

Review

The Carbon Sequestration Potential of Skyscraper Greenery: A Bibliometric Review (2003–2023)

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Abstract: Nature-based solutions (NBS) encompass a diverse range of ecosystem-based strategies aimed at addressing urban sustainability challenges. Among these, skyscraper greenery emerges as a specialized application of NBS, integrating vertical vegetation systems into high-rise architecture to enhance carbon sequestration, mitigate urban heat islands, and improve air quality. By extending NBS principles into the vertical dimension of cities, this approach offers a scalable solution for climate adaptation in high-density urban environments. This study provides a comprehensive bibliometric analysis of skyscraper greenery research from 2003 to 2023, employing advanced tools such as CiteSpace and Bibliometrix to assess publication trends, elucidate key research themes, and identify prevailing knowledge gaps. The findings underscore the environmental benefits of skyscraper greenery, including its role in alleviating the urban heat island effect, improving air quality, and enhancing urban biodiversity. Additionally, economic advantages, such as reductions in energy consumption and operational costs, further highlight its multifaceted utility. Carbon sequestration within skyscraper greenery primarily occurs through vegetation's photosynthetic processes, which are influenced by plant species, substrate composition, and system design. Thermal performance, ecosystem services, and biodiversity emerge as pivotal themes driving research in this domain. However, the field faces persistent challenges, including inconsistent methodologies for measuring carbon sequestration, a lack of technical standards, and limited public awareness. Future studies must prioritize the standardization of carbon measurement protocols, optimization of plant and substrate selection, and integration of skyscraper greenery within comprehensive urban sustainability frameworks. Addressing socio-economic barriers and enhancing policy incentives will be essential for widespread adoption. This review emphasizes the transformative potential of skyscraper greenery as a multifunctional strategy for climate mitigation, advancing resilient, low-carbon, and sustainable urban environments.

Keywords: skyscraper greenery; carbon sequestration; nature-based solutions; green infrastructure; urban sustainability; Bibliometrix



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1. Introduction

The rapid pace of global urbanization has intensified spatial pressures in urban environments while exacerbating the critical challenges posed by climate change. Urban expansion has significantly increased CO₂ fossil fuel consumption and energy demand, which have paralleled cumulative emissions since the pre-industrial era [1]. Greenhouse

gases remain the principal drivers of climate change [2], prompting the international community to establish governance frameworks such as the Paris Agreement to mitigate temperature rise [3]. Despite these initiatives, global greenhouse gas emissions have continued to escalate, reaching unprecedented levels from 2021 to 2022 due to persistent reliance on fossil fuels and anthropogenic deforestation [4]. In response, urban development strategies have increasingly prioritized energy-efficient, low-carbon urbanization through measures such as green building initiatives and ultra-low energy consumption designs [5]. Achieving sustainable development necessitates retrofitting building components to align with low-energy objectives [6]. Within this paradigm, Low Impact Development practices, which encompass sustainable architectural approaches, eco-friendly designs, and resource-efficient methodologies, have emerged as pivotal models for urban planning [7].

Advocated by the European Research and Innovation Policy Agenda, nature-based solutions represent a transformative approach to urban sustainability [8]. The International Union for Conservation of Nature (IUCN) defines nature-based solutions (NBS) broadly as actions to protect, sustainably manage, and restore ecosystems to address societal challenges, while simultaneously providing human well-being and biodiversity benefits, where biodiversity refers to the variety of plant, animal, and microbial life within a given ecosystem, and in urban settings, high biodiversity enhances ecological resilience, improves pollination and pest control, and supports microclimate regulation. NBS encompass a broad range of strategies, including wetland restoration, urban forests, and sustainable drainage systems, each designed to harness natural processes for ecological and social resilience. Within this framework, this study focuses on a specific subset of NBS—vertical greening systems (VGSs) integrated into high-rise architecture. These systems, which include green walls, sky gardens, and rooftop vegetation, leverage plant-based interventions to provide targeted ecological services such as carbon sequestration, the process by which plants absorb atmospheric CO₂ through photosynthesis and store it in biomass and soil, playing a critical role in climate change mitigation by reducing greenhouse gas concentrations [1], improving microclimate regulation, and enhancing air quality in spatially constrained urban environments. Unlike horizontal green infrastructure (e.g., parks), skyscraper greenery uniquely addresses the challenges of vertical urbanization by creating high-density green spaces within built-up cityscapes. By critically analyzing the past five years of NBS reviews (Table 1), a significant research gap emerges: most existing studies predominantly emphasize horizontal green infrastructure (a network of natural and semi-natural systems, e.g., green roofs, vertical gardens, and urban forests that provide ecosystem services, such as stormwater management, carbon sequestration, and air purification; GI is a key component of sustainable urban planning), such as urban parks and green roofs, while providing limited exploration of vertical greening systems. Notably, there remains a paucity of quantitative data on carbon sequestration rates, lifecycle environmental impacts, and the long-term sustainability of skyscraper greenery. Furthermore, a systematic assessment of skyscraper greening’s technical adaptability across diverse climatic conditions, particularly in arid regions and high-wind urban environments, is conspicuously lacking.

Table 1. Comparative analysis of recent NBS reviews.

Author	Year	Title	Scope	Key Findings	Gaps Related to Skyscraper Greenery
Pérez [9]	2014	Vertical Greenery Systems (VGS) for energy saving in buildings: A review	Energy efficiency of green facades in temperate zones	Quantifies 12% heating demand reduction with deciduous climbers.	Excludes extreme climates (e.g., desert or monsoon regions); no dynamic carbon modeling.

