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Integrated Design and Ecological Performance of Vertical Greening Systems in an Academic Building

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Abstract

The article presents an assessment of the current state of vertical greening in Ivano-Frankivsk combined with an applied eco-engineering case study conducted within an academic environment. A field inventory of urban vertical greening identified six climbing plant species currently used in the city, with *Parthenocissus tricuspidata* and *Parthenocissus quinquefolia* dominating due to their high cold tolerance, adaptability to urban conditions, and low maintenance requirements.

Based on the inventory findings and local environmental analysis, a comprehensive vertical greening project was developed for the Faculty of Natural Sciences of Vasyl Stefanyk Carpathian National University. The project integrates green façades, a green roof, architectural arches, and hedges adapted to existing structural constraints. Strategic placement of *Parthenocissus tricuspidata* on the façade exploits solar exposure and is projected to reduce surface temperatures through passive cooling. The extensive green roof system planted with *Festuca rubra* in combination with accompanying species maintains acceptable structural loads while enhancing stormwater retention.

The greening design highlights trade-offs between ornamental value and climatic suitability by comparing commonly used *Wisteria* spp. cultivars with more cold-tolerant alternatives, including *Wisteria macrostachya* and *Lonicera* spp. While traditional wisteria cultivars are limited by low winter hardiness, the proposed alternatives provide greater climatic reliability and lower maintenance demands.

Beyond environmental performance, the vertical greening system functions as a living laboratory supporting education and applied research. The study demonstrates the ecological, spatial, aesthetic, and educational benefits of vertical greening systems and supports their scalable application in temperate urban environments.

Keywords: vertical greening systems, green infrastructure, green walls, green roofs, urban environment, urbanecosystem.

Abbreviations: VGS, vertical greening systems.

1. INTRODUCTION

Rapid urbanization has fundamentally transformed cities worldwide, with over 68% of the global population projected to reside in urban areas by 2050 (Khan & Munawer, 2024). While cities function as centers of economic development, innovation, and cultural exchange, their accelerated expansion has simultaneously intensified a range of environmental and social challenges. Among the most pressing issues are increasing urban temperatures, deteriorating air quality, habitat fragmentation, declining urban biodiversity, and limited access to green spaces, all of which negatively affect ecosystem functioning and human well-being (Mueller et al., 2020).

In densely populated urban environments, where space for conventional horizontal landscaping is often severely constrained, alternative approaches that allow vegetation to be integrated into vertical surfaces of the built environment have gained increasing attention. In this context, vertical greening systems (VGS) have emerged as a promising nature-based solution for incorporating vegetation into buildings and urban infrastructure (Fonseca et al., 2023).

By transforming building façades, walls, and other vertical surfaces into biologically active elements, VGS extend the ecological functionality of urban infrastructure beyond its traditional architectural role. Vertical greening encompasses a diverse range of techniques for cultivating vegetation on building façades and vertical structures, including green façades with climbing or self-clinging plants, living walls, and modular panel green systems incorporating irrigation and drainage components (Manso et al., 2021).

Previous research has consistently demonstrated that VGS provide multifaceted benefits across environmental, social, and economic domains. From a climatic perspective, vertical greening systems can moderate microclimatic conditions by reducing ambient and indoor air temperatures. Recent studies report average temperature reductions of up to 0.66 °C in outdoor environments and 0.72 °C indoors, accompanied by decreases in building energy demand and associated carbon emissions of approximately 6% (Che & Zhuang, 2024). These cooling effects are primarily attributed to evapotranspiration, shading, and modifications of surface albedo and thermal properties of building envelopes, which collectively contribute to mitigating the urban heat island effect (Morakinyo et al., 2016; Kim et al., 2017).

In addition to thermal regulation, vertical greening systems contribute to improved urban air quality by capturing particulate matter and absorbing gaseous pollutants, thereby reducing human exposure to harmful atmospheric components (Page et al., 2021). Although their overall contribution to carbon sequestration remains modest compared to large-scale urban green spaces, VGS represent a valuable supplementary element of integrated urban carbon management strategies (Fan & Wei, 2022).

