High-Performance Climbing Plants for Urban Climate Improvement: Maintenance Strategies for Climbing Plants in Vertical Greening Systems

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Abstract:

Vertical Greening Systems (VGS) in urban areas play a crucial role in urban climate adaptation, energy efficiency, and biodiversity, but their sustaining benefits depend on species-specific care and maintenance. This study focuses on ground- and planter-based VGS with climbing aids for woody, deciduous plants, introducing the concept of High-Performance Climbing Plants (HPCP): species with superior growth, resilience and greening efficiency. Tailored interventions from planting through preservation maintenance are essential to optimise Plant Coverage (PC) and Wall Leaf Area Index (WLAI), enabling effective cooling and bioshading that directly impact these ecosystem services. Maintenance strategies were systematically developed, tested, and demonstrated under real-site conditions, integrating species selection, structural design, plant training, and pruning techniques. Practical recommendations and checklists, based on national and international guidelines, support the sustainable management of VGS. The study underscores the link between maintenance quality and Green Infrastructure (GI) performance, providing a practical framework for building owners, planners, and facility managers to maximise environmental, economic, and aesthetic benefits.

Keywords:

High-Performance Climbing Plants, Vertical Greening Systems, plant training, maintenance strategies

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1. Introduction

Urban GI has become an essential strategy for mitigating the impacts of climate change in densely built and settlement environments (European Commission, 2013; UN-Habitat, 2011). VGS have the potential to counteract the problem of high solar irradiation as plants act as a natural external shading layer and solar filter (Stangl et al., 2022). Reducing solar irradiation impact on the building envelope substantially decreases the building's surface temperatures) and thus helps to improve indoor thermal comfort (Cetiner et Özkan, 2005; Hoelscher et al., 2016).

This paper introduces the concept of ground- and planter-based HPCP, addressing deciduous, woody species with rapid growth and high biomass production capacity. Therefore, these plants offer a good base for high shading and cooling properties for VGS applications. This work focuses on care and maintenance needs as well, which are often neglected or underestimated during planning and continuous functioning of VGS. It presents findings and insights from the Austrian research project GLASGrün from BOKU University which developed, implemented and evaluated VGS specifically for large-scale glass facades in commercial buildings (Stangl et al., 2025). While VGS has been widely applied to solid facades, solutions for fully glazed building facades remain limited. The GLASGrün research project addressed this gap by developing new VGS typologies tailored for glass facades and retrofitting.

The GLASGrün project implemented two real-life demonstration sites (Söll, Tyrol and Kreuzgasse, Vienna), where plant development and -physiology, microclimatic performance, and maintenance needs were systematically studied over three years.

The project started in August 2021, the implementation of the first study site in Tyrol took place in June 2022 and the monitoring continued up to December 2024. These insights form the basis for the care and maintenance strategies presented in this paper. Despite the growing popularity of VGS, there is still a lack of standardised care concepts that are adapted to the specific needs of different plant species, system designs, and facade materials. Without suitable maintenance, even well-designed systems can suffer from poor plant development, aesthetic loss, or technical failure. The GLASGrün project responded to this problem by developing comprehensive guidelines with a catalogue of variants for VGS on glass facades (Briefer et al., 2025) as well as a guideline for maintenance strategies for VGS (Poiss et al. 2025b).

The concept of HPCP, introduced in this work addresses a gap in practice-oriented research by highlighting that, although climbing plants are often chosen for aesthetic reasons, certain species have the traits needed to excel in supporting climate adaptation goals such as heat mitigation, microclimate improvement, and energy balance (Stangl et al., 2022). Care and maintenance are often underestimated in VGS, though success relies on targeted interventions such as pruning, training shoots, controlling growth, ensuring structural integrity, and safe access for workers. Based on the findings of the GLASGrün monitoring phase, transferable care guidelines with structured phases for establishment, development and preservation linked to vegetation targets set during planning were developed (Poiss et al., 2025b).

Based on this framework, this concept study investigates following research questions:

- RQ1: How can the HPCP Concept be conceptualized to open new perspectives for the planning and implementation of VGS?
- RQ2: How can maintenance strategies align with the HPCP Concept ensure rapid establishment, sustained functionality, and consistent delivery of ecosystem services in VGS?

2. Methodology

2.1 Site Design and System Setup

The GLASGrün Project represents real-site applications of VGS for glass facades, addressing both technical and vegetation-specific challenges. As part of this applied research initiative, two demo systems were implemented in different climatic regions of Austria in central Europe – Söll in Tyrol (Figure 1) and Kreuzgasse in Vienna (Figure

2) – to develop and test tailored VGS solutions under practical conditions. The facts about both Demo sites are included in Table 1. The systems included ground- and planter-based plantings combined with customised climbing aids for retrofit.