Table 1. *Cont.*

Author	Year	Title	Scope	Key Findings	Gaps Related to Skyscraper Greenery
Jim [10]	2015	Thermal performance of climber greenwalls: Effects of solar irradiance and orientation	Solar irradiance effects on vertical greenery	Demonstrates 80% solar radiation reflection by green walls.	Limited to temperate climates; ignores long-term maintenance challenges (e.g., biofilm accumulation).
Medl [11]	2017	Vertical greening systems—A review on recent technologies and research advancement	Technological advancements in vertical greening systems (VGSs)	Evaluates modular hydroponics and lightweight substrates for green walls.	Omits lifecycle carbon assessments and region-specific climate adaptations.
Zaid [12]	2018	Vertical Greenery System in urban tropical climate and its carbon sequestration potential: A review	Carbon sequestration potential of VGSs in tropical cities	Reports 0.5–3.0 kg CO ₂ eq/m ² annual absorption rates for climbing plants.	Limited to short-term data (<5 years); no standardized protocols for carbon measurement.
Manso [13]	2021	Green roof and green wall benefits and costs: A review of the quantitative evidence	Cost–benefit analysis of green roofs and walls	Highlights energy savings (15–25%) but notes high upfront costs (300–1000 USD/m ²).	Overlooks socio-economic equity (e.g., payback periods in low-income regions).
Al-Kodma [14]	2023	Greenery-Covered Tall Buildings: A Review	Technical innovations in skyscraper greenery	Emphasizes modular systems and biodiversity benefits.	Lacks comparative analysis of arid/tropical climates; minimal policy integration recommendations.

Green infrastructure is a critical strategy for enhancing urban resilience and mitigating the environmental impacts of rapid urbanization. By integrating vegetation into the built environment, it plays a key role in stormwater management, urban cooling, and air quality improvement. Recent studies emphasize the importance of synergizing green and gray infrastructure to maximize environmental benefits and cost efficiency [15–17]. Among the various green infrastructure solutions, skyscraper greenery offers a high-density approach to ecological integration, particularly in space-constrained cities. By incorporating vegetation into high-rise structures, it provides multifunctional benefits, including solar radiation absorption, evapotranspiration-driven cooling, and reductions in air conditioning energy consumption. Additionally, vertical greenery systems contribute to biodiversity conservation, rainwater retention, and air pollutant filtration, while helping to mitigate the urban heat island (UHI) effect, a phenomenon where urban areas exhibit significantly higher temperatures than their rural surroundings due to heat absorption by impervious surfaces, reduced vegetation, and waste heat emissions from human activities. UHIs exacerbate energy consumption, air pollution, and health risks [18–21]. The effectiveness of skyscraper greenery is strongly influenced by plant selection, substrate composition, and structural design. Climbing plants, particularly those with high chlorophyll content and strong adherence properties, are widely used for carbon sequestration and microclimate regulation [22]. The choice of nutrient-rich, lightweight substrates further enhances plant health and carbon capture potential [23]. However, optimizing the long-term ecological and structural

performance of vertical greenery requires a comprehensive understanding of plant–soil interactions, water management strategies, and lifecycle material sustainability [24–28].

Socially, skyscraper greenery fosters mental health and physical well-being by re-connecting urban populations with nature while creating aesthetically appealing environments [29]. Economically, it enhances energy efficiency by providing thermal insulation and reducing cooling loads, contributing to substantial energy savings [30]. Its applications in densely populated urban areas extend to reducing the carbon footprint through innovative urban agriculture solutions, positioning skyscraper greenery as a critical strategy for climate mitigation. Multi-layered membranes (e.g., root-resistant PVC) coupled with gradient-based drainage systems prevent water infiltration. Case studies from Singapore’s PARKROYAL Hotel demonstrate a 90% reduction in leakage incidents post-implementation [12,31]. Widespread adoption could offset significant CO₂ emissions while delivering auxiliary environmental benefits, including thermal regulation and air quality improvements, by mitigating pollutants such as black carbon and fine particulate matter [32]. Although natural and anthropogenic disturbances may limit carbon sequestration potential in urban green spaces, the cumulative benefits remain substantial [33–35].

Despite its promising advantages, existing reviews predominantly focus on horizontal green infrastructure, such as parks and green roofs, with limited attention to the unique challenges and opportunities of vertical systems. This gap is particularly evident in the lack of standardized metrics for carbon sequestration efficiency in high-rise environments and region-specific design guidelines for extreme climates. In addition, the implementation of skyscraper greenery encounters technical, economic, and regional challenges. Ensuring long-term viability requires addressing irrigation systems, structural load considerations, and optimal plant selection [36,37]. Economic barriers, including high initial installation costs and ongoing maintenance requirements, further impede large-scale adoption [28]. Moreover, the efficacy of skyscraper greenery varies depending on geographic location, architectural design, and climatic conditions. A systematic bibliometric analysis, facilitated by tools such as Bibliometrix and CiteSpace, can synthesize research trends and identify emerging insights in this domain [38,39]. However, existing reviews of NBS focus on horizontal green spaces (such as urban forests) and ignore the unique challenges and opportunities of vertical systems. A comprehensive assessment of the carbon sequestration potential of skyscraper greening remains underexplored. This study fills this gap by synthesizing two decades of research on skyscraper greening, focusing on carbon sequestration mechanisms and scalability barriers, synthesizing current research findings, comparing theoretical and empirical evidence, and charting pathways for future research to address this gap.

2. Research Methods and Technical Routes

2.1. Data Collection and Search Strategy

This review employed the Web of Science (WoS) Core Collection database as the primary repository for English-language literature, systematically examining studies on carbon sequestration within skyscraper greenery spanning the period from 2003 to 2023. A rigorous search strategy was designed, combining targeted keywords with Boolean operators within the Topic (TS) field of WoS to ensure exhaustive coverage of relevant publications. The search terms utilized included TS = (“skyscraper greenery” OR “green roofs” OR “green walls” OR “green buildings” OR “urban farming” OR “super high-rise green” OR “sky gardens” OR “vertical greening system”) AND (“carbon sequestration” OR “carbon neutral” OR “low-carbon landscapes” OR “heat island effect” OR “emission reduction”). This comprehensive approach identified 306 journal articles categorized under “article” and “review”, providing a robust foundation for analysis.

2.2. Bibliometric Analysis

Bibliometric analysis, a rigorous methodology that unveils intellectual structures and research trajectories [40], incorporates performance metrics and scientific mapping to elucidate thematic concentrations and collaborative networks in skyscraper greenery research [41]. Two advanced visualization tools, CiteSpace and VOSviewer, were utilized to facilitate this analysis. CiteSpace generated knowledge maps to visualize author networks, keyword co-occurrences, citation clusters, and thematic distributions, offering a comprehensive understanding of structural patterns and research trajectories [42].