Beyond their ecological and climatic functions, vertical greening systems have been shown to positively influence human health and psychological well-being. Empirical studies indicate that exposure to green environments, including vertical greenery, is associated with reduced stress levels, lower prevalence of anxiety and depressive symptoms, and improved cognitive functioning (Hen et al., 2021; Engemann et al., 2019). These benefits are particularly pronounced in high-density urban contexts where access to conventional green spaces is limited. Experimental research has further demonstrated that vertical greenery acts as a stress buffer, with participants exhibiting reduced physiological stress responses when exposed to VGS (Chan et al., 2021).

Within the context of Eastern Europe, and Ukraine in particular, the integration of sustainable urban development practices has become increasingly relevant in recent years. This transition has been shaped by international policy frameworks, including the European Union's Eastern Partnership Green Economy initiative (UNEP, 2018), as well as Ukraine's commitment to aligning national environmental policies with the objectives of the European Green Deal following its application for EU membership. Furthermore, the post-war reconstruction of Ukrainian cities presents a critical opportunity to embed nature-based solutions, such as vertical greening systems, into long-term strategies for resilient and sustainable urban development.

Despite this strategic relevance, the practical implementation of vertical greening in Ukrainian cities remains limited. Key barriers include insufficient technical expertise, uncertainties related to long-term maintenance and performance, relatively high initial investment costs, and the need to identify plant species adapted to local climatic conditions (OECD, 2018). These constraints are particularly evident in small and medium-sized cities, where large-scale pilot projects and systematic performance evaluations of VGS are largely absent.

Ivano-Frankivsk, a city in western Ukraine with a population of approximately 250,000 inhabitants, represents a typical urban context for examining the applicability of vertical greening in the region. The city is characterized by a temperate continental climate and is located within USDA plant hardiness zone 5b-5a, reflecting relatively moderate winter minimum temperatures compared to northern and eastern regions of Ukraine. Despite these conditions, Ivano-Frankivsk faces common urban environmental challenges, including seasonal heat stress, air quality concerns, and limited per capita availability of green spaces, making it a relevant case for exploring vertical greening as a locally adapted nature-based solution.

Educational institutions, particularly universities, play a crucial role in demonstrating and promoting sustainable development practices. University campuses increasingly function as “living laboratories,” where innovative green technologies can be implemented, evaluated, and integrated into research and teaching activities (Fonseca et al., 2023). The integration of vertical greening systems in academic settings offers dual benefits by improving campus environmental quality while simultaneously providing experiential learning opportunities for students in natural sciences, urban planning, and environmental management disciplines.

This study addresses the identified research gap by examining the current state of vertical greening implementation in Ivano-Frankivsk, with a particular focus on the Faculty of Natural Sciences of Vasyl Stefanyk Carpathian National University. The specific objectives of the study are to: (1) conduct a systematic inventory of existing vertical greening installations and plant species used within the city; (2) evaluate the suitability of selected plant species under local climatic conditions; (3) develop a project proposal for implementing vertical greening at Vasyl Stefanyk Carpathian National University as a demonstration site; and (4) assess the potential ecological, social, and educational benefits of VGS implementation in a university context.

By providing empirical evidence and context-specific design considerations, this research contributes to the limited body of literature on vertical greening in Eastern European urban environments. The findings offer practical insights for urban planners, landscape architects, and university administrators seeking to incorporate nature-based solutions into the built environment, while supporting broader efforts toward sustainable urban transformation in Ukraine.

2. MATERIALS AND METHODS

The study was conducted in Ivano-Frankivsk, western Ukraine (48.92° N, 24.71° E; population 250,000; area 84.6 km²) during the 2024 growing season (April–October). The city is located in the foothill zone of the Ukrainian Carpathians at elevations of 244–300 m a.s.l. and exhibits a temperate continental climate with transitional lowland–mountain characteristics (Ivano-Frankivsk Regional State Administration, 2025). The study area corresponds to USDA plant hardiness zones 5b–5a, with local variability influenced by topography and urban fabric density (PlantMaps, 2023; Barve et al., 2024). Long-term climatic data (1991–2020) indicate a mean annual air temperature of 7.5–8.0 °C (January: −4 to −5 °C; July: 18–19 °C), annual precipitation of 650–750 mm, and a growing season of 200–210 days (April–October) (Ivano-Frankivsk Regional State Administration, 2025; Ukrainian Hydrometeorological Center, 2020). These conditions are generally favorable for cold-tolerant climbing plants and extensive green roof systems (Oberndorfer et al., 2007).