Table 4: Facts About the two Demo Sites from the GLASGrün Project (Briefer et al., 2025)

	Demo Site Söll, Tirol	***Demo Site Kreuzgasse, Vienna***
Location	6306 Söll, Dorf 140, AUT	1180 Vienna, Kreuzgasse 74, AUT
Architecture	RATAPLAN-Architektur ZT GmbH	lichtblauwagner architekten zt gmbh
Planting Concept	BOKU IBLB	BOKU IBLB
Client	MPREIS Supermarket	TB Obkircher
Planning Phase:	August 2021 – May 2022	November 2021 – June 2023
Completion	June 2022	July 2023
Greened Glass	154 m²	77.5 m²
Exposition	south-east	south-south-west

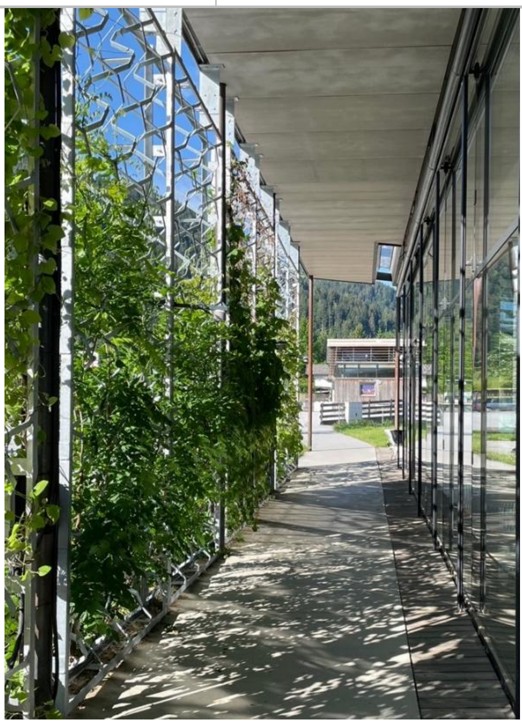

Figure 1: Demonstration site in Söll, Tirol – GLASGrün bioshading based on a 3D flat steel climbing support in front of a glass facade - 3 years after implementation (Auer, 2024)

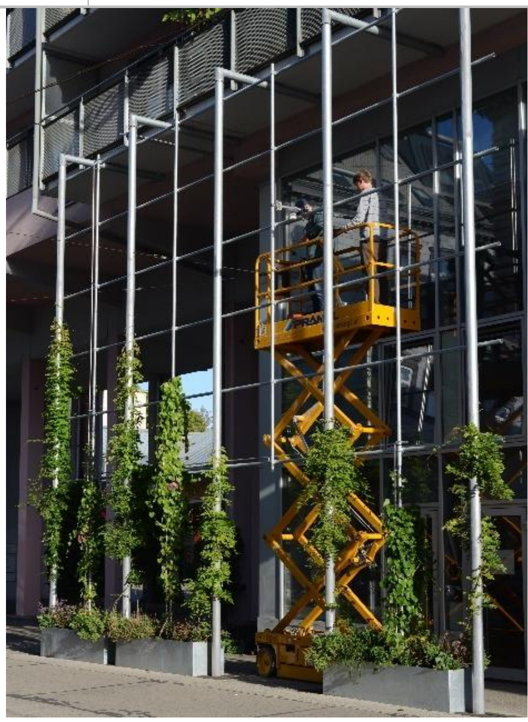

Figure 2: Demonstration site at Kreuzgasse, Vienna – GLASGrün bioshading based on a tubular steel frame climbing support in front of a glass facade - 2 years after implementation (Briefer, 2024)

Both study sites lie within the Central European temperate zone, characterised by four distinct seasons. According to the Köppen-Geiger classifications (Table 2), Vienna exhibits a temperate oceanic climate (Cfb) 220 meters above sea level, while Söll, Tyrol is classified as in the middle between ocean climate (Cfb) and humid continental (Dfb), reflecting its alpine surroundings and elevation of 703 meters above sea level (Kottek et al., 2006; GeoSphere Austria, 2025).

Table 5: Temperature Zone Location Analysis of the Demo-Study Sites (Kottek et al., 2006; GeoSphere Austria, 2025)

<table>
<tr><th>Location</th><th>Temperate Zone</th><th>Köppen-Geiger Classification</th><th>Climate Type</th><th>Description</th></tr>
<tr><td>Söll, Tyrol</td><td rowspan="2">Central European</td><td>Cfb – Dfb</td><td>Temperate Oceanic Climate – Humid Continental Climate</td><td>cold winters with snow and warm summers; year-round precipitation; alpine influence</td></tr>
<tr><td>Kreuzgasse, Vienna</td><td>Cfb</td><td>Temperate Oceanic Climate</td><td>mild and dry winters, warm summers, no complete dry season, even distribution of rain</td></tr>
</table>