Through the application of bibliometric paradigms, this study delineates the foundational knowledge base and thematic trends associated with skyscraper greenery and carbon sequestration. To enhance the inferential validity of bibliometric trends, a Pearson correlation analysis was conducted between annual publication volumes (2003–2023) and global CO₂ emissions data (source: UNEP Emissions Gap Report 2023). This analysis aimed to assess whether scholarly attention to skyscraper greenery aligns with escalating climate challenges. In addition, performance indicators were calculated, and evolutionary trends, research frontiers, and knowledge associations were identified. The analysis further highlighted key contributors to the field, including prolific authors, institutional affiliations, geographic origins, and prominent publication venues, enabling a comprehensive evaluation of the field's development trajectory.

To execute this analysis, the Bibliometrix R package, a statistical computing and graphics environment, was employed for an exploratory assessment of skyscraper greenery research. Subsequently, CiteSpace 6.2 R4 was utilized to produce an array of advanced visualizations to illuminate research trends and priorities. The analytical process comprised three core stages: The first stage was data preprocessing, in which textual data were normalized and imported into CiteSpace 6.2 R4, followed by a meticulous deduplication process to ensure data integrity and analytical precision. The second stage was parameter configuration and calibration, in which relevant parameters within CiteSpace, including the 2003–2023 time span, were configured to accurately capture the temporal evolution of research within the field. The 2003–2023 period was selected to encompass two decades of significant advancements in sustainability-focused architectural research. Articles outside this timeframe or unrelated to the specified keywords were excluded to maintain relevance. The third stage was visualization and application, in which CiteSpace's advanced visualization features were employed to create graphical outputs, offering insights into prominent research themes, collaborative networks, and potential future directions within the domain.

3. Bibliometric Insights on Carbon Sequestration in Skyscraper Greenery

The correlation analysis revealed a statistically significant positive relationship between annual publication counts and global CO₂ emissions ($r = 0.76$, $p < 0.001$). This indicates that increased academic focus on skyscraper greenery corresponds to rising global carbon levels, underscoring its perceived relevance as a climate mitigation strategy. As depicted in Figure 1, the annual volume of publications in this domain exhibits a pronounced upward trajectory, underscoring its growing prominence in academic discourse.

This study examines the dynamics of publication patterns, visualizes knowledge structures, and traces the progression of research through bibliometric techniques and knowledge mapping. These analyses include constructing topic co-occurrence and citation relationship networks, which illuminate key research hotspots, emerging trends, and pathways of knowledge dissemination within the field. Furthermore, the findings identify existing knowledge gaps and underexplored areas, providing critical insights into potential avenues for future research.

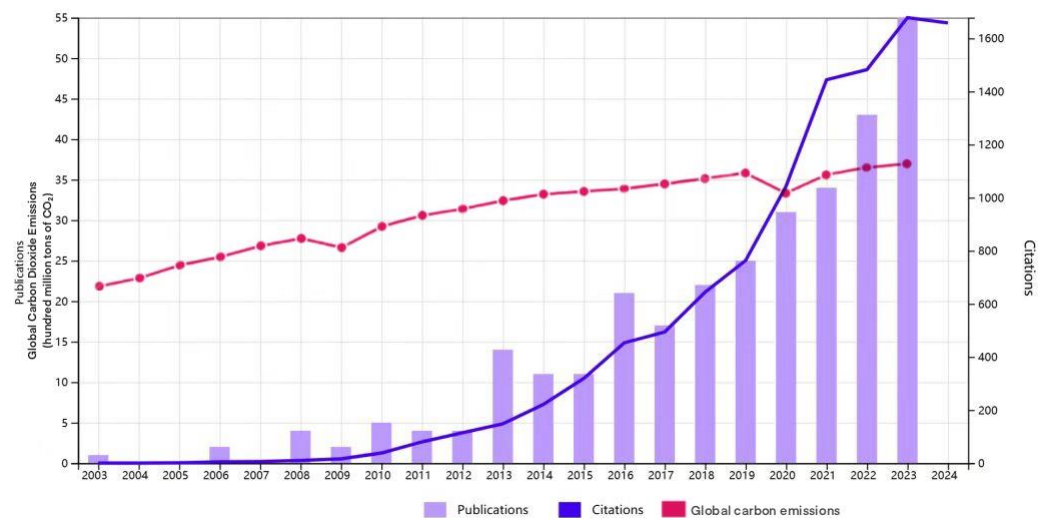


Figure 1. Annual publication trends on carbon sequestration of skyscraper green plants and global carbon emissions (2003–2023). The chart depicts the number of publications (vertical purple bar), citation frequency (dark purple line), and global carbon emissions (pink line).

3.1. Analysis of Author Relationships

Analyzing author relationships is instrumental in understanding the diversity of academic contributions, fostering multidisciplinary perspectives, quantifying scholarly influence, and promoting collaboration and knowledge exchange. This analysis also elucidates the developmental trajectory of research within the field, enhancing the efficiency and impact of academic outputs. The chronological analysis of research activity (Figure 2) highlights metrics such as the number of papers published (N. Articles) and total citations per year (TC per Year) by key authors from 2006 to 2022. While the publication volume among most authors remains relatively stable, the total citations per year demonstrate a consistent upward trend, reflecting the field's maturation and expanding impact.

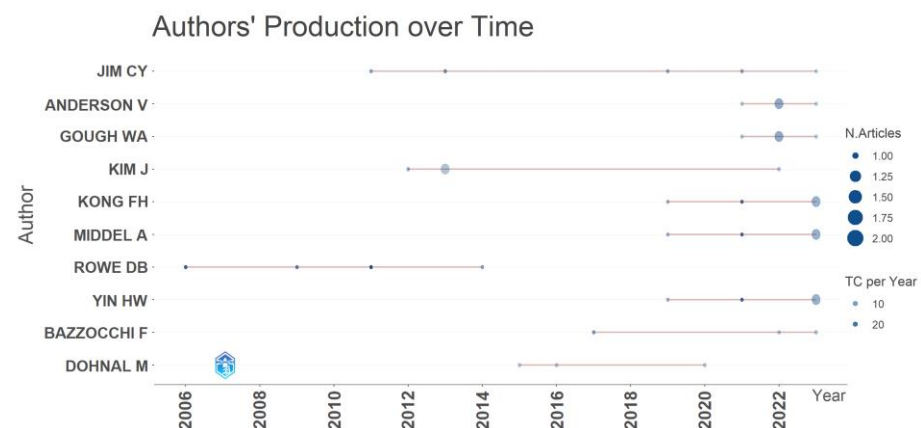


Figure 2. Key authors and publication timeline for skyscraper greenery research. This timeline visualization, generated using the Bibliometrix R package 4.3.0 (represented by the blue logo), maps the contributions of leading researchers in the field of skyscraper greenery. The horizontal axis spans the study period (2006–2024), while the vertical axis lists authors ranked by publication volume and citation impact.