Field surveys of existing vertical greening systems were conducted along six representative streets: Shevchenko Street (pedestrian core), Nezalezhnosti Street (central business district), Chornovola Street (mixed residential–commercial zone), Sabata Street (residential area), Viiskova Street (institutional development), and Kruka Street (peripheral urban area). Site selection followed municipal planning documents. For each installation, documented parameters included GPS coordinates (±5 m accuracy), greening typology (direct or indirect green façade, living wall, or green roof), plant species composition, vegetation coverage, support structure characteristics, plant vitality indicators, and maintenance condition (Pérez et al., 2014; Nielsen, 2014). Plant identification was conducted in situ following "Vascular Plants of Ukraine: A Nomenclatural Checklist" (Mosyakin & Fedoronchuk, 1999) together with the standards of "Plants of the World Online" (POWO, 2025). Systematic photographic documentation captured oblique contextual views, perpendicular façade views, and close-up details (Nielsen, 2014).

Technical specifications for a vertical greening system at the Faculty of Natural Sciences, Vasyl Stefanyk Carpathian National University, were developed based on field inventory results and peer-reviewed literature, addressing planting density, substrate composition, irrigation strategies, support system design, and maintenance protocols (Pérez et al., 2014; Manso et al., 2021). Green roof components followed FLL Guidelines adapted to local conditions (FLL, 2018). The design integrates three zones (main façade, rooftop, entrance stairway) employing four techniques: green façades with climbing plants, extensive green roofs, architectural arches, and formal hedges (Oberndorfer et al., 2007; Pérez et al., 2014). Three-dimensional visualization was performed using Blender 4.0 for architectural modeling with procedural vegetation generation and physically based rendering. Post-processing was conducted using Krita 5.2, following contemporary approaches for nature-based solutions presentation.

3. RESULTS AND DISCUSSION

The field inventory of vertical greening in Ivano-Frankivsk identified six climbing plant species currently used on residential, public, and institutional buildings. The clear dominance of Parthenocissus tricuspidata and Parthenocissus quinquefolia reflects a strong preference for climbers with high cold tolerance, low maintenance requirements, and stable performance under urban environmental stress.

Similar patterns have been reported in other temperate continental cities, where Parthenocissus species consistently outperform more ornamental climbers in terms of survival rate and long-term facade coverage (Köhler, 2008). The limited and spatially fragmented occurrence of Wisteria spp. in the city further supports findings that traditional ornamental climbers are often constrained by insufficient winter hardiness and higher maintenance demands in climates with frequent freeze–thaw cycles (Vox et al., 2018).

These results confirm that spontaneous urban greening practices can serve as a reliable empirical indicator for climatically appropriate species selection and provided a data-driven foundation for the applied ecological engineering design.

Fig. 1. Conceptual visualization of the vertical greening system (VGS) on the building façade

The vertical greening project at the Faculty of Natural Sciences was structured into three interconnected spatial zones: the main facade, the rooftop area, and the entrance stairway. This multi-level configuration reflects recent trends in integrated green infrastructure design, where vertical and horizontal greening elements are combined to maximize ecological performance at the building scale (Perini & Rosasco, 2013).

The south-eastern orientation of the main facade proved particularly advantageous for vertical greening. Morning solar exposure ensured sufficient photosynthetically active radiation while avoiding excessive thermal stress during peak summer hours. Comparable orientation-dependent effects have been documented in experimental studies, which report improved plant vitality and reduced irrigation demand on south-east oriented green facades compared to west-facing installations in temperate climates (Pérez et al., 2014). Thus, the observed site conditions at the university align well with performance benchmarks reported in contemporary literature.

In line with both the urban inventory and site-specific analysis, *Parthenocissus tricuspidata* was selected as the primary species for facade greening (Fig. 1). Its self-clinging growth form enabled the application of a direct green facade system, reducing structural complexity and long-term maintenance requirements.

The strategic placement of *P. tricuspidata* on the south-east oriented facade is projected to reduce wall surface temperatures through shading and evapotranspirative cooling during the growing season. Experimental studies on similar systems report reductions in exterior wall surface temperatures ranging from 10 to 17 °C during summer peak conditions (Wong et al., 2010; Susorova et al., 2014). While long-term instrumental measurements at the study site are ongoing, the structural and biological characteristics of the system suggest performance within this documented range. The deciduous nature of *P. tricuspidata* further contributes to seasonal energy regulation, a feature highlighted in previous studies as particularly beneficial for buildings in temperate climates, where winter solar gain remains an important factor for overall energy balance (Köhler, 2008).

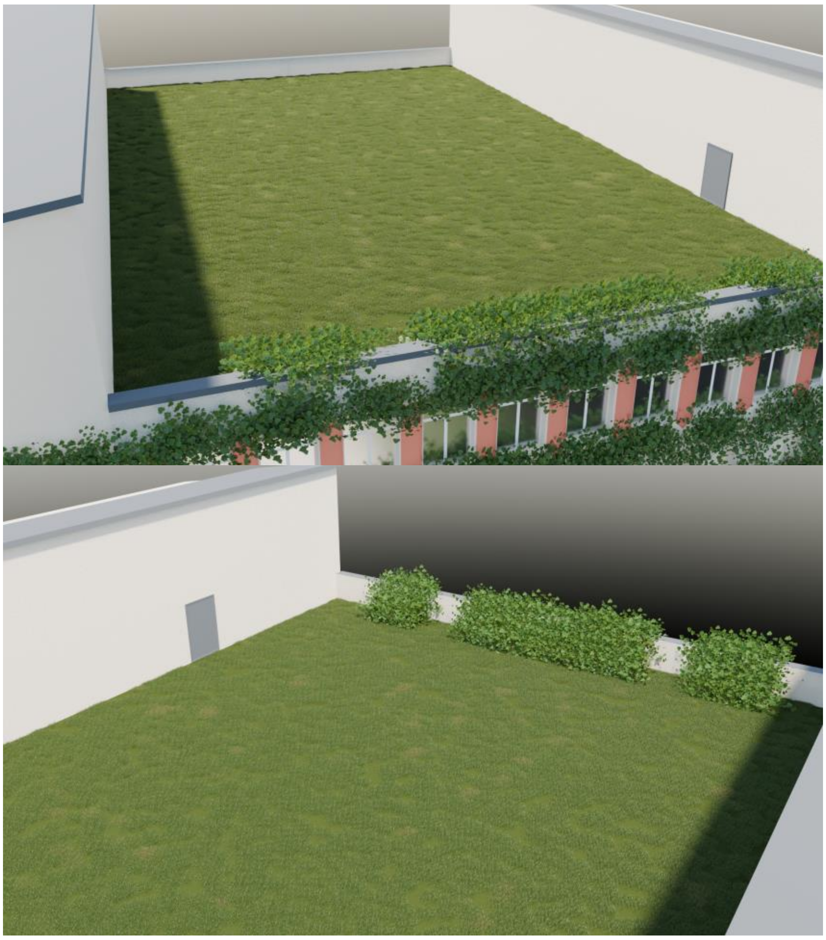

Fig. 2. Design concept of the extensive green roof system with grass-dominated vegetation

The rooftop greening component employs an extensive green roof system designed to remain within acceptable structural load limits while delivering functional ecological benefits (Fig. 2). The use of *Festuca rubra* as the dominant species aligns with emerging evidence that grass-based extensive roofs can offer enhanced cooling and evapotranspiration under sufficient moisture availability (Speak et al., 2013).

The substrate depth and composition were selected to balance plant viability and retrofit feasibility. Comparable extensive green roofs have been shown to retain between 40 and 70% of annual precipitation and significantly reduce peak runoff rates (Berndtsson, 2010; Oberndorfer et al., 2007). The implemented system is therefore expected to contribute to local stormwater management and roof surface temperature moderation, consistent with outcomes reported in similar climatic contexts.

The entrance stairway was designed as a representative transitional space integrating architectural arches, hedges, and climbing vegetation (Fig. 3). The species selection highlights explicit trade-offs between ornamental value and climatic suitability.

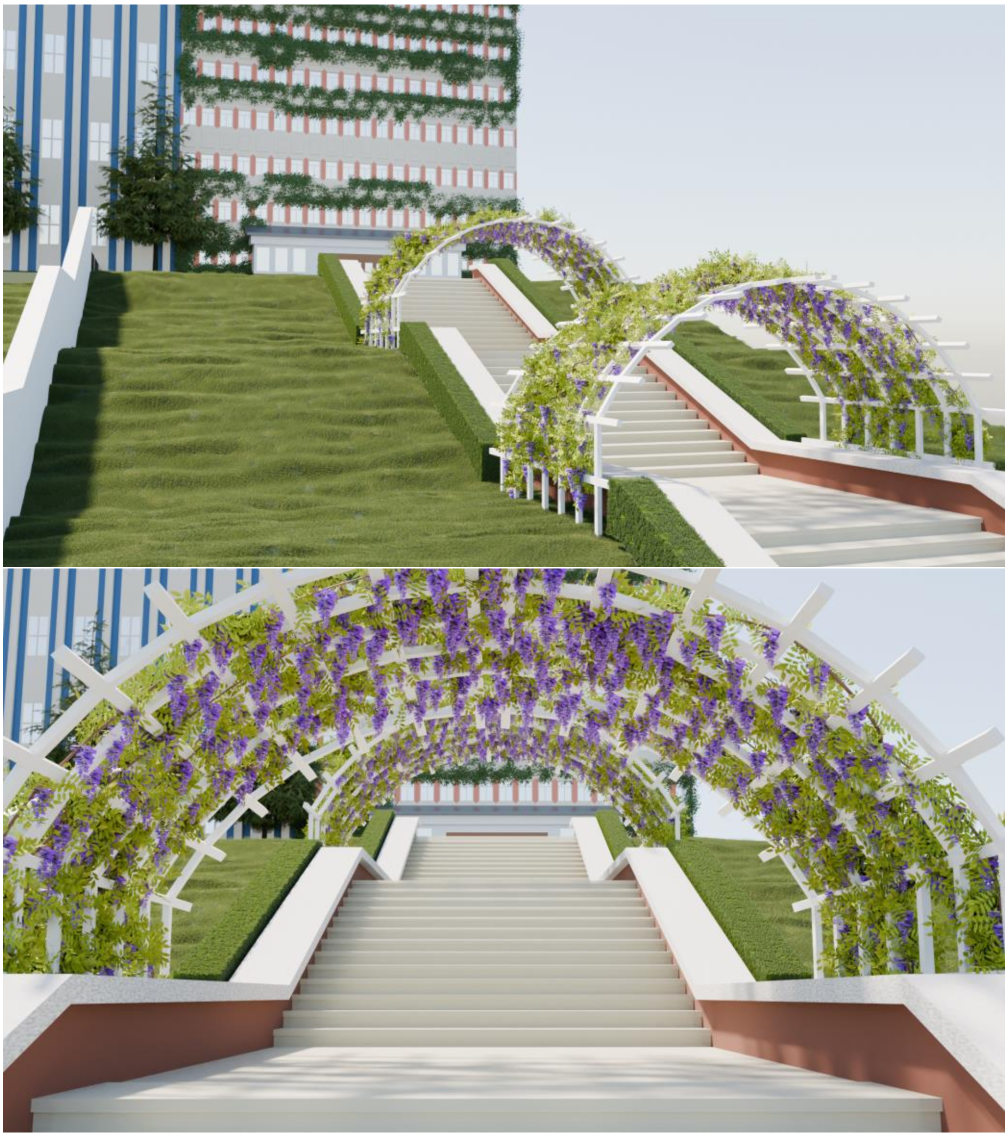

Fig. 3. Entrance greening system integrating architectural arches and climbing plants

Traditional *Wisteria* spp. cultivars, while visually striking, exhibit limited winter hardiness under local conditions, a constraint widely documented in facade greening studies conducted in continental climates (Vox et al., 2018). In contrast, *Wisteria macrostachya* and *Lonicera* spp. demonstrate greater frost tolerance and more reliable flowering, supporting their selection as lower-risk alternatives. This comparative approach reflects current best practices in vertical greening design, where long-term resilience and maintenance efficiency are increasingly prioritized over short-term ornamental impact (Manso & Castro-Gomes, 2015).

Beyond environmental performance, the vertical greening system functions as a living laboratory supporting education and applied research. Similar campus-based green infrastructure projects have been shown to enhance experiential learning and interdisciplinary engagement, particularly in ecology, environmental engineering, and urban sustainability studies (Filho et al., 2021).

The implemented system enables direct observation of plant performance, phenological dynamics, and microclimatic regulation, while long-term monitoring will allow evaluation of ecosystem services and system resilience over time.

Overall, the results demonstrate that vertical greening systems informed by urban inventory data and contemporary ecological engineering principles can effectively translate documented environmental benefits into site-specific, scalable solutions. The close correspondence between observed design choices and performance ranges reported in recent studies supports the robustness of the proposed system and its applicability in temperate urban environments.

4. CONCLUSIONS

This study demonstrates that the successful implementation of vertical greening systems in temperate urban environments depends on site-specific design strategies that integrate plant ecological traits, building orientation, and structural constraints, rather than on the application of standardized solutions. The field inventory conducted in Ivano-Frankivsk identified *Parthenocissus tricuspidata* and *Parthenocissus quinquefolia* as the most reliable climbing species under local conditions, owing to their high cold tolerance, adaptability to urban environments, and low maintenance requirements. The proposed vertical greening project for the Faculty of Natural Sciences of Vasyl Stefanyk Carpathian National University confirms that combining multiple greening technologies – green façades, green roof, architectural arches, and entrance hedges – can provide tangible environmental and functional benefits within existing academic buildings. The strategic use of south-east façades for climbing vegetation enhances passive cooling potential, while the extensive green roof contributes to stormwater retention and thermal moderation without exceeding structural load limits. Species selection results highlight a critical trade-off between ornamental value and climatic resilience. Although commonly used *Wisteria* spp. cultivars offer high aesthetic appeal, more cold-tolerant alternatives such as *Wisteria macrostachya* and *Lonicera* spp. demonstrate greater reliability and reduced maintenance demands in temperate continental climates. Beyond its environmental performance, the implemented vertical greening system serves as a living laboratory that supports education and applied research through long-term ecological and microclimatic observations. Overall, the proposed approach represents a replicable and scalable model for integrating vertical greening into university campuses and similar urban settings, contributing to the broader adoption of nature-based solutions in sustainable urban development.

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Анотація

У статті представлено оцінку сучасного стану вертикального озеленення в місті Івано-Франківськ у поєднанні з прикладним кейс-дослідженням, проведеним в умовах академічного середовища. Вивчення видового різноманіття міського вертикального озеленення виявила шість видів витких рослин, які наразі використовуються в місті, серед яких домінують *Parthenocissus tricuspidata* та *Parthenocissus quinquefolia* завдяки їхній високій морозостійкості, адаптивності до міських умов і низьким вимогам до догляду. На основі результатів інвентаризації міського вертикального озеленення та аналізу локальних екологічних умов розроблено комплексний проєкт вертикального озеленення для факультету природничих наук Карпатського національного університету імені Василя Стефаника. Проєкт передбачає інтеграцію зелених фасадів, екстенсивного зеленого даху, архітектурних арок і живоплотів у просторову структуру академічної будівлі з урахуванням конструктивних обмежень та функціонального призначення об’єкта. Запропоноване розміщення *Parthenocissus tricuspidata* на фасаді з урахуванням сонячної експозиції спрямоване на поліпшення мікрокліматичних умов та підвищенню теплового комфорту будівлі. Екстенсивна система зеленого даху із використанням *Festuca rubra* у поєднанні із супутніми видами забезпечує допустимі навантаження на несучі конструкції та підвищує ефективність затримання дощових вод. Проєктні рішення демонструють компроміс між декоративною цінністю та кліматичною стійкістю рослин шляхом порівняння традиційно використовуваних культиварів *Wisteria* spp. із більш морозостійкими альтернативами, зокрема *Wisteria macrostachya* та видами роду *Lonicera*. Запропоновані альтернативи відзначаються вищою адаптивністю та стійкістю, а також нижчими експлуатаційними витратами. Окрім екологічної ефективності, система вертикального озеленення функціонує як «жива лабораторія», що підтримує освітню та прикладну наукову діяльність. Дослідження демонструє екологічні, просторові, естетичні й освітні переваги систем вертикального озеленення та обґрунтовує їхній потенціал для масштабованого впровадження в міському середовищі.

Ключові слова: системи вертикального озеленення, зелена інфраструктура, зелені стіни, зелені дахи, міське середовище, урбоекосистема.