2.2. Elaboration of the HPCP Concept

The concept of HPCP was developed through a literature-based identification of key plant physiological parameters relevant for VGS. Parameters such as PC, WLAI, BSC, stomatal conductance, plant life cycle, climbing mechanism, biomass accumulation, and leaf retention type were defined following established sources. Based on these criteria, species suitable for Central European climates were pre-selected from botanical literature and guidelines. Their performance was subsequently validated at the GLASGrün demo-site in Söll (Tyrol) through monitoring of PC and WLAI between 2023 and 2024. Species were classified as HPCP if they combined rapid facade coverage, structural adaptability, and resilience under local climatic and maintenance conditions.

2.3. Monitoring Parameters Supporting the Maintenance Framework

Monitoring data from the two demo sites were collected during the first three years after installation. The key parameters assessed included:

- yearly growth rates,
- PC development and foliage density, respectively WLAI over time,
- shading performance via the Bioshading Coefficient (BSC) through species-specific solar transmission in the VGS (Poiss et al. 2025a),
- plant vitality, stomatal conductance,
- maintenance effort, frequency, and complexity of interventions.

At the Söll site, two maintenance interventions were conducted in 2022: one during implementation and a second in autumn. In 2023 and 2024, maintenance was performed four times per year – in spring, early summer, late summer, and autumn. At the Kreuzgasse site, two maintenance interventions took place during the year of implementation (2023) as well. In 2024, the same seasonal maintenance cycle of four interventions per year was applied.

2.4. Maintenance Framework for Vertical Greening Systems

Effective maintenance strategies include three core phases and are adopted from BMDW (2021) and Poiss et al. 2025b for this study:

1. establishment phase (Year 1): supports rooting, survival, and early structure formation.
2. development phase (Years 2–3): shapes the growth toward the defined target coverage and structural form.
3. preservation phase (Year 3+): ensures the sustaining stability and aesthetics/functionality of the system.

2.5. Regulation and Requirement Basis

The care concept developed and tested within the GLASGrün project is based on national and German up-to-date guidelines and best practices in vegetation engineering. All recommendations are aligned with national and international standards, including:

- ÖNORM L1120 (2016) – Maintenance and Conservation of Green Areas.
- ÖNORM L1136 (2021) – Vertical Greening in Outdoor Spaces.

- ÖNORM B2241 (2013) – Standard Contract Conditions for Landscape Works.
- FLL Guidelines (2018) – Facade Greening Standards for Planning, Execution, and Maintenance.

These standards form the backbone of the GLASGrün maintenance protocol, which includes checklists, scheduling tools, and performance indicators.

3. Results

3.1. Identification and Selection of High-Performance Climbing Plants (HPCP)

Initial findings confirmed that early, intensive care significantly accelerated the achievement of target vegetation structures. Species identified as HPCP – characterised by vigorous yet manageable growth, environmental resilience, and structural adaptability – demonstrated superior performance in both greening efficiency and maintenance responsiveness. Table 3 outlines the key plant physiological parameters used to define and monitor HPCP. These parameters allow for the identification of species most suitable for the optimal development of VGS, ensuring extensive coverage, vertical growth—provided that appropriate maintenance practices are applied.

Table 6: Key Plant Physiological Parameter Used for HPCP Definition and Monitoring

Parameter	*Definition / Description*	*Unit*	*Reference*
Projected Plant Coverage (PPC)	Percentage of vertical surface area occupied by vegetation, measured as vertical projection (of a measurement frame e.g., 0.5 m²) of above-ground plant parts onto the wall; accordingly, describes vegetation density projected onto a frame (0 – 100 %).	[%]	Law et al., 2020 SeyrekŞık et al., 2022 Li et al., 2023
Target Plant Coverage (TPC)	Percentage of vertical surface area occupied by vegetation, measured by plant coverage of a predefined target area (e.g. total glass facade area or climbing aid in front of a facade) on percent; accordingly, describes the vegetation density on a target (0 – 100 %).	[%]	Koyama et al., 2013 Poiss et al., 2025a* *here classified as PC