Prominent contributors, such as Jim, C.Y. and Anderson, V., exhibit significantly higher citation rates from 2018 to 2022 compared to their peers, underscoring the innovation and influence of their research during this period. Rowe, D.B., a pioneer in the field, laid the groundwork for skyscraper greenery and carbon sequestration studies through foundational contributions. Jim, C.Y., a prolific author with one of the most extended

publication records, has significantly advanced the field alongside influential scholars such as Kong, F.H., Middel, A., and Yin, H.W., who collectively exhibit remarkable academic productivity and sustained research engagement.

Jim, C.Y. et al. [43] demonstrated the effectiveness of green walls with climbing plants in mitigating urban heat islands and improving energy efficiency by reducing direct solar radiation exposure. A radiation-sharing model quantified the insulation effects of green walls, revealing their potential for widespread urban climate adaptation [43]. Rowe, D.B. et al.'s [44] research on green roofs underscored the importance of plant diversity and substrate depth in maximizing carbon sequestration, providing empirical evidence that informs sustainable urban planning [44]. Similarly, Kong, F.H. et al. [38] have extensively reviewed the integration of green roofs into urban landscapes, contributing to a deeper understanding of their role in climate resilience [38]. Recent advancements also include Bazzocchi, F. et al.'s [45] work, which evaluates the efficiency of vertical greenery systems in improving building energy performance, particularly in warm climates [45]. Furthermore, Kim, J. et al. [46] introduced a multi-criteria evaluation framework that integrates green roof designs with energy-saving measures, offering a holistic perspective on their economic and environmental benefits. Anderson, V. et al.'s [47] multi-scale analyses reveal the potential of green walls to reflect up to 80% of solar radiation, further emphasizing the importance of nature-based solutions in combating urban climate change. These contributions collectively shape the theoretical and applied dimensions of skyscraper greenery research, forming a robust knowledge network that bridges empirical findings with practical implementation. By synthesizing these advancements, this study provides a foundational understanding of skyscraper greenery's role in urban sustainability while identifying key knowledge gaps for future research.

The collective analysis of research contributions from ten leading scholars in green building and urban greening reveals a broad and deep scope, addressing multiple levels from macro-strategic frameworks to micro-technological innovations. Significant variations in academic influence are observed, with prolific contributors like Jim, C.Y. advancing the field through a high volume of publications, while others, such as Gough, W.A. and Anderson, V., achieve high innovation and breakthrough impact despite fewer outputs. Together, these contributions form a systematic knowledge network, facilitating the translation of theoretical advancements into practical applications. This robust body of work provides critical support for urban sustainability and offers valuable guidance for future research directions and innovative explorations.

3.2. Pertinent Countries and Their Collaborative Network Dynamics

The intensifying global imperative to combat climate change has foregrounded the dual objectives of reducing carbon emissions and enhancing carbon sequestration as critical priorities in both academic research and international policy agendas. Advancing the implementation of skyscraper greenery for carbon sequestration requires robust international collaboration to foster resource sharing, technological innovation, and policy harmonization. A bibliometric analysis of research outputs in this domain identifies China as the leading contributor, with 88 publications comprising 27.1% of the total, underscoring its central role in advancing the field. Following China, the United States, Italy, Canada, and the United Kingdom have produced 47, 23, 20, and 19 publications, respectively (Figure 3). Collectively, developed nations contribute approximately 50% of global research output, driven by heightened environmental awareness, socio-economic incentives, and advanced technological infrastructure that underpin skyscraper greenery research and application.

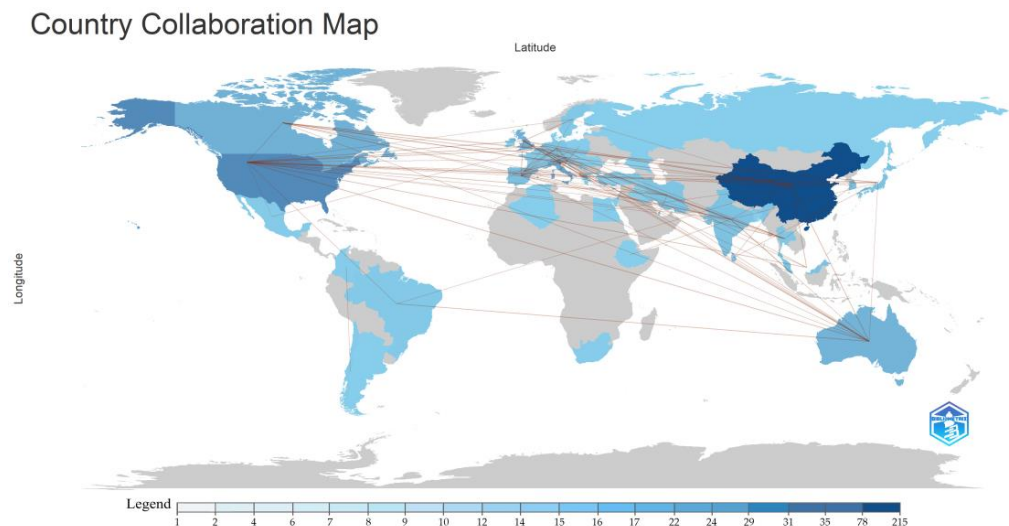


Figure 3. Global collaboration map for skyscraper greenery research. Manuscript counts are represented by darker shades, while connecting lines denote collaborative relationships between authors from different countries.

While developed countries dominate research contributions, the potential and necessity for skyscraper greenery adoption in developing nations remain significant. These regions face accelerated urbanization and pronounced environmental challenges, necessitating targeted initiatives to bridge the research and application gap. International collaboration and capacity-building programs will be essential in ensuring a more equitable and impactful global response to climate change, extending the benefits of this innovative approach to all regions.

The trajectory of international cooperation in skyscraper greenery research is strongly influenced by national policies. In recent years, China has prioritized ecological civilization through green development initiatives that align with its climate change mitigation and environmental protection strategies [48]. Skyscraper greenery has emerged as an integral component of China's urban ecological resilience framework, enhancing its role as a global leader in this domain. The dominant role of China (27.1% of publications) aligns with its 2020 "Ecological Civilization" policy, which prioritizes vertical greening as a national strategy. Conversely, limited collaboration with tropical countries (e.g., India, Brazil) highlights a critical gap, given their high urbanization rates and carbon-intensive economies. Figure 3 highlights the breadth and depth of international cooperation. This partnership exemplifies a multifaceted approach, encompassing theoretical advancements, practical implementations, academic exchanges, training programs, knowledge sharing, and research alliances. Such cooperation has been instrumental in amplifying global awareness of skyscraper greenery's potential for carbon mitigation and in driving the expansion of research frontiers [49].

International cooperation fosters innovation and accelerates research progress by promoting resource sharing, technological advancement, and global knowledge exchange. These collaborative efforts have not only enhanced the scientific understanding of skyscraper greenery but have also catalyzed its application in addressing urban sustainability challenges worldwide. Through the integration of diverse expertise and the establishment of global research networks, the role of skyscraper greenery in mitigating climate change continues to gain prominence, offering a scalable solution to enhance urban ecological resilience and reduce global carbon footprints.

3.3. Delving into Dominant Research Themes

Keyword analysis is a pivotal tool for optimizing literature retrieval, offering a structured means to uncover prevailing research themes in skyscraper greenery and its role in carbon sequestration. By identifying core research areas, elucidating thematic trends, and highlighting emerging frontiers, this approach enhances both efficiency and depth in scholarly inquiry.

3.3.1. Keyword Extraction

The systematic extraction and classification of keywords provide critical insights into research hotspots and evolving trends in skyscraper greenery literature. Using the Bibliometrix R package's network structure analysis capabilities, comprehensive lists of author keywords were compiled, and visual word clouds were generated, as depicted in Figures 4 and 5.

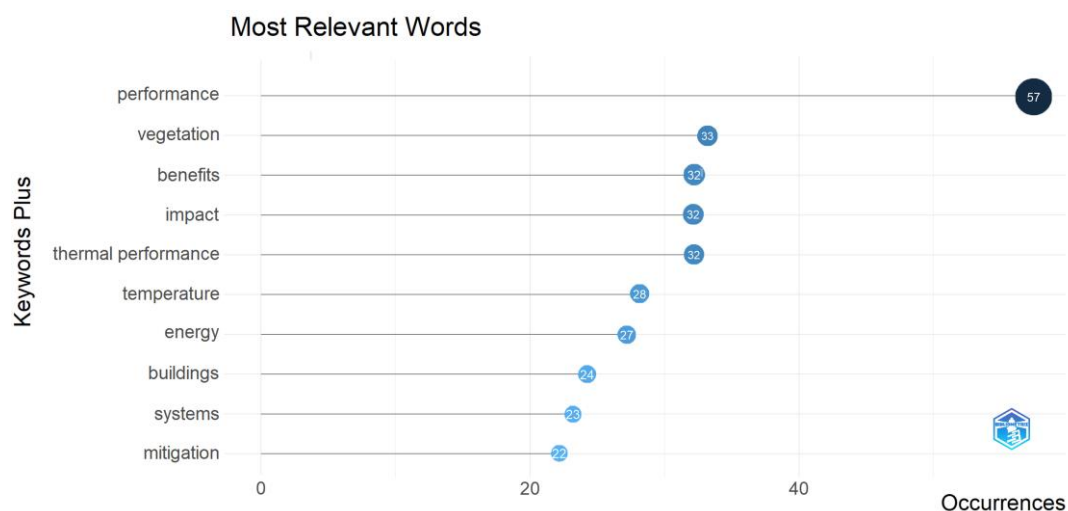


Figure 4. List of the most frequently used keywords in skyscraper greenery research, highlighting dominant themes and recurring terms.



Figure 5. Word cloud analysis of keywords related to carbon sequestration in skyscraper greenery. Keywords were extracted from titles, abstracts, and key phrases across different periods (2003–2023).

Among the identified keywords, “performance” emerges as a central theme, cited 57 times, reflecting its importance across multiple dimensions such as plant survival, growth, and overall health. These factors are indispensable for ensuring the ecological sustainability and aesthetic quality of skyscraper greening systems [50]. Landscape design is also prominently featured, highlighting its role in enhancing urban biodiversity, mitigating the urban heat island effect, and managing stormwater. These elements collectively underscore the growing significance of green infrastructure in bolstering urban resilience [51]. Additionally, VGSs impose additional static and dynamic loads (e.g., substrate weight, wind forces). Engineers must integrate lightweight modular frameworks (e.g., aluminum or fiber-reinforced polymer panels) with load capacities of $\geq 1.5 \text{ kN/m}^2$; structural and waterproofing components, essential for maintaining the integrity of high-rise buildings and preventing water infiltration, illustrate the necessity of integrating ecological, engineering, and design considerations into high-rise greening initiatives [14,52].

The keyword “vegetation” is cited 33 times, emphasizing its foundational role in skyscraper greening. Research in this area focuses on understanding the physiological adaptations of plants at high altitudes and the strategic layout of plant communities to maximize ecological functions. This includes air purification and enhanced carbon sequestration within spatially constrained urban environments [24].

The keywords “benefits” and “impact”, each cited 32 times, reflect the field’s emphasis on the multifaceted advantages and environmental implications of high-rise greening. From an environmental perspective, skyscraper greening alleviates urban heat islands, reduces air pollution, and regulates urban humidity. Economically, it lowers long-term building operational costs and enhances property values. Socially, it improves residents’ quality of life and provides urban biodiversity habitats. In terms of environmental impact, research explores not only localized microclimatic effects but also broader implications for urban ecosystems, landscape aesthetics, and cultural significance.

“Thermal performance”, also cited 32 times, underscores the critical importance of skyscraper greening in the context of increasing awareness of building energy consumption [9]. This theme is closely linked to the keyword “systems”, cited 23 times, which highlights the complexity of supporting systems essential for high-rise greening. These include advanced irrigation systems tailored to specific plant species and environmental conditions, drainage systems to prevent waterlogging during extreme weather, and structural support systems to securely attach vertical greenery to building facades.

The keyword “mitigation”, cited 22 times, highlights research on the potential of skyscraper greening to address urban environmental challenges. Beyond mitigating heat islands and air pollution, it explores rainwater management capabilities. Green infrastructure’s water storage and infiltration functions reduce the burden on urban drainage systems and mitigate flood risks, further solidifying its role in sustainable urban development.

Research on skyscraper greening exemplifies a multidisciplinary and integrative approach, blending ecological, engineering, and design perspectives. This synergy spans plant selection and configuration, system design and maintenance, environmental impact assessment, and comprehensive benefit analysis. The field’s holistic focus drives the development of innovative solutions to urban sustainability challenges, offering transformative strategies for the sustainable evolution of cities.

3.3.2. Keyword Co-Occurrence Analysis

The “Keyword Co-occurrence” function of CiteSpace 6.2 R4 provides profound insights into the associative structures within skyscraper greenery research related to carbon sequestration. In the “Keyword Co-occurrence View” (Figure 6), keywords are represented as nodes, where the size of each node corresponds to its frequency in the literature. Connect-

ing lines illustrate co-occurrence relationships, with line thickness indicating the strength of these associations. Notably, “green roof” emerges as the most prominent keyword, appearing 65 times, followed closely by “performance” (59 times), “carbon sequestration” (44 times), and “urban heat island” (42 times), highlighting the extensive and interconnected nature of this research domain.

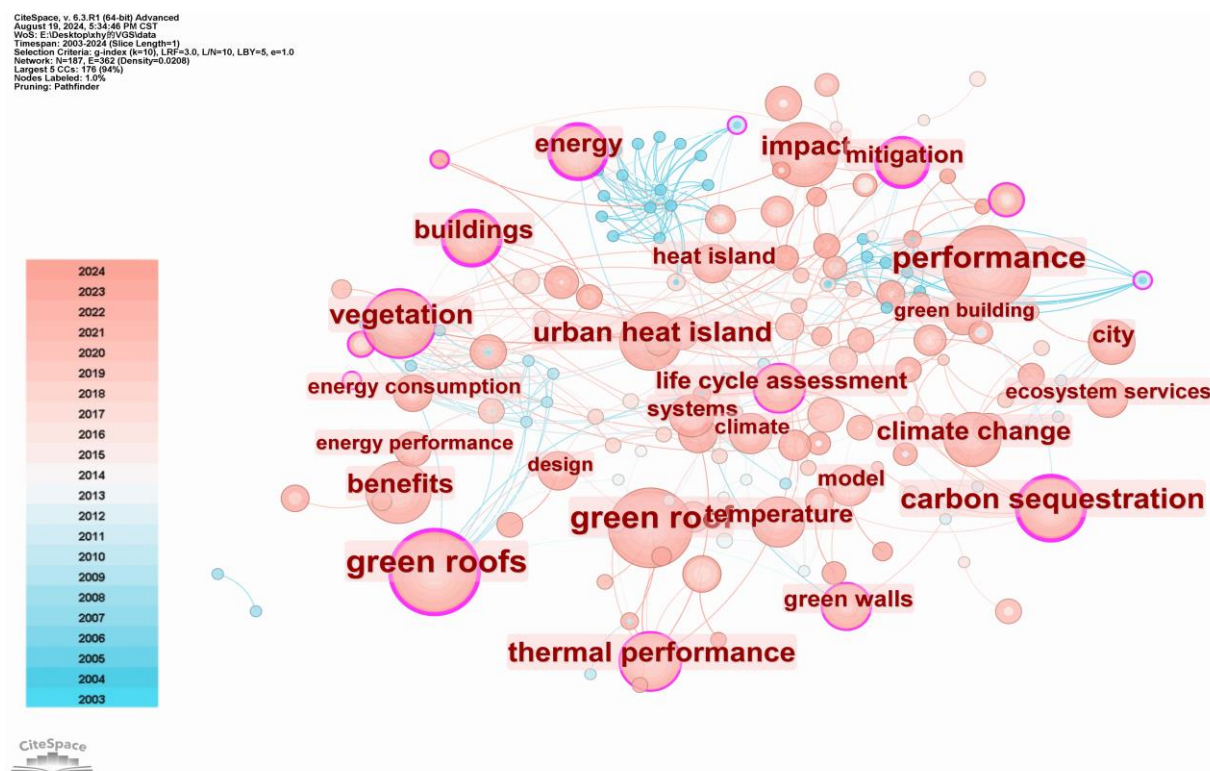


Figure 6. Keyword co-occurrence network for carbon sequestration in skyscraper greenery. Nodes represent keywords, with size indicating frequency and connecting lines illustrating co-occurrence relationships.

A comprehensive analysis of green roofs and wall greenery examines the environmental and aesthetic attributes of building green facades. The findings indicate that vegetation significantly contributes to thermal regulation and exhibits remarkable energy-saving effects, corroborating previous studies. Aesthetically, greenery transforms the visual appearance of skyscrapers and is associated with the well-being of occupants. Collectively, these insights underscore the multifaceted benefits of greening, encompassing carbon sequestration, energy efficiency, and aesthetic enhancement, thereby establishing a robust foundation for continued investigation in this burgeoning field [53].

The performance of skyscraper greenery is assessed across multiple dimensions: ecological, environmental, economic, and social. Ecologically, it has been demonstrated to mitigate urban heat island effects [54], enhance air quality [55], and preserve biodiversity [56]. Environmentally, optimizing construction materials can augment both the carbon sequestration capacity and the service lifespan of skyscraper greenery. Notably, stainless steel is often favored for structural support due to its exceptional durability, offering a service life exceeding 50 years; however, its recyclability remains a significant concern [28].

Given the centrality of carbon sequestration in this study, keyword frequency analyses affirm its prominence in skyscraper greenery literature. Comparative evaluations of plant species facilitate the identification of regional carbon sequestration potential. Climbers (e.g., *Ficus pumila*, *Hedera helix*) are prioritized for their adhesion and low maintenance. Tropical species (e.g., *Epipremnum aureum*) are favored in humid climates, while succulents

(e.g., *Sedum* spp.) dominate arid regions [57]. Dynamic modeling techniques are utilized to quantify and monitor the sequestration capacities of selected flora, providing precise estimations of their carbon capture efficacy [58]. Consistent findings highlight the energy-saving benefits of skyscraper greenery, particularly during periods requiring cooling [59–61]. Importantly, factors such as wall orientation [62,63], climatic conditions, and vegetation types substantially influence the performance of skyscraper greenery systems [64].

Mitigation of the urban heat island (UHI) effect remains a primary impetus for investigating the carbon sequestration potential of skyscraper greenery. UHIs, exacerbated by elevated surface temperatures resulting from rapid urbanization and intensified anthropogenic activities, increase energy consumption and carbon emissions, thereby contributing to global warming [65]. The accelerating expansion of urban environments amplifies these impacts, highlighting the pressing need for implementing skyscraper greenery as a strategy to alleviate UHI phenomena [66].

The keyword clustering analysis depicted in Figure 7 serves as an essential instrument for comprehending the green building research landscape. The generation of clusters, arrangement logic, and thematic correlations constitutes a comprehensive and incisive academic paradigm, unveiling the complexity, breadth, and evolutionary trajectory of the field, and guiding subsequent exploration and development [67].

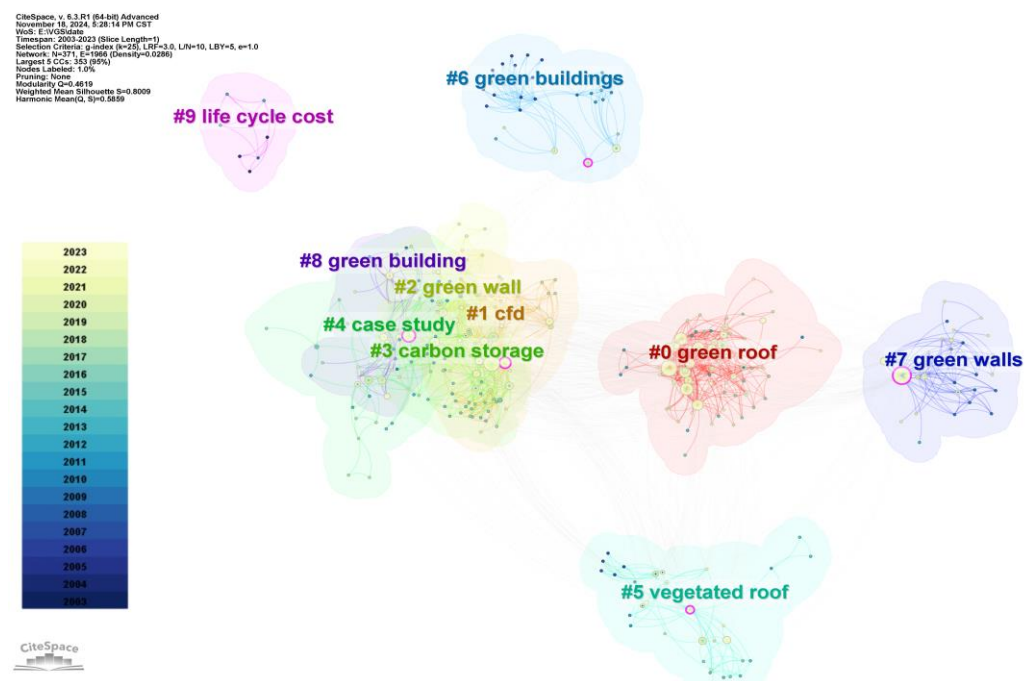


Figure 7. Keyword clustering analysis for skyscraper greenery research. Clusters reveal thematic groupings and connections, providing insights into the research landscape.

The clustering is generated by a rigorous algorithm that identifies semantic associations among keywords and organizes them numerically. The “green roof” cluster, encompassing 61 related keywords, is particularly prominent. This not only underscores its central position within the research but also reflects its profound connection to skyscraper greenery, propelling innovation in building facade technologies [53]. The overlap among research areas across clusters fosters a dynamic academic ecosystem. Scholars from diverse disciplines including economics, fluid dynamics, and materials science collaborate to address critical issues in green building, such as lifecycle cost–benefit analyses, enhancements in energy efficiency, and material development [68]. This interdisciplinary synergy surmounts numerous challenges and accelerates the field’s progression. Additionally,

In the middle period, beginning in 2014, keywords such as “thermal performance”, “buildings”, and “CO₂” gained prominence, signifying a shift in research towards optimizing building thermal performance, integrating buildings and greenery, and reducing CO₂ emissions [72]. Studies during this period emphasized quantifying the impact of greening on building energy consumption and carbon emissions through experimental and simulation methodologies [73,74], while exploring design models that seamlessly integrate architectural and greening elements.

Top 20 Keywords with the Strongest Citation Bursts

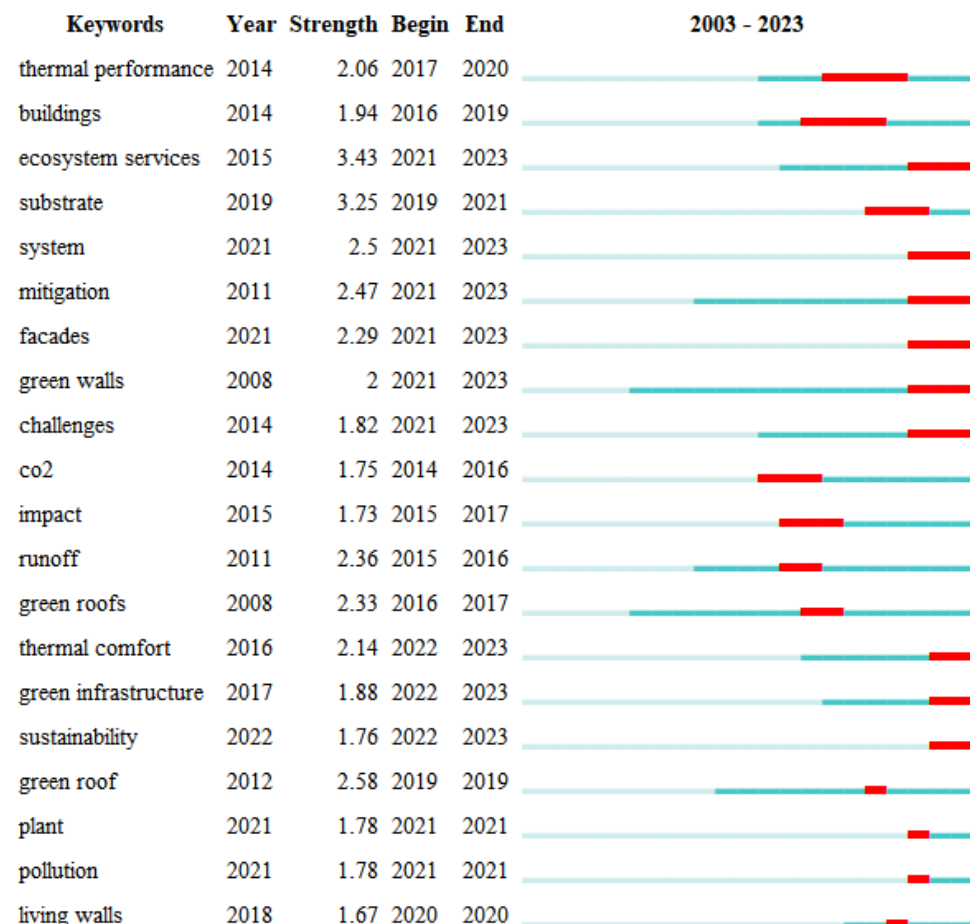


Figure 9. Keyword breakout analysis for skyscraper greenery research. This analysis identifies keywords that experienced sudden surges in usage over time, highlighting shifts in research priorities (The red line indicates the time period of emergence.).

From 2021 to 2023, research focus shifted to keywords such as “ecosystem services”, “substrate”, and “system”, reflecting a growing emphasis on evaluating the ecological value of greenery, developing specialized substrates, and constructing complex greening systems. This includes quantifying the contributions of greenery to biodiversity and air quality, as well as engineering substrates and systems optimized for skyscraper environments. Simultaneously, keywords such as “mitigation” and “challenges” underscored ongoing efforts to address environmental issues and technological barriers. These challenges, such as high-altitude conditions, load-bearing capacities, and maintenance costs, have remained central to research efforts. Investigations during this period explored innovative strategies and technological advancements aimed at overcoming these obstacles to enhance skyscraper greenery’s contribution to urban sustainability, ecological quality, and green building performance.

In the context of ecosystem services, skyscraper greenery contributes to carbon sequestration through plant biomass, with studies indicating annual CO₂ absorption rates ranging from 0.44 to 3.18 kg CO_{2eq} m⁻² [58]. Additionally, skyscraper greenery operates as an energy-efficient urban technology, reducing emissions and energy consumption [75]. Vertical vegetation systems further enhance microclimatic regulation, underscoring their role in mitigating urban thermal challenges [76]. Expanding research emphasizes skyscraper greenery's role in fostering biodiversity, serving as a natural solution for optimizing urban ecosystem services by supporting local species [77].

The keyword “thermal comfort” reflects increasing interest in urban green infrastructure as a critical strategy for mitigating UHI effects and alleviating heat stress exacerbated by climate change [78]. Skyscraper greenery has demonstrated significant potential for passive energy conservation and heat reduction at the building scale, positioning it as an effective intervention for urban climate resilience [79]. As greenhouse gas emissions accelerate, surpassing earlier projections, global warming poses escalating challenges [80]. In response, carbon sequestration has emerged as a cornerstone in achieving carbon neutrality and mitigating the adverse effects of climate change on ecosystems and societies [81].

3.3.4. Contextual Feasibility of Skyscraper Greenery

The successful integration of greenery into high-rise architecture is influenced by four interdependent dimensions: locational constraints, climatic adaptability, social considerations, and economic viability. Each of these dimensions plays a critical role in determining the feasibility, performance, and long-term sustainability of vertical greenery systems within the urban built environment.

Locational factors, particularly urban density and land costs, significantly impact the adoption and scalability of vertical greening strategies. High-density cities such as Hong Kong and New York, where severe land scarcity limits the availability of ground-level green spaces, have increasingly incorporated vertical greenery despite substantial retrofit costs ranging from USD 500 to USD 1200 per square meter [49]. In these urban centers, vertical greening presents a viable alternative to traditional parks and gardens, offering ecological benefits without compromising valuable real estate. Conversely, lower-density cities such as Phoenix, where land pressures are considerably lower, tend to prioritize horizontal green infrastructure, favoring large-scale urban parks and street-level vegetation over high-rise greenery [49]. In addition to urban density constraints, regulatory frameworks and green building policies significantly influence the adoption of VGSs. In cities with stringent sustainability mandates, such as Singapore, zoning incentives such as the LUSH 3.0 program provide financial mechanisms to promote skyscraper greenery. Under this initiative, developers integrating VGSs into new construction projects are granted floor area ratio bonuses, effectively offsetting 15–20% of installation costs, thereby making vertical greening more economically viable [15].

Climatic adaptations are equally critical in ensuring the long-term performance and ecological functionality of skyscraper greenery. The selection of plant species, irrigation technologies, and structural configurations must be carefully calibrated to accommodate local environmental conditions. In tropical climates such as Singapore, where high humidity and frequent rainfall create an environment conducive to rapid vegetative growth, fast-growing species such as *Epipremnum aureum* are commonly employed [12]. However, the same climatic conditions that promote plant growth also facilitate the proliferation of fungal biofilms, necessitating the application of anti-fungal coatings to prevent structural deterioration and maintain system integrity [12]. In contrast, arid environments such as Dubai, where water scarcity presents a major challenge, require alternative approaