting in a higher proportion of the initial costs. Data reporting also lacks clarity regarding the VGS typology. For instance, Dong and Huang (2021) reported costs without adequately describing specific typologies, such as 'climbing vertical green wall' and 'blanket vertical green wall,' making it difficult to determine the VGS type. The absence or ambiguity of the VGS descriptions can lead to misinterpretation of the data. As advocated by Radić, Dodig and Auer (2019), establishing a standardized framework is crucial for facilitating future research and ensuring clarity.

This review presents a detailed analysis of the economic viability of VGS as a practical means to mitigate the effects of climate change on urban environments. The findings suggest that although the initial investment in VGS may be high, it can provide long-term financial benefits to building owners and operators in the form of energy savings, increased property value, and reduced maintenance costs. The VGS type and context affect economic viability and sustainability. Therefore, stakeholders should carefully consider the unique elements of each case when evaluating the feasibility and financial viability of VGS implementation. In addition, the assessment of economic sustainability can be improved if all possible co-benefits of VGS are quantified and analysed to provide a comprehensive understanding of these systems.

Future research should focus on context-specific studies, particularly in underrepresented regions, to better understand the potential for mitigating climate change and improving urban sustainability. This would boost VGS adoption and create greener, healthier, and more sustainable cities.

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