Wall Leaf Area Index (WLAI)	Total one-sided leaf area per vertical facade area; indicates canopy density and potential for evapotranspiration and shading.	dimensionless	DeBock et al., 2023 Pérez et al., 2017
Bioshading Coefficient (BSC)	Fraction of incident solar radiation intercepted by the plant canopy under standard solar geometry; indicates shading efficiency.	[0 – 1]	Ip et al., 2010 Poiss et al., 2025a
Stomatal Conductance	Rate of gas exchange per unit leaf area, reflecting plant physiological activity and cooling potential.	[mmol m^{-2} s^{-1}]	Li et al., 2022 Lin, 2015
Plant Life Cycle	Divides plants into two main types based on the duration and pattern of their life cycle. Annual plants complete their entire life cycle within one growing season and then die off. Perennial plants live for multiple years and typically reproduce multiple times throughout their lifespan.	annuals and perennials	Friedman, 2020
Climbing Mechanism	Climbing plants use active or passive mechanisms, with specialised features, to attach and ascend climbing aids.	twiners, tendrils, adhesive roots, hooks and spines, scramblers	Mahabadi et al., 2018
Biomass Accumulation	Increase in plant dry mass over time, reflecting growth and productivity.	[g per plant or g per area]	Wyka et al., 2019
Leaf Retention Type	Categorisation of plants based on whether they retain or shed leaves seasonally	deciduous and evergreen	Elosegi, 2005

Building on the physiological parameters defined in Table 3, Table 4 lists climbing plant species that align with these criteria and are suitable for Central European climate conditions. Species highlighted in bold indicate those that were tested within the scope of this research.

Table 7: Identified HPCP | IP = Invasive Plant acc. to Rabitsch et al., 2016; EU 2022/1203

Species	*Climbing Mechanism*	*Avg. Growth Height (in m)*	*Shoot Diameter at Base (in cm)*
Actinidia deliciosa	twining	6–8	3–5
Akebia quinata	twining	8–10	2–3
Aristolochia macrophylla	twining	8–10	up to 3
Celastrus orbiculatus (IP)	twining	8-15	up to 10
Clematis montana	tendril-like stems	8–10	2–3
Clematis vitalba	twining and scrambling hybrid	10–12	3–4
Fallopia baldschuanica (IP)	twining	12–15	4–6
Humulus lupulus	twining (annual)	5–7 / year	up to 1.5–2 (annual stem)
Vitis coignetiae	tendril climber	8–12	up to 4–5
Vitis vinifera	tendril climber	8–15	3–5
Wisteria floribunda	twining	10–12	up to 6–8
Wisteria sinensis	twining	15-30	up to 25

The HPCP-list reflects both botanical characteristics and performance criteria observed during the GLASGrün demo-study, which included *Aristolochia macrophylla*, *Humulus lupulus*, *Vitis coignetiae* and *Wisteria sinensis* (Figure 3). *Fallopia baldschuanica* and *Celastrus orbiculatus* are both considered invasive plants (IP) in parts of Europe. According to Rabitsch et al. (2016), *Fallopia baldschuanica* is an established neophyte and shows invasive behaviour in certain regions such as Austria and Bavaria. Although it is not listed in the official EU Regulation (EU) No. 1143/2014 on invasive alien species, it is recognised in regional strategies as potentially invasive. Similarly, *Celastrus orbiculatus* is included on the official EU list of invasive plant species under Regulation (EU) No. 2022/1203. Due to their invasive potential, neither species is recommended for use in vertical greening of buildings.

Aristolochia macrophylla	*Humulus lupulus,*	*Vitis coignetiae*	*Wisteria sinensis*

Figure 3: VGS at the GLASGrün demo-site in Söll (Tyrol) covering Aristolochia macrophylla, Humulus lupulus, Vitis coignetiae and Wisteria sinensis (Briefer, 2023)

Monitoring data from the demo-site Söll (Tyrol) are presented in Table 5 on page 7. Including information about growth speed of different climbing species through the increases of PC development and WLAI from one monitoring to the next.

Table 8: Monitoring Parameters Plant Coverage (PC) and Wall Leaf Area Index (WLAI) Supporting the Maintenance Framework (Stangl et al., 2025)

South-East from Söll, Tyrol	***Vitis coignetiae***	***Humulus lupulus***	***Wisteria sinensis***	***Aristolochia macrophylla***
Jun 23 PC [%]	10.8	32.5	24.5	19.8
Jun 23 WLAI	0.9	1.3	1.0	1.0
Sep 23 PC [%]	57.7	70.5	79.6	67.1
Sep 23 WLAI	1.7	2.0	3.0	2.3
Mai 24 PC [%]	30.9	66.8	43.1	57.0
Mai 24 WLAI	1.2	2.5	1.6	1.9
Jul 24 PC [%]	78.8	95.0	83.5	91.3
Jul 24 WLAI	4.5	5.9	4.8	5.5
Aug 24 PC [%]	78.3	96.5	98.3	94.3
Aug 24 WLAI	3.0	4.3	4.3	4.1
Sep 24 PC [%]	67.2	91.0	92.9	92.3
Sep 24 WLAI	2.2	4.0	3.6	3.8

3.2. Maintenance Framework for Vertical Greening Systems

The maintenance of VGS does not necessarily require high levels of effort, but intelligence and targeted interventions. In the context of GI, maintenance refers to the planned and regular steering of plant development rather than occasional large-scale corrections after neglect. Proper care enables optimal plant performance and reduces the likelihood of costly restorative interventions. The here applied framework was adopted from BMDW (2021) and extended by an additional phase:

Definition and Planning Phase

A fundamental principle in vertical greening projects is that the target vegetation structure and coverage must be clearly defined during the planning phase. This target state forms the basis for the maintenance strategy. The target vegetation structure is defined by the dimensions of the support structure and climbing aids, which should be designed according to the desired shaded area. In line with Austrian Standard ÖNORM L1136:2021, at least 80 % PC of the target area must be achieved three years after installation for facade greening at a 4-story height. It is necessary to distinguish between plant coverage of the target area (as defined in ÖNORM L1136:2021, referring to the proportion of the designated facade area to be covered) and the projected PC, which refers to the proportion of vegetation within the vertical projection of a predefined frame (e.g., 0.5 m²) (Li et al., 2023; Law et al., 2020; SeyrekŞık et al., 2022).

Establishment Phase

The establishment phase is essential for root development, plant survival, and the initial structural setup of climbing plants. According to Austrian Standard ÖNORM B2241:2013, this period covers all maintenance measures between planting and handover. In the context of glass-based architecture, special attention is needed to guide plant growth in harmony with the building’s design. Key actions during this phase include shoot training, tying to the trellis, pruning to stimulate branching, and checking technical systems such as irrigation systems and climbing supports.

Development Phase

Following the handover, the development phase begins (see ÖNORM L2241). This phase aims to ensure full PC, healthy growth, and proper integration into the vertical system. Depending on the species, growth rate, and defined target structure and area, development care may extend over several years.

Key maintenance activities include:

- regular inspection for pests, diseases, or nutrient deficiencies,
- removing dead plant parts,
- guiding shoots to close gaps and cover the facade evenly,
- clearing plants from technical components,
- performing structural and shaping cuts,
- fertilising as needed,
- replacing any dead or damaged plants.

Preservation Maintenance

The aim of preservation maintenance is to preserve the plant structure and develop it further in line with the defined goals (ÖNORM L1120:2016). To ensure the sustaining health, functionality, and visual quality of the planting system, several key maintenance actions must be regularly carried out. These are provided as Checklist in Table 6.

Table 9: Checklist for Regular Preservation Maintenance Actions During the Preservation Phase (Poiss et al., 2025b)

Maintenance Task	*Checklist*
Water supply	• manual watering or automated irrigation systems • check and, if necessary, replacing of irrigation system components
Removal of unwanted growth	• manual removal of weeds and self-seeded plants • removal of suckers from rootstock, trunk, or base shoots • prevention of mechanical trimmers; protect plant stems with guards
Soil loosening and mulching	• careful loosening of soil in planting areas • avoiding of damaging the root collar or fine roots

	• renewing mulch layer as needed, or underplanting with perennials
Fertilisation	• application according to plant species and needs • important in planters where root space and soil-fertility are limited • regular nutrient replenishment required in older substrates
Pruning	• performing maintenance and rejuvenation pruning as needed • cutting back of overhanging or undesired shoots • removing dead or diseased shoots
Check for trunk constriction	• inspecting and loosening of plant ties if necessary • checking for signs of stem strangulation or tight bindings • inspecting and resecuring or removing of loose and unstable components

4. Discussion

4.1 HPCP-Concept

Through the course of the demo-study, it became evident that not all climbing plants are equally suited to deliver the functional and ecological performance expected from contemporary VGS, particularly in urban contexts where shading, cooling, and space efficiency are crucial. This insight led to the idea of the development and introduction of the concept of HPCP, a term introduced and proposed for the first time within this study.

HPCP refer to a distinct group of species that fulfil a set of performance-based criteria addressing both ecological and technical dimensions of VGS design. Specifically, HPCPs should be able to:

- Provide substantial bioshading performance, effectively reducing solar heat gain on facades (Ip et al., 2010; Poiss et al., 2025a).
- Achieve rapid growth rates and vertical coverage, reaching up to 8 m in height within three years and delivering PC of the target area, as required by Austrian Standard ÖNORM L1136:2021 and min. 80 % projected PC within the period of 3 years after installation for highest possible shading performance
- Demonstrate resilience and vitality under typical urban stressors such as heat, drought, wind exposure, and air pollution (Gräf et al., 2021; Spörl et al., 2023).

- Integrate with structural systems, ensuring that both plant growth and support structures remain stable under biomass and wind loads (Stangl et al. 2025).
- Respond to structured maintenance routines, including pruning, guiding, and irrigation, which are essential to sustain the target vegetation state (Briefer et al. 2025).

In contrast to purely horticultural or aesthetic selection criteria, the HPCP concept emphasises quantifiable, performance-oriented outcomes such as growth and coverage rates, biomass production, and bioshading efficiency. The latter can be measured using the BSC introduced by Ip et al. (2010), allowing for objective comparison of species performance.

A key contribution of this study is the systematic definition and monitoring of plant physiological variables that operationalise the HPCP concept. These include PC, WLAI, BSC and Stomatal Conductance, which were measured across both demonstration sites over three growing seasons and are described in more detail in the project report (Stangl et al., 2025) and the research paper (Poiss et al. 2025a). Examples of HPCPs were identified and tested within the GLASGrün project all of which demonstrated strong vertical growth, high seasonal shading potential, and sustaining viability under proper care protocols. Growth and bioshading performance of *Aristolochia macrophylla*, *Humulus lupulus*, *Vitis coignetiae* and *Wisteria sinensis* were demonstrated and BSC data throughout the annual cycle are provided in Poiss et al. (2025a).

The HPCP conept is proposed as a transferable model for future GI projects and can support both simulation-based planning and building physical model calculations using BSC data, and real-world application of vegetation-based climate solutions. The results of the presented HPCP-concept study highlight critical considerations for the successful implementation and sustaining performance of VGS. For planners and designers, the findings emphasise the need to select appropriate climbing species based on growth form and maintenance requirements. Integrating species-specific behaviour into the very early planning phase supports structural integrity and maximises ecological benefits. Here a clear focus on the target vegetation scenario plays a key factor.

4.2 Maintenance Framework

Up-to-date and acknowledged maintenance regulations for VGS exhibit shortcomings for the GLASGrün systems tested and the purpose of explicitly provide bioshading using vertical greenery. Therefore, the GLASGrün-project requirements included the elaboration and testing of establishment and maintenance strategies and to provide a guideline for the new GLASGrün system and bioshading of glass facades. A guideline in this connex was presented in Briefer et al. (2025), and together with the results presented in Stangl et al. (2025) and in Poiss et al. (2025b) this was the basis for the here presented framework.

For facility management, the study underlines that VGS are not passive systems. Instead, and similarly to horizontal greenery, they require well-structured maintenance strategies including early establishment care, regular training of plant growth, and ongoing pruning, as defined in respective guidelines and used as starting point within this demo-study. Plant specific know-how is required, and involving gardeners qualified for VGS must be ensured. The checklists and tables provided are intended to serve as practical aids in daily operations and help to coordinate responsibilities.

Our results can directly improve existing facade and vertical greenery maintenance guidelines. Integrating the defined care phases—establishment, development, and preservation (BMDW 2021)—into project workflows ensures plant vitality and sustained ecosystem services like shading, cooling, and biodiversity. For bioshading, achieving high PC quickly requires focused plant training (e.g., shoot guiding and fixation), while species-specific pruning can stimulate additional shoot formation for faster coverage.

However, after the target PC has been achieved, pruning gains other significance in the preservation phase and beyond: (I) in order to stimulate biomass body and WLAI; (II) in terms of keeping shoots from undergrowing of building or facade elements (yearly but sensitive removal of shoots is necessary without harming the canopy and leaf body); (III) in terms of regulating light transmission. E.g. to promote full shading in peak summer, to avoid unwanted over-darkening, or to provide landscape views and indoor shading designs, pruning can be applied in season-specific frequencies and to a predefined extent. Efficient care means doing the right thing at the right time – based on a predefined goal, not maximum intervention.

5. Conclusions

In this contribution a concept and classification for HPCP and a maintenance framework for vertical greenery systems, built upon acknowledged strategies for greenery establishment, is presented. By combining empirical data from two demonstration sites with performance monitoring over three years, the following key insights were derived to answer the guiding research questions in Table 7.

Table 10: Research Questions and Study Findings

	Main Findings
RQ1: HPCP Concept	• The HPCP Concept is a flexible framework emphasizing performance-based outcomes. • Core principles: rapid vertical coverage, urban stress resilience, structural integration, and maintenance responsiveness. • Supports early integration of plant-specific behavior into planning for ecological and technical optimization. • Transferable to other GI projects and supports simulation-based planning and real-world applications.
RQ2: Maintenance Strategies for VGS	• Maintenance as a strategic, phased based process: Definition and Planning, Establishment, Development, and Preservation Maintenance. • Early establishment care is critical for rapid coverage and bioshading. • Seasonal pruning regulates shading and light transmission while maintaining plant vitality. • Practical tools and qualified VGS expertise are essential for sustaining success. • Structured care regimes must be embedded into facility management plans to ensure sustaining bioshading effect, plant health, and ecosystem service delivery. • Maintenance strategies must align with project-specific goals and integrate into workflows from the start.

From a sustainability perspective, maintenance must be viewed as a central component of GI, not a secondary task. Without regular and proper care on a yearly basis, plant systems loose functionality and could potentially develop shortcomings within the biomass structure or become damaging to building elements. As such, target structures with target areas and target PC must be defined, and budgeting and contracting for maintenance services should be a mandatory request in all vertical greening projects.

However, our study also features some limitations. It focuses primarily on a selected group of climbing species used in limited building contexts. Further research and evaluation are needed on adult plant structures, species performance under extreme climatic and stress conditions, in mixed-plant systems, and across varying architectural typologies. Future work should also explore smart technologies for monitoring, irrigation purposes and assessing life-cycle costs more comprehensively.

6. References

Austrian Standards International ÖNORM L 1112 (2022): *Anforderungen an die Bewässerung von Grünflächen*. Wien, Austrian Standards International.

Austrian Standards International: ÖNORM L 1120 (2016): *Gartengestaltung und Landschaftsbau - Grünflächenpflege, Grünflächenerhaltung*. Wien, Austrian Standards International.

Austrian Standards International: ÖNORM L 1122 (2024): *Baumkontrolle und Baumpflege*. Wien, Austrian Standards International.

Austrian Standards International: ÖNORM L 1131 (2010): *Gartengestaltung und Landschaftsbau - Begrünung von Dächern und Decken auf Bauwerken - Anforderungen an Planung, Ausführung und Erhaltung*. Wien, Austrian Standards International.

Austrian Standards International: ÖNORM L 1136 (2022): *Vertikalbegrünung im Außenraum - Anforderungen an Planung, Ausführung, Pflege und Kontrolle*. Wien, Austrian Standards International.

BMDW (2021): *Standardisierte Leistungsbeschreibung Leistungsgruppe* (LG) 58 - Gartengestaltung und Landschaftsbau Kennung: HB-Version: 022. Leistungsbeschreibung Hochbau 31.12.2021. BDWW, Wien.

Briefer, A., Poiss, M., Wultsch, T., Scharf, B., Pitha, U., Smetschka, B., Haas, B., Bintinger, R., Lipp, B., Wagner, S., Huber, G., Maus, K, Formanek, S., Stangl, R. (2025): *GLASGrün-Leitfaden und Variantenkatalog zum wirksamen Einsatz von Vertikalbegrünungen bei Gebäuden mit Glasflächen*. Projekt GLASGrün. Projektbericht im Rahmen des Programms Stadt der Zukunft, 60b/2025, Wien.

Cetiner, I., et Özkan, E. (2005): *An approach for the evaluation of energy and cost efficiency of glass façades*. Energy and Buildings, 37(6), 673–684. DOI: 10.1016/J.ENBUILD.2004.10.007

DeBock, A., Belmans, B., Vanlanduit, S., Blom, J., Alvarado-Alvarado, A. A., Audenaert, A. (2023). A review on the leaf area index (LAI) in vertical greening systems. In Building and Environment (Vol. 229). Elsevier Ltd. DOI: 10.1016/j.buildenv.2022.109926

Elosegi, A. (2005): *Leaf Retention. Methods to Study Litter Decomposition: A Practical Guide*. DOI: 10.1007/1-4020-3466-0_2

European Commission (2013): *Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions Green Infrastructure (GI)*. Luxembourg, Publications Office of the European Union.

FLL (2015): *Empfehlungen für Baumpflanzungen – Teil 1: Planung, Pflanzarbeiten, Pflege*. Bonn, Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V -FLL.

Friedman, J. (2020): *The Evolution of Annual and Perennial Plant Life Histories: Ecological Correlates and Genetic Mechanisms*. Annu. Rev. Ecol. Evol. Syst., 51, 461–481

GeoSphere Austria (2025): *Temperature zone location analysis from Tyrol and Vienna*. Online: https://data.hub.geosphere.at/showcase/klimaklassifikation-nach-kppen-und-geiger (last access: 14.05.2025).

Gräf, M; Immitzer, M; Hietz, P; Stangl, R. (2021): Water-Stressed Plants Do Not Cool: Leaf Surface Temperature of Living Wall Plants under Drought Stress SUSTAINABILITY-BASEL, 13(7), 3910. DOI: 10.3390/su13073910

Hoelscher, M.-T., Nehls, T., Jänicke, B., Wessolek, G. (2016): *Quantifying Cooling Effects of Facade Greening: Shading*, Transpirationand Insulation. Energy Build. 2016, 114, DOI: 10.1016/j.enbuild.2015.06.047

Ip, K., Lam, M., Miller, A. (2010): *Shading performance of a vertical deciduous climbing plant canopy*, Build Environ 45:2010, 81–88. DOI: 10.1016/j.buildenv.2009.05.003

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. (2006): World Map of the Köppen-Geiger Climate classification updated. *Meteorol. Z.*, 15, 259-263. DOI: 10.1127/0941-2948/2006/0130

Koyama, T., Yoshinaga, M., Hayashi, H., Maeda, K., Yamauchi, A. (2013): Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls. Building and Environment, 66: 96-103. DOI: 10.1016/j.buildenv.2013.04.020

Law, C., Li, S. M., Lam, C. Y. (2020): *Plant Diversity and Plant Performance of Indoor and Outdoor Vertical Greening Systems in Hong Kong*. Environ.Behav. Proc. J., 5(14), 171–177. DOI: 10.21834/ebpj.v5i14.2268

Li, L., Mu, X., Jiang, H., Chianucci, F., Hu, R., Song, W., Qi, W., Liu, W., Zhou, J., Chen, L., Huang, H., Yan, G. (2023): Review of ground and aerial methods for vegetation cover fraction (fCover) and related quantities estimation: definitions, advances, challenges, and future perspectives. 199:133-156. DOI: 10.1016/j.isprsjprs.2023.03.020

Li, S., Tan, T., Fan, Y., Raza, M. A., Wang, Z., Wang, B., Zhang, J., Tan, X., Chen, P., Shafiq, I., Yang, W., Yang, F. (2022): *Responses of leaf stomatal and mesophyll conductance to abiotic stress factors.* Integrative Agriculture, 21(10), 2787–2804. DOI: 10.1016/j.jia.2022.07.036

Lin, Y.S. (2015): *Optimal stomatal behaviour around the world*. Nature Climate Change, 5, 459–464. DOI: 10.1038/NCLIMATE2550

Mahabadi, M., Althaus, C., Bartel, Y.C., Bott, P., Brandmeier, Thomas; Brandwein, T. (2018): *Richtlinien für die Planung, Ausführung und Pflege von Wand- und Fassadenbegrünungen*. Hg. v. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL).

Pérez, G., Coma, J., Sol, S., Cabeza, L. F. (2017): *Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect*. Applied Energy187:424-437. DOI: 10.1016/j.apenergy.2016.11.055

Poiss, M., Briefer, A., Scharf, B., Spörl, P., Stangl, R. (2025a): Vertical Greenery as Natural Shading of Glass Facades: Bioshading Coefficients for 4 Climbing Plant Species for Assessment of Shading Performance. Building and Environment, 113399. DOI: 10.1016/j.buildenv.2025.113399

Poiss, M, Briefer, A., Wultsch, T., Scharf, B., Pitha, U., Stangl, R. (2025b): *GLASGrün-Pflegeleitfaden zum wirksamen Einsatz von Vertikalbegrünungen bei Gebäuden mit Glasflächen*. Projekt GLASGrün. Projektbericht im Rahmen des Programms Stadt der Zukunft, 60c/2025, Wien.

Seyrek Şık, C.I.S., Woźniczka, A., Widera, B. (2022): *A Conceptual Framework for the Design of Energy-Efficient Vertical Green Façades*. In Energies (Vol. 15, Issue 21). MDPI. DOI: 10.3390/en15218069

Spörl, P., Trimmel, S., Haluza, D., Sauerbrey, S., Irrgeher, J., Prohaska, T., Pitha, U. (2023): Façade Greening for Healthy Urban Air: An Umbrella Review on Particulate Matter Reduction, Challenges, and Future Directions. Sustainability 2024, 16(1), 446; DOI: 10.3390/su16010446

Stangl, R., Briefer, A., Poiss, M., Wultsch, T., Scharf, B., Pitha, U., Smetschka, B., Haas, B., Bintinger, R., Lipp, B., Wagner, S., Huber, G., Maus, K., Formanek, S.: *GLASGrün Regulierung von Klima, Energiebedarf und Wohlbefinden in GLASverbauten durch bautechnisch integriertes, vertikales GRÜN*. GLASGrün Projektbericht im Rahmen des Programms Stadt der Zukunft. Wien, Berichte aus Energie und Umweltforschung 60a/2025.

Stangl, R., Minixhofer, P., Wultsch, T., Briefer, A., Scharf, B. (2022): *Green-blue infrastructure in the built environment - sustainable and resource-saving designs for urban structures and open spaces*, in: IOP Conf Ser Earth Environ Sci, Institute of Physics, DOI: 10.1088/1755-1315/1078/1/012132

UN-Habitat (2011): Cities and Climate Change: global report on human settlements. London, Washington, DC: Earthscan, DOI: 10.1080/1523908X.2014.891343

Wyka, T. P., Zadworny, M., Mucha, J., Żytkowiak, R., Nowak, K., Oleksyn, J. (2019): *Species-specific responses of growth and biomass distribution to trellis availability in three temperate lianas*. Trees - Structure and Function, 33(3), 921–932. DOI: 10.1007/s00468-019-01828-3