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**DOI**

[10.1016/j.ufug.2025.128931](https://doi.org/10.1016/j.ufug.2025.128931)

**Publication date**

2025

**Document Version**

Final published version

**Published in**

Urban Forestry and Urban Greening

**Citation (APA)**

Bakker-den Hartog, D., Lugten, M., & Ottele, M. (2025). Multi-criteria-decision-making framework using ecosystem-services for an integral design of vertical greenery systems. *Urban Forestry and Urban Greening*, 112, Article 128931. <https://doi.org/10.1016/j.ufug.2025.128931>

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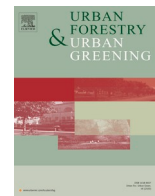
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## Original article

# Multi-criteria-decision-making framework using ecosystem-services for an integral design of vertical greenery systems

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## ARTICLE INFO

## Keywords:

Vertical greenery systems  
Ecosystem services  
Multi-criteria Decision-Making  
Urban design  
Sustainable architecture

## ABSTRACT

Vertical greenery systems (VGS) are recognized for providing a range of ecosystem services (ESS), including biodiversity enhancement, property value increase, and stormwater management. However, there are significant challenges in comparing VGS designs due to the lack of standardized metrics and the limited understanding of their integrated performance across multiple ESS. This study introduces a multi-criteria decision-making (MCDM) model to assess and compare the full spectrum of ESS provided by VGS. Through an extensive literature search, VGS typologies, system components, and performance metrics were identified for ESS and synthesized. The application of the MCDM model was tested in a case study, showcasing its potential for improving decision-making and selection of VGS designs. Findings from the literature review stress a need for standardizing research methods, improving data quantification, and explaining and modelling ESS interactions. The study concludes that the MCDM framework supports context-specific evaluations, while further refinement is needed to reduce subjectivity and to include emerging ESS. These approaches are critical for advancing both research and practical applications in green infrastructure.

## 1. Introduction

Vertical greenery systems (VGS) are acknowledged for supporting and providing a broad variety of ecosystem services (ESS), i.e., biodiversity support, aesthetic values, water management, and noise and air pollution mitigation, with some of these benefits being monetizable. The potential benefits of VGS vary across systems, depending on their design, and are divided into (1) systems with plants growing from planter boxes mounted on walls (living walls), and (2) systems with plants climbing from the ground surface (green facades). The impact of systems and individual or combined ESS has been published in various academic fields, and a comprehensive and standardised overview of key performance indicators and boundary conditions is seen as missing (Ascione et al., 2020; Su et al., 2024). Research methods and metrics vary substantially across studies, making it difficult to compare and combine results (Hollands and Korjenic, 2021). Defining design requirements for VGS based on the assessment of impacts and aggregation for a broad range of ESS is, therefore, challenging. Various studies have highlighted the need for quantitative, evidence-based models for scoring VGS types

(Ascione et al., 2020; Su et al., 2024), which hinders the integration of ecological and societal benefits into investment and policy decisions. This observation is shared in more recent publications (Farrokhirad et al., 2024; Irga et al., 2023), which also highlight the importance of understanding ESS effects for successful integration during the earliest phase of building design projects (Farrokhirad et al., 2024). In this light, there is a demand for methods that systematically model relations and interactions between system components, which are needed to bridge this gap (Ascione et al., 2020).

The ecosystem service concept has been widely adopted since the introduction of the UN's Ecosystem Assessment in 2005 (Fontana et al., 2013), defining ESS as 'the benefits which humans obtain from ecosystem functions and resources', classifiable in many ways along so-called 'market' and 'non-market' ESS or 'goods'. Comprising four ESS categories – supporting, provisioning, regulating, and cultural services – as well as key indicators (European Environment Agency, 2011), the ESS framework conceptualizes crossovers between ESS. This information is key to selecting a design that meets predefined performance criteria (Ascione et al., 2020; Manso et al., 2021). However, the framework's

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highly conceptual character, with ESS operating at different spatial scales, limits practical adaptation in architectural design and planning-oriented decision-making. Predicting the outcomes of design choices, even for a single ESS, requires a detailed understanding of ESS as systems, with interconnected input and output variables that span across spatial scales. Most studies address this complexity by focusing on case studies or examining ESS at fixed scales (Koschke et al., 2012).

To address this challenge, previous studies have employed multiple-criteria decision-making (MCDM) methods to bridge the gap between the ESS framework and decision-making processes. MCDM, a common approach in ecological economics, proves effective when dealing with a discrete number of alternatives and outputs that depend on diverse and partially non-quantifiable metrics (Sons, 1988). Typically grounded in decision trees, these MCDM models require a clear definition of the problem, alternatives, and decision criteria (Sons, 1988).

Through stakeholder and expert interviews, these models identify and rank the most relevant ESS based on a given problem or design brief. MCDM methods leverage the ESS concept by mapping key indicators and interdependencies (Fontana et al., 2013; Koschke et al., 2012). Examples of MCDM templates applicable to (sustainable) architectural and urban planning include MIVES, AHP, and ANP (Velasquez and Hester, 2013). Despite their ability to weigh, summate, and compare sets of non-aligned, heterogeneous metrics, these methods assume that input data is quantifiable, with predictable interactions between system components. Consequently, they may not inherently facilitate comprehensive ESS assessments, as the lack of a 'clear identification, definition, and quantification of services' hampers their adaptability due to limited knowledge of ecosystem functioning [10]. Resulting in overly complicated and academic methods deemed non-operational in practice (Koschke et al., 2012), it explains why some studies on MCDM for ESS assessments adopted less numerical and computationally oriented MCDM frameworks (Fontana et al., 2013).

This article introduces a model designed to assess the effectiveness of Vertical Greenery Systems (VGS) by leveraging the Ecosystem Service (ESS) concept. The model employs a Multiple-Criteria Decision-Making (MCDM) approach to enhance the design and decision-making processes related to VGS. Developed through a thorough literature search, the model undergoes testing in a small-scale case study. The study aims to achieve the following four objectives:

1. Identify relevant ecosystem services associated with VGS through an extensive literature search.
2. Decompose VGSs into system components defined in the literature as key indicators for delivering specific individual ecosystem services.
3. Map interactions between ecosystem services based on key VGS components, synthesising this information into a decision-support tool.
4. Evaluate the potential of MCDM to assess VGS designs based on overall ecosystem services performance.

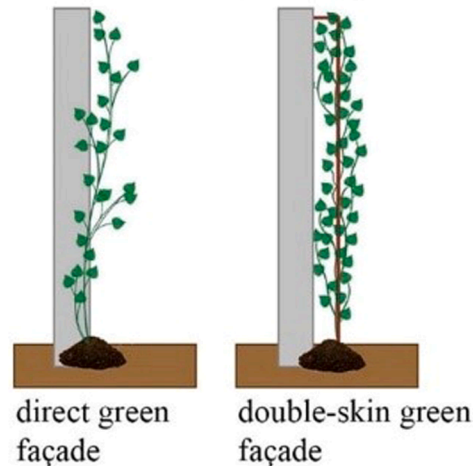
## 2. Types of VGS

Vertical greenery systems (VGS) have been classified in various ways, based on main system components relating to (i) the vegetation, (ii) the growing media (substrate), (iii) the support system, and (iv) the irrigation system (Wood et al., 2014). A classification was made based on the systems' characteristics for the most common types of VGS (Medl et al., 2017).

VGS are commonly divided into two groups, i.e., green façades and living walls. Green façades are ground-based natural climbers, further separable into direct and indirect systems, see also Fig. 1. Direct green façades refer to self-adhesive climbers that affix themselves to a wall. Indirect systems consist of a structural frame to support climbing plants, equipped with built-in droplet irrigation.

Living walls are fully wall-based and can be divided into three types. Continuous living walls (i) commonly consist of aluminium-framed

## Ground based systems: green façades



## Wall-based systems: green walls

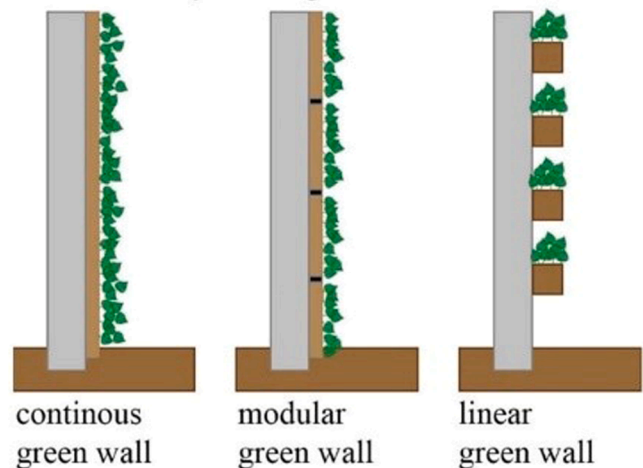


Fig. 1. Classification of VGS, based on (Medl et al., 2017).

support systems with geotextile felt layers partially serving as substrate. Modular living walls (ii) also have an aluminium frame as a support system, but are commonly made from modular panels containing, e.g., foam or mineral wool substrates. Lastly, linear living walls are systems based on separate planter soil-filled boxes. Shrubs, grasses, and perennials mainly grow in linear systems, while succulent plants can grow in both modular and linear systems. All living walls are usually equipped with hydroponic irrigation systems, e.g., drip lines placed at the top of the wall, or rows of individual boxes/mats.

## 3. VGS and ecosystem services

Ecosystem services (ESS) refer to benefits harvested from ecosystems. The Millennium Ecosystem Assessment from 2005 identifies four groups of benefits, widely used in literature (European Environment Agency, 2011):

- 1) Supporting: services providing basic elements that are fundamental for life
- 2) Provisioning: services providing commodities and resources, crucial to sustain life (e.g. food or water)
- 3) Regulating: services mitigating or regulating environmental systems (e.g. climate mitigation or disease control)
- 4) Cultural: services adding a social or cultural value (e.g. recreation, aesthetic enjoyment, and cultural values).

Vertical Greening Systems (VGS) tie into ecosystem services (ESS) across all four categories, as outlined in Table 1. A literature review was conducted systematically, focusing on scientific peer-reviewed review articles presenting VGS performance indicators and ecosystem services benefits. Relevant papers were retrieved via Scopus with the following search query: TITLE-ABS-KEY ("impact" OR "benefits" OR "performance" OR "value") AND TITLE-ABSKEY ("vertical greenery systems" OR "green wall" OR "green façade" OR "living wall") AND (LIMIT TO (DOCTYPE, "re")). Additionally, a 'snowball approach' was used for screening other relevant or pooled articles.

Table 2 summarises the studies included in this research per ESS, which is presented in the following paragraphs.

### 3.1. Biodiversity support [BS]

Biodiversity is commonly defined by species-related indicators, including richness and diversity, describing the robustness of ecosystems (Millennium Ecosystem Assessment, 2005; Zhao et al., 2024). VGS can connect natural areas and improve greenery networks, and provide food, shelter, and reproduction habitat (Mayrand et al., 2018; Tiago et al., 2024). Depending on its location and design, several studies have reported a positive effect of VGS on the number of insects, spiders, beetles, snails, and birds (Chiquet, 2014; Madre et al., 2015; Mayrand et al., 2018; Salisbury et al., 2023; Treder et al., 2024). These effects are associated with the density and thickness of the plant layer, as measured by the Leaf Area Index (LAI) in leaves per cubic meter. Mayrand et al. (2018) argued that biodiversity support provided by VGS is most effective if the plant layer 1) grows from seedlings, 2) consists of a diverse selection of non-cultivated plant species, 3) requires as little maintenance as possible, and the substrate layer 1) water and nutrients are equally distributed, 2) is made of local organic soil, 3) and not too densely compressed. VGS can connect green structures, as nodes in a larger ecological system, which are essential for habitat support and biodiversity (Tiago et al., 2024). Mapping the geo-spatial variety, location, and ecological functions is vital for understanding these systems and the potential of VGS (Shanahan et al., 2011). It is therefore recommended to first analyse (existing) local ecosystems and networks before designing a VGS (Madre et al., 2015). For locations without nearby natural areas and robust green networks, VGSs are seen as unfit for most urban-avoiding or urban-adapted species (Mayrand and Clergeau, 2018), and it is uncertain to what extent VGSs contribute to urban wildlife corridors (Mayrand & Clergeau, 2018; Mayrand et al., 2018).

### 3.2. Thermal regulation [TR]

Operating at the building (BTR) and urban level (UTR), the thermal properties of VGS have attracted more scientific attention compared to other ESS (Bustami et al., 2018; Safikhani et al., 2014). On the building level, VGS can reduce energy demand for heating and cooling (Besir & Cuce, 2018; Campiotti et al., 2022; Detommaso et al., 2023; Nocera et al., 2024; Shuhaimi et al., 2022; Tang et al., 2023; Vijayalaxmi &

Gandham, 2023; Zuckerman & Lensky, 2023), through shading, insulation, and surface temperature regulation linked to evapotranspiration (Ascione et al., 2020; Koch et al., 2020). VGS are associated with urban heat island (UHI) mitigation, linked to short-wave radiation absorption by plants (Safikhani et al., 2014; Su et al., 2024), and reducing solar re-radiation from hard surfaces through shading (Safikhani et al., 2014; Su et al., 2024), which reduces surface temperature (Detommaso et al., 2023; Safikhani et al., 2014; Zheng et al., 2023), increases albedo levels, and affects perceived temperatures (PT) (Khan & Munawar, 2024; Wong et al., 2021). Most variance in thermal properties of VGS depends on the substrate (Koch et al., 2020), e.g., linked to thickness, porosity, and moisture content. Recommended dimensions and values are season-dependent, e.g. dry and porous substrates improve the thermal insulation (winter), juxtaposing with requirements for optimal cooling performance. This is opposite in summer, as evaporation and temperature potentials between substrate and air depend on moisture influx (Bakhshoodeh et al., 2022; Besir & Cuce, 2018), but also depend on lowering wind velocities in air cavities, which seem more effective for indirect green walls (Perini et al., 2011; Safikhani et al., 2014). Compared to inorganic materials, such as mineral rockwool, natural materials (soil) possess a greater moisture uptake capacity combined with a low porosity (Safikhani et al., 2014). Plants also contribute to thermal regulation (Nocera et al., 2024), linked to the LAI (Koch et al., 2020; Safikhani et al., 2014), thermal resistance (Vijayalaxmi & Gandham, 2023), and the plant layer porosity (Tang et al., 2023). Linked to shading and insulation, the cooling potential is correlated with LAI, linked to stationary air volumes in the foliage. These effects are greatest for plant species with small leaves (Charoenkit and Yiemwattana, 2017), high leaf stomatal conductance, thin and light-coloured leaves (Monteiro et al., 2017), and strongest if the distance from a wall is less than a meter (Zuckerman & Lensky, 2023). Thermal regulation effects are strongest for VGS containing combined substrate and plant layers, i. e., living walls (Koch et al., 2020; Manso et al., 2021). However, thermal insulation depends on air cavity dimensions between layers, and/or between a VGS and the supporting wall (Bakhshoodeh et al., 2022; Besir & Cuce, 2018), and the VGS system (Perini et al., 2011; Safikhani et al., 2014). These effects are, however, non-linear, as the probability of internal circulation of hot and cold air, which lessens the thermal insulation of the system, increases for wider cavities (van der Linden, 2006). Overall, the thermal performance of various VGS types can be ranked as follows (from 'strong' to 'weak'): modular living walls, linear living walls, continuous living walls, indirect green façades, and the direct green façade (Koch et al., 2020; Perini et al., 2011; Su et al., 2024; Van de Wouw et al., 2017).

### 3.3. Noise control [NC]

Operating at the building (BNC) and urban level (UNC), the propagation and transmission of sound through a medium depend on its boundary and fluid properties, which relate to wave reflection, absorption, transmission, and scattering (Bakker et al., 2023; Yan et al.,

Table 1

VGS types and their system components based on (Fernández-Cañero et al., 2018; Manso and Castro-Gomes, 2015; Medl et al., 2017; Reyhani et al., 2022).

Vertical greenery systems	Support system	Growing media	Vegetation	Irrigation system	
Green façades	Direct	NA	Soil	Self-adhesive climbers, e.g., Hedera helix	NA
	Indirect	Structural frame of cables, meshes, trellis or nets	Soil	Climbing plants, e.g. Hedera helix	NA
Living walls	Continuous	Aluminium frame with geotextile felt layers	Soil (e.g.)	Shrubs, grasses, and perennials	Hydroponic system: Drip line on the top of the wall
	Modular	Structural aluminium frame with modular panels	Foam substrate	Shrubs, grasses, perennials, and succulent plants	Hydroponic system: Drip line on top of each module
	Linear	Modular plastic planter boxes and aluminium frames	Soil	Shrubs, grasses, perennials, and succulent plants	Hydroponic system: Drip line on top of each module

**Table 2**  
Literature included in this article, clustered for spatial scales and ESS.

Ecosystem services		Spatial scale		Literature
		Urban	Building	
<b>Supporting</b>	Biodiversity	X		(Besir and Cuce, 2018; Manso et al., 2021; Radić et al., 2019; Salisbury et al., 2023; Teotónio et al., 2021; Tiago et al., 2024; Treder et al., 2024; Zhao et al., 2024)
<b>Regulating</b>	Weathering control		X	(Manso et al., 2021; Radić et al., 2019; Teotónio et al., 2021)
	Noise control	X	X	(Ascione et al., 2020; Manso et al., 2021; Radić et al., 2019; Teotónio et al., 2021)
	Thermal regulation	X	X	(Antoszewski et al., 2020; Ascione et al., 2020; Bakhshoodeh et al., 2022; Besir & Cuce, 2018; Campiotti et al., 2022; Detommaso et al., 2023; Khan and Munawer, 2024; Koch et al., 2020; Manso et al., 2021; Nocera et al., 2024; Radić et al., 2019; Safikhani et al., 2014; Shuhaimi et al., 2022; Tang et al., 2023; Teotónio et al., 2021; Vijayalaxmi & Gandham, 2023; Wong et al., 2021; Zheng et al., 2023; Zuckerman and Lensky, 2023)
	Greywater treatment	X		(Addo-Bankas et al., 2021; Boano et al., 2020; Gholami et al., 2023; Liu et al., 2022; Manso et al., 2021; Pradhan et al., 2019; Teotónio et al., 2021; Zhao et al., 2024)
	Stormwater management	X		(Addo-Bankas et al., 2021; Loh & Stav, 2008; Manso et al., 2021; Radić et al., 2019; Teotónio et al., 2021; Zhao et al., 2024)
	Air quality control	X	X	(Addo-Bankas et al., 2021; Heindri et al., 2024; Jeyasurya et al., 2024; Manso et al., 2021; Tang, 2023; Ysebaert et al., 2021)
	Energy efficiency		X	(Manso et al., 2021; Safikhani et al., 2014; Su et al., 2024; Wang et al., 2023; Zluwa & Pitha, 2021)
<b>Provisioning</b>	Food	X		(Manso et al., 2021; Prihatmanti & Taib, 2018; Teotónio et al., 2021; Xing et al., 2017)
<b>Cultural</b>	Aesthetic value	X	X	(Besir & Cuce, 2018; Goel et al., 2022; Manso et al., 2021; Radić et al., 2019; Teotónio et al., 2021)
	Education	X		(Radić et al., 2019)
	Health	X		(Besir & Cuce, 2018; Fonseca et al., 2023; Manso et al., 2021; Radić et al., 2019; Teotónio et al., 2021; Xing et al., 2017)

2022). These properties are influenced by the texture, geometry, and material of VGS and similar porous structures (Yan et al., 2022). VGS obstruct sound propagation between street canyons (Van Renterghem et al., 2013). Subjective soundscape perception is influenced by VGS as well, which is attributed to visual-auditory masking and natural sounds, improving soundscape perception and environmental stress (Radić et al., 2019; Yang & Jeon, 2020). Although most studies point to the noise-mitigating properties of VGS, the effect size and metrics vary across studies. Insert losses (IL) vary between 0 and 10 dB for living walls (Manso et al., 2021), and between 5 and 10 dB for the plant layer alone (Yang and Jeon, 2020). The sound absorbing effects induced by VGS and similar porous materials are frequency dependent and primarily effective above 250 Hz (Pérez et al., 2016; Wong, Tan, Tan, et al., 2010; Yang & Jeon, 2020). Sound abatement variances across VGS are attributed to vegetation type and growing mediums (Yang and Jeon, 2020). On a component level, the substrate contributes most to acoustical absorption, depending on, e.g., substrate thickness, porosity, tortuosity, and moisture content (Bakker et al., 2023; Oquendo-Di Cosola et al., 2022; Radić et al., 2019; Yang & Jeon, 2020). Acoustical absorption is associated with acoustical-thermal energy conversion, induced by friction between air volumes and substrate material inside pores (Yang and Jeon, 2020), for frequencies lower than 2000 Hz, above which scattering becomes indicative (Wong, Tan, Tan, et al., 2010). Noise regulating plant later indicators include, e.g., (W)LAI (Horoshenkov et al., 2013; Pérez et al., 2016; Wong, Tan, Tan, et al., 2010), leaf area density (LAD), and angle of leaf orientation (ALO) (Horoshenkov et al., 2013). For urban noise mitigation, VGS types comprising a dry substrate and a thick-dense plant layer seem most effective (Bakker et al., 2023; Horoshenkov et al., 2013; Oquendo-Di Cosola et al., 2022). For indoor noise regulation, systems with a high mass volumetric density, benefiting from moisture to add weight, were found to be more insulating (Yang and Jeon, 2020). Various studies on the soundproofing effect of different types of VGS show a vast range of results (Attal et al., 2019; Pérez et al., 2016). Based on the VGS categories used in this article, systems were ranked as follows (from best to worst sound attenuation): modular living wall, linear living wall, green facades. Especially for linear living walls, the performance depends on how the planters are placed and the thickness of the substrate. Green facades with an air cavity perform better compared to greening mounted directly on the façade.

### 3.4. Stormwater management [SWM]

Porous materials, like VGS, possessing 'sponge-like' properties, which are associated with storm water (SWM) and sewage system regulation (Manso et al., 2021; Xie et al., 2022; Zhao et al., 2024). Integrated into urban drainage ecosystems (Lau and Mah, 2018), VGS can store excess water temporarily, temperately releasing water contained in the substrate (Lau & Mah, 2018; Orta-Ortiz & Geneletti, 2021; She-weka & Magdy, 2011; Zhao et al., 2024), regulating sewage capacity and rainwater supply. Compared to other nature-based SWM interventions at urban and building levels, such as green roofs, the effects of VGS are reportedly understudied (Zhao et al., 2024), resulting in substantial error margins around estimated quantified effects of VGS on SWM (Ascione et al., 2020). Simulations for tropical climates found a reduction between 52 % and 87 % for sewage runoff (Lau and Mah, 2018), which is likely higher for temperate and continental climates (Manso et al., 2021). Alongside saturation levels and atmospheric pressure, water-absorbing properties, e.g., speed and volume, have been associated with the substrate materials. This also applies to retention, which has been associated with, e.g., substrate thickness, composition, pore volume, and moisture content (Manso et al., 2021). Run-off efficacy has been found to increase if microbes are added to the substrate layer, stimulating plant growth (Xie et al., 2022). Substrates comprising organic materials were found to retain their porosity more effectively, compared to other materials, improving water uptake capacity

(Berndtsson, 2010; Getter et al., 2007; Speak et al., 2013). Evaporation and retention capacity rates are linearly correlated (Pérez & Coma, 2018; Roehr & Laurenz, 2008) for both plant and substrate layers. Plant layers comprising 1) thick and dense plant sheets, 2) tall shoots, and 3) biomass/mulch were found most effective for retention (Nagase & Dunnett, 2012; Teemusk & Mander, 2007). Single-layered systems, e.g., green facades, lack sponge qualities pivotal for SWM. For living walls, the retention capacity of linear systems outperforms modular systems, 33 % and 19 % respectively (Van de Wouw et al., 2017), reportedly opposite for evaporation rates (Van de Wouw et al., 2017).

### 3.5. Grey water treatment [GWT]

VGS are associated with the provision of grey water treatment, depending on, e.g. soil composition and substrate micro-organism ecology (Gholami et al., 2023). The impact is measured by percolation rates and percentage removal efficiency (Gholami et al., 2023; Rysulova et al., 2017; Svete, 2013). Leaching can increase pesticide and fertilizer concentrations in water after treatment in a VGS (Rahman et al., 2020). Using inorganic lightweight materials was found beneficial for leaching prevention (Berndtsson et al., 2009). Filtering properties have been attributed to the substrate as well as the plant layer (Pradhan et al., 2019). The efficacy of substrates to remove pollutants depends mostly on moisture content, retention time, and pore-clogging sensitivity (Addo-Bankas et al., 2021; Prodanovic et al., 2017), and substrate thickness (Gholami et al., 2023). These last two are at odds, as pore size correlates with retention time, as well as pore congestion (Prodanovic et al., 2017; Svete, 2013). VGS with mixed substrate materials are recommended (Pradhan et al., 2019). Substrate height in the vertical dimension correlates with the pollutant removal potential, with taller walls seen as more resilient for dealing with extreme hydraulic and nitrification loading conditions (Svete, 2013). Since aeration of the substrate can improve removal rates, linear living walls may perform worse compared to modular and continuous living walls, which is circumventable by making the substrate deeper or 'thicker'. Hydraulic loading rate impacts redox and contact capacity (Gholami et al., 2023), and more optimal modular and linear living walls. Besides nitrogen and phosphorus, there is no conclusive evidence that GWT and plant type are correlated (Addo-Bankas et al., 2021; Pérez & Coma, 2018). The majority of plant species respond to nitrogen, contrasting the few species that leverage phosphorus disposition (Fowdar et al., 2017). Soil patches around the root structure of the climber plants of green facades supply GWT, but the effects are substantially small compared to other VGS types (Fowdar et al., 2017). Support systems made from coated materials are associated with GWT efficacy (Hachoumi et al., 2021). For nitrogen removal rates, modular living wall outperform indirect green walls, with effects ranging between 48 % and 93 % (MLW) compared to 7–91 % (IGW), which is opposite for phosphorus removal, where effects range between 7 % and 67 % (IGW) compared to 2–53 % (MLW) (Gholami et al., 2023).

### 3.6. Weathering control [WC]

VGS are associated with weathering mitigation, elongating the lifespan of facades and reducing maintenance costs (Radić et al., 2019; Rosasco & Perini, 2018). These effects depend on wall dimension indicators (coverage), and are most effective in combination with an air cavity for ventilation (Haggag, 2010). Continuous and modular living walls were reportedly more effective than green walls, due to an additional protective layer in front of the wall. VGS moderate diurnal temperature extremes by leaf-shading, which improves the lifespan of walls (Wong, Tan, Chen, et al., 2010). These effects are not necessarily positive for all situations, as plants and roots growing into small cracks and slits of the wall can cause severe damage. For contemporary and modern buildings, the risks of plant-induced damage were reportedly small and overstated (Johnston and Newton, 2004).

### 3.7. Air quality control [AQC]

VGS are associated with air quality mitigation in cities (Jayasooriya et al., 2017), reducing e.g. ground-level ozone (O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), particulate matter (PM), sulphur dioxide (SO<sub>2</sub>), carbon monoxide (CO), carbon dioxide sequestration (CO<sub>2</sub>) (Manso et al., 2021; Tang, 2023), but also e.g. microbial air pollution (Heindri et al., 2024). Recent review articles highlight that the remainder of AQC studies focus on PM mitigation, which is most effective for VGS with a variety of plant species (Tang, 2023), also correlating most AQ effects to the plant layer (Jeyasurya et al., 2024). Based on existing literature, the pollution removal rate depends primarily on the plant layer and its deposition capacity, as well as precipitation, which washes off pollutants from leaves, resetting the removal capacity (Tang, 2023). Through the uptake of gases for photosynthesis in the leaves' stomata, plants possess natural pollutant filtering properties (Jayasooriya et al., 2017). Uptake and deposition of pollution depend on e.g. chemical composition and molecular particle dimensions. Smaller particles and molecules, such as CO<sub>2</sub> and nitrogen, are nutrients for plants, with extraction capacity varying between plant species. The disposition rate is associated with e.g. (Jayasooriya et al., 2017; Weerakkody et al., 2018) vegetation density, porosity, leaf morphology, and micromorphology, and relates to stagnant air volumes contained in the plant layer, which correlates with LAI and plant layer porosity (Tang, 2023). Forming a porous layer on top of the substrate, the biomass from decaying plants increases air pollution filtering for horizontal and vertical greenery (Rowe, 2011). Air purification rates are greatest for plants that have small and rough-furry-textured leaves (Jayasooriya et al., 2017; Weerakkody et al., 2018). Hydroponic substrates have been associated with excess air filtering performance and lower greenhouse gas emissions from soil (Jeyasurya et al., 2024).

### 3.8. Energy efficiency [PVP]

Photovoltaic panel efficiency (PVP) improves if panels are placed above horizontal or vertical greenery (Wang et al., 2023), due to air temperature moderation and wind flow conduction (Manso et al., 2021; Moren & Korjenic, 2017; Wang et al., 2023). To avoid shading effects, thin substrates and short-leaved plant species with a great transpiration capacity are recommended (Zluwa & Pitha, 2021), as well as a surface-panel distance of 60 centimetres, and continuous moist substrates (Zluwa & Pitha, 2021).

### 3.9. Food provisioning [FP]

VGS have been attributed to the promotion of vegetable-based diets and local food production, reducing transportation costs, and the use of pesticides (Prihatmanti & Taib, 2018; Xing et al., 2017). Food supply depends on plant and locational factors, including plant type, climate, maintenance requirements, and disease control. Both green façades and living walls with perennials are relevant and fit for food production. For green façades, various types of gourds, beans, and vines can be used to facilitate food provisioning (Prihatmanti and Taib, 2018). Integrating urban food production in living walls has been found to work well for a variety of perennial plants (Mårtensson et al., 2016; Nagle et al., 2017). Overall, the literature on food provisioning only included shrubs and perennials, leaving unclear the potential of grasses or succulents.

### 3.10. Aesthetic value [AV]

Aesthetics and visual presentation form the main argument for property owners to invest in wall greening (Juszczak and Zima, 2018). VGS are aesthetically most appreciated if the plant layer consists of full-grown vegetation and mature plants (Thayer, 1989), contributing to the perception and quality of the built environment (Goel et al., 2022). Ecological beauty and natural aesthetic appeal are, as concepts, difficult

to comprehend due to the complex interaction between user, system, and surroundings (Sutton, 2014). In architectural theory, visual aesthetic appraisal ties into composition, which, as an overarching concept, can be understood by looking at, e.g., balance, contrast, movement, unity, proportion, emphasis, and rhythm (Coburn et al., 2019). Adjustability of a support system is therefore important, for e.g. visual patterns, as well as, a plant layer with a balanced vegetation and colour scheme, and even foliage coverage (Manso and Castro-Gomes, 2015). Aesthetic value (of VGS) is not easily measurable or quantifiable, although some studies attempted to quantify effects through proxy variables such as (added) property values (Hernández-Morcillo et al., 2013), or the impact of urban appraisal (Goel et al., 2022). The situation is different for mere subjective and categorical indicators. Walls composed of flowers, varieties of plant species, resembling wilderness (Coburn et al., 2019), are regarded as more aesthetically pleasing compared to designs that are less rich and diverse (Layke, 2009). As seen through this lens, vegetation density and plant verdancy contribute to VGS aesthetics (Sulistiyantara and Sesara, 2017), stressing the importance of irrigation and maintenance, and a careful selection of resilient plant species to keep the plant layer visually healthy (Bustami et al., 2018).

### 3.11. Education support (ES)

VGS can help raise awareness about, e.g., nature and human attitudes towards the natural environment. In this light, studies have suggested using VGS for biology and art classes (Radić et al., 2019), although quantitative impact-assessment studies are lacking (Radić et al., 2019).

### 3.12. Health support (HS)

Ecosystem services are seen as contributing to human health, determining and constituting indirect well-being factors, including e.g., security, critical materials (for sustaining life), and social relations (Millennium Ecosystem Assessment, 2005; Xing et al., 2017). In the original ecosystems' framework, human health was not identified as an independent ecosystem service, lacking sufficient evidence for effects-causality (Fonseca et al., 2023). Recent publications on stress mitigation and VGS, pointing to health benefits derived from VGS, could change this view in future frameworks (Chan et al., 2021; Lotfi et al., 2020). These effects are associated with safety perception (Tong, 2013), patient recovery duration, and proneness to illnesses (Sheweka & Magdy, 2011; Xing et al., 2017). As the restorative effects of VGS are positively correlated with aesthetic and natural perception indicators (Hoyle et al., 2017), floral plants are recommended over other plant varieties. Subtle green plant schemes with a high natural structure were evaluated best for their natural value (Hoyle et al., 2017; Liu et al., 2022).

## 4. Synthesis of VGS ecosystem services performance indicators

The results of the literature review were synthesised and charted for relevant indicators and metrics clustered for each ESS, see Table 3. The direction of relationships is indicated ordinally using a three-point scale, i.e. 'weakening' (-) and 'strengthening' (+) and neutral or contested effects (-/+), based on the literature as presented in the previous paragraphs. For example, the moisture content of the substrate correlates with a reduction of the system's noise absorption capacity (UNC score -) while improving cooling performance (UTR score +). Based on the conclusions for each ESS, the authors ranked the priority of indicator(s), as aggregated on the level of the substrate and plant layer. For each ESS, the first-ranked layer has been indicated by a dark background colour for the corresponding cells.

## 5. Ecosystem services evaluation for VGS designs

### 5.1. MCDM framework

In this study, we built on the conceptual framework presented and validated by Fontana et al. (2013). Deploying a multi-attribute decision analysis method, the model blends 'discrete and finite number of alternatives' (Fontana et al., 2013). In MCDM, alternatives are ranked numerically, which requires an integer conversion of ordinal scores. Point scales are seen as a viable and flexible approach to award scores across different levels, e.g. 0–4 = very weak; 5–8 = weak; 9–12 = medium; 13–16 = strong; 17–20 = very strong (Chen et al., 2010; Hatush & Skitmore, 1998; Mustafa & Ryan, 1990).

Fig. 2 shows the MCDM framework that was developed for this study, based on the framework by Fontana et al. (2013). In this study, 'alternatives' refer to VGS types, 'decision criteria' refer to relevant ESS (columns in Table 3), and 'indicators' refer to the metrics (rows in Table 3). Steps 1–3 are based on the previous two chapters in this paper. Steps 4–5 depend on case and location-specific conditions. For most ESS, a scoring range was assigned, as results may be context-specific or vary across different studies. Scores are based on the assumption that 1) VGS cover a full wall, 2) planter boxes density is maximised for LLW, 3) vegetation species are subdivided into four classes (succulents, grasses, perennials, shrubs) and LAI and evapotranspiration rates were considered.

In case it was not possible to derive the scores from the literature, the corresponding ESS was discarded for the criteria assessment. Following this rule, the ESS 1) greywater treatment, 2) Education support, and 3) health support were taken out of the framework.

The criteria assessment in step 3 forms the spine of the MCDM framework, allowing the model to rank alternatives quantitatively. Ordinal impact scores were attributed to ESS for each VGS variant, based on literature and literature synthesis in Table 3, for the same reasons as explained in Section 4. System components, as listed in Table 3, were synthesised into VGS types. Secondly, VGS types were ranked and clustered within separate ESS silos, and possibly sub-ranked. Ordinal scores were converted to integers using a 0–20-point scale, which is shown in Table 4. Steps and considerations made by the authors are well illustrated by the following two examples, relating to 1) thermal regulation and 2) stormwater management.

[1] Substrate-based systems are more substantially more effective for thermal cooling compared to plant-layered systems (IDFG or DGF). Thermal insulation increases if an air cavity is applied between the supporting wall and VGS. It was therefore decided to separate scores into two classes.

[2] Stormwater provisioning is mostly attributed to the properties of the substrate. Living walls are therefore ranked above other systems, while the authors reasoned that continuous systems are ineffective, as often thin felt layers are used. Foam-substrate MLS will likely moderately improve SWM, while LLW is arguably more effective if it comprises a thick organic substrate. LLW and MLS are further subdivided and ranked depending on the type of vegetation, considering evapotranspiration capacity.

### 5.2. Case study evaluation

Following step 3 (see Fig. 2), weights were attributed based on input from case-specific stakeholders (step 4). The model was tested for a case study in which a VGS was developed; for the study, the project 'Virgo Aalsmeer' warehouse in Aalsmeer, the Netherlands, was used. The property developer had expressed the ambition to balance architecture, usability, nature, and technology, by various nature-inclusive interventions, e.g., a rooftop garden of 1.900 m and a VGS. Building on the study by Fontana et al., the PROMETHEE (preference ranking organization method for enrichment evaluation) II method was used for this evaluation step. Similar to the MCDM model introduced in Section 5.1,

**Table 3**

Synthesis of relevant performance indicators and ESS. Note: BS = Biodiversity Support, BTR = Building level Thermal Regulation, UTR = Urban level Thermal Regulation, BNC = Building Noise Control, UNC = Urban Noise Control, GWT = Greywater Treatment, SWM = Storm Water Management, WC = Weathering Control, AQC = Air Quality Control, PVP = PV Performance, FP = Food Provisioning, AV = Aesthetic Value.

Performance indicators			Ecosystem services									Provisioning	Cultural												
			Supporting		Regulating																				
			BS	BTR	UTR	BNC	UNC	SWM	GWT	WC	AQC	PVP	FP	AV											
	Metrics	Species density, Species richness	+	+	PET (C°)	+	Transmission Loss (dB)	+	Insertion Loss (dB), Absorption coefficient (%), Scattering coefficient (%)	+	Retention capacity (%), Run-off rate (%), Saturation rate (%)	+	Percolation rate, Removal efficiency (%)	+	Devaluation time (years), Maintenance costs	+	Pollution removal rate (%)	+	Return efficiency (%)	+	Supply, Commodity/variety	+	Aesthetic appraisal (score), Real estate price		
<b>Substrate layer</b>	Tissue	Porosity	+	+		+																			
		Moisture		+	+																				
		Tortuosity				+																			
<b>Plant layer</b>	Volume	Pore dimensions																							
		Thickness		+		+																			
		Vertical height	+																						
<b>Supporting system</b>	Material	Horizontal width	+																						
		Natural soil materials	+	+																					
		Mircobes																							
<b>Plant layer</b>	Tissue	WLAI	+	+		+																			
		LAD																							
		ALO/texture																							
<b>Plant layer</b>	Species	Thickness (layer)	+	+			+/ -																		
		Thermal resistance		+																					
		Plant layer porosity		+		+																			
<b>Plant layer</b>	Volume	Leave dimensions		+		+																			
		Colour		-		-																			
		Plant type variation	-/+																						
<b>Supporting system</b>	Materials	Plant	+																						
		Cavity width		+																					
		Coated wall materials																							
<b>Supporting system</b>	Materials	Waterproof wall materials																							
		Waterproof wall materials																							
		Waterproof wall materials																							

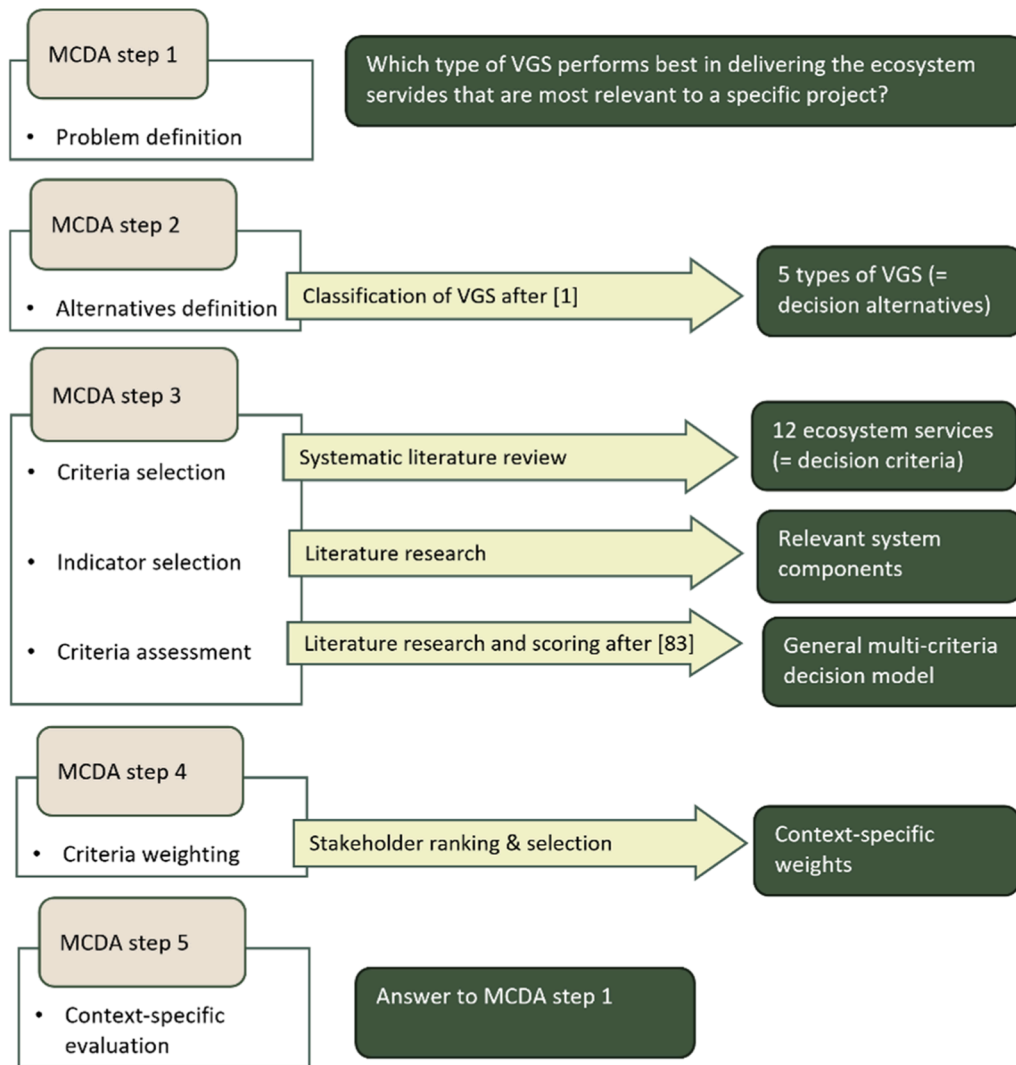


Fig. 2. MCDM framework for ecosystem services of VGS consisting of five steps based on [7].

Table 4

Impact scores on classified types of VGS based on the ESS framework. Note: BS = Biodiversity Support, BTR = Building level Thermal Regulation, UTR = Urban level Thermal Regulation, BNC = Building Noise Control, UNC = Urban Noise Control, GWT = Greywater Treatment, SWM = Storm Water Management, WC = Weathering Control, AQC = Air Quality Control, PVP = PV Performance, FP = Food Provisioning, AV = Aesthetic Value.

Vertical Greenery Systems	BS	BTR	UTR	BNC	UNC	SWM	WC	AQ	PVP	FP	AV	Max. total score
<b>Direct green façade (DGF)</b>	1–12	4	1	1	5	0–4	1–4	9–20	9–12	4–8	0–16	<b>87</b>
<b>Indirect green façade (IDGF)</b>	1–12	8	1	4	7	0–4	9–12	9–20	9–12	4–8	0–16	<b>104</b>
<b>Continuous living wall (CLW)</b>	1–12	10–12	1–2	10–12	10–12	9–12	17–20	9–12	9–12	0–8	0–20	<b>131</b>
<i>Shrubs</i>		12	2	12	12					4–8		
<i>Perennials</i>		11	2	11	11					4–8		
<i>Grasses</i>		10	1	10	10					0		
<b>Modular living wall (MLW)</b>	1–12	16–20	1–3	13–16	17–20	13–16	17–20	9–16	13–16	0–8	0–20	<b>176</b>
<i>Shrubs</i>		20	3							4–8		
<i>Perennials</i>		19	3							4–8		
<i>Grasses</i>		18	2							0		
<i>Succulents</i>	1–4	16	1			13			8	0		
<b>Linear living wall (LLW)</b>	1–12	12–16	1–3	9–12	13–16	16–20	13–16	9–16	1–4	0–8	0–20	<b>141</b>
<i>Shrubs</i>		16	3							4–8		
<i>Perennials</i>		15	3		15					4–8		
<i>Grasses</i>		14	2		14					0		
<i>Succulents</i>	1–4	12	1		13	16			4	0		

PROMETHEE only allows for a limited number of decision criteria (Macharis et al., 2004; Patel et al., 2017), which means that only those ESS most relevant for a project were selected by a ranking score (1 =

most important – 6 = least important).

Weights were selected by transposing the order of scores (see Table 5), while criteria not included as part of the MCDM were

**Table 5**  
Context-specific weights, allocated by case-specific decision makers.

	Architect	Plan developer	Weights
Biodiversity	4	4	0,4
UHI mitigation	1	1	0,1
Air quality control	2	2	0,2
Aesthetic value: property	3	3	0,3

discarded. For specific ESS, such as aesthetic value (AV), scores were averaged and aggregated. Although grey water treatment and stress reduction were identified by stakeholders, these criteria were discarded due to the scope of the MCDM. For the case study model, outcomes were ranked for VGS typologies as follows 1) modular living wall, 2) indirect green façade, 3) direct green façade, 4) linear living wall, and 5) continuous living wall.

## 6. Discussion and reflections

In this section, we reflect on the outcomes of this study in the light of the four objectives as formulated in the introduction. First, we highlight various limitations that relate to the design of the study, including methodology, data, and selected models. Second, we reflect on the practical implications and potential of the model, based on the results of the case study.

### 6.1. Study limitations and areas for improvement

While the model offers a valuable tool for assessing VGS benefits, certain limitations warrant attention. One notable challenge is the variability of VGS performance across different climates and geographic contexts. For example, some studies from arid climates indicate significantly different results for water use efficiency and thermal regulation compared to temperate regions. The reliance on literature relevant to Cfb climates in this study ensures relevance to such settings but limits broader applicability. Additionally, gaps in quantitative data for certain ESS, such as stormwater management and greywater treatment, necessitate further research to establish robust metrics for inclusion in future models.

### 6.2. Reflections on method, input data, and model

In comparison to prior studies, which often focus on isolated ecosystem services or specific VGS types, this study presents a multifaceted assessment framework using MCDM. While this approach captures a broader range of benefits, its reliance on qualitative rankings in certain areas could introduce subjectivity. This limitation underscores the need for future work to integrate more quantitative data and statistical modelling, as suggested in some recent works exploring thermal and noise regulation in green infrastructure systems. The outcomes of the literature search underscore the broad variety of results in Vertical Greening Systems (VGS) research, highlighting significant data gaps and disparities in research methods. Addressing these challenges is crucial for advancing the field of VGS research. We believe that further research is necessary to uncover potential correlations between system components and determine whether interactions are linear or nonlinear. This is particularly urgent in the fields of 1) stormwater management, 2) air quality control, and 3) greywater treatment.

Despite the progress made in clarifying the relationships between VGSs and Ecosystem Services (ESS) in this study, the effect sizes identified are, at best, indicative. For instance, thermal regulating services at the building level are influenced not only by the properties of VGSs but also by factors such as wall orientation and VGS coverage. It's crucial for future research in the field to address the following:

1. Standardization and homogenization of research methods to facilitate cross-comparison and aggregation of results, ideally applying equal methods across related ESS.
2. Quantification of effects per ESS and further specification of interactions between system components and results, particularly for those ESS where possible.

Utilization of these results to develop high-fidelity prediction models per ESS, such as numerical models for simpler cases or deploying unsupervised models to uncover patterns and nonlinear interactions, especially in cases of large datasets. Existing numerical methods may suffice for some ESS, such as acoustic and thermal services.

Furthermore, integrating and consolidating these models into a unified prediction tool, aligned with the Multi-Criteria Decision Making (MCDM) concept, holds the potential to enhance outcome accuracy, thereby bolstering decision-making processes and the quantification of effects. We believe that adopting a holistic approach is pivotal for propelling advancements in Vertical Greening Systems (VGS) research and its practical application. Additionally, delving deeper into the guiding mechanisms associated with each Ecosystem Service (ESS) is essential for gaining a comprehensive understanding of VGS functionality and optimizing their performance.

Secondly, the Multi-Criteria Decision Making (MCDM) framework utilized in this study, based on Fontana et al. (2013), provides a valuable framework for weighing and comparing both quantitative and qualitative indicators. This comprehensive approach is essential for covering the broad range of Ecosystem Services (ESS) attributed to Vertical Greening Systems (VGS), making methods like cost-benefit-analysis models less suitable for the study's purpose.

However, the lack of quantitative data in certain fields renders the current model relatively subjective, and likely more subjective compared to the MCDM by Fontana et al. (2013). To mitigate this, we suggest that further research should delve into the effects and underlying mechanisms of each ESS in greater detail. Illustratively, some studies highlight the substantial noise reduction potential of living walls, while others suggest that this effect is highly dependent on substrate material and plant density. Similarly, discrepancies exist in the reported benefits of aesthetic services, with some studies attributing greater value to continuous living walls than modular systems. These inconsistencies point to the need for standardized methodologies in ESS evaluation for transparent and reliable cross-comparison of results. This would enable the adoption of more complex and mathematical MCDM methods, such as the MIVES method, or the amendment and extension of the PROMETHEE model.

Since the model presented in this paper was tested for a small case study, refinement of the ranking and scoring procedure (steps 4 and 5 in Fig. 2) is necessary for its successful application in projects with a larger number of stakeholders. Methods like the weighted-sum-method (WSM) or the weighted-aggregated-sum-product-assessment-method (WASPAS) may be suitable for this purpose. Alternatively, subjectivity in the current model could be reduced through the best-worth-method (BWM), utilizing pairwise comparisons based on expert reviews of the current model. This would enhance the robustness and applicability of the model in real-world scenarios.

Thirdly, we identified eleven Ecosystem Services (ESS) linked to Vertical Greening Systems (VGS) based on existing literature, acknowledging that this number is not necessarily fixed. For instance, positive emotional effects related to workplace satisfaction and decreased perceived task load have been observed, stemming from the visual impact of living walls (Loh, 2008; Yeom et al., 2022), potentially enhancing labour productivity.

Future research has the potential to uncover additional ESS not captured in the current model. Therefore, it is imperative to maintain the model's flexibility for expansion and adaptation. By remaining open to incorporating new ESS as they are discovered or recognized, the model can evolve to provide a more comprehensive understanding of the

benefits associated with VGSs. This adaptability ensures that the model remains relevant and effective in guiding decision-making processes in the field of green infrastructure.

### 6.3. Reflections on practical advancements

Comparing the overall ecosystem services performance of Vertical Greening Systems (VGS) across the full spectrum of ESS, as outlined in this study (Table 4), reveals that living walls outperform green façades. Living walls achieved an overall score twice as high, with modular living walls ranking highest. However, it is important to note that the effects of VGS may vary depending on the location and project specifics.

The Multi-Criteria Decision Making (MCDM) framework presented in this article is well-suited for conducting context-specific impact assessments, allowing decision-makers to tailor evaluations based on case-specific valuation and the selection of relevant ecosystem services. Moreover, the MCDM offers a valuable tool for decision-makers to explore the robustness of choices and alternatives. For instance, decision-makers can consider expanding or narrowing the range of ecosystem services included in the assessment to better align with project priorities and objectives.

### 6.4. Recommendations and future directions

The MCDM framework serves as a foundation for further refinement and development. Efforts should focus on integrating statistical methods, expanding the range of included ESS, and enhancing the framework's ability to accommodate varying stakeholder perspectives. By addressing these areas, the model can provide a more comprehensive, objective, and actionable tool for assessing the benefits of Vertical Greening Systems. The following recommendations are therefore proposed:

1. **Standardization of Research Methods:** To enhance the comparability and reliability of VGS research, it is essential to standardize and homogenize methodologies, especially for quantifying the effects of Ecosystem Services (ESS). This would address existing data gaps and facilitate cross-study comparisons.
2. **Improved Quantification and Modelling:** Future research should focus on quantifying the effects of ESS and exploring the nonlinear interactions between system components, particularly for critical areas like stormwater management, air quality, and greywater treatment. This would lead to the development of high-fidelity prediction models, enhancing the accuracy of decision-making processes.
3. **Integration of Complex MCDM Methods:** To reduce subjectivity in the Multi-Criteria Decision Making (MCDM) framework, further research should incorporate more sophisticated methods, such as the MIVES or PROMETHEE models, and refine the ranking and scoring procedures. This would improve the robustness and applicability of the model in diverse project settings.
4. **Expansion of ESS Scope:** Given that the number of ESS linked to VGS is not fixed, the model should remain flexible to incorporate emerging ESS as they are identified. This adaptability will allow the model to evolve and offer a more comprehensive understanding of the full range of benefits provided by VGS.
5. **Context-Specific Decision-Making:** The MCDM framework should continue to be used for context-specific assessments, allowing decision-makers to tailor the evaluation of VGS based on project-specific priorities. It is also important to refine the model for use in larger projects with multiple stakeholders to ensure its broad applicability.

## 7. Conclusions

In conducted research, we propose a novel model to evaluate the

performance of Vertical Greening Systems (VGS) based on the Ecosystem Services (ESS) concept, using the Multi-Criteria Decision Making (MCDM) framework to assist designers and decision-makers in selecting the most suitable VGS for project-specific conditions. The main findings of the presented study are:

- **Importance of Standardization and Data Improvement:** The research highlights the pressing need for standardization and homogenization of research methods in the Vertical Greening Systems (VGS) field to address significant data gaps and disparities. Particularly, efforts should focus on quantifying effects per Ecosystem Service (ESS) and specifying interactions between system components, especially in crucial areas like stormwater management, air quality control, and greywater treatment. Standardized methods would facilitate cross-comparison and aggregation of results, thus advancing the accuracy and reliability of research outcomes.
- **Enhancing Decision-Making with Multi-Criteria Decision Making (MCDM):** The study underscores the value of the Multi-Criteria Decision Making (MCDM) framework in evaluating VGS designs based on overall ecosystem services scores. MCDM offers a comprehensive approach, allowing decision-makers to weigh and compare both quantitative and qualitative indicators, which is crucial for covering the broad range of ESS attributed to VGS. However, efforts to reduce subjectivity and enhance the robustness of the MCDM model are necessary, including refining ranking and scoring procedures and exploring more complex mathematical methods like the MIVES method or the PROMETHEE model.
- **Flexibility and Expansion of Ecosystem Services Scope:** The research identifies eleven ESS linked to VGS based on existing literature but acknowledges that this number is not fixed. The model's flexibility for expansion and adaptation is essential to accommodate new ESS as they are discovered or recognized. By remaining open to incorporating additional ESS, the model can evolve to provide a more comprehensive understanding of the benefits associated with VGS. This adaptability ensures the continued relevance and effectiveness of the model in guiding decision-making processes in the field of green infrastructure.

Based on the results, we believe these three pathways are pivotal for future research focusing on ecosystem-services and VGS, and further translation of scientific findings to hands-on models to aide building and engineering practice.

### CRedit authorship contribution statement

**Martijn Lugten:** Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Dieuwertje Bakker-den Hartog:** Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Ottolé Marc:** Resources, Conceptualization.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgments

The research is funded by the municipality of Haarlemmermeer, the Dutch ministry for Infrastructure and Water Management, the Dutch ministry for housing and domestic affairs, and the Stichting Lee-fomgeving Schiphol.

### Data availability

Data will be made available on request.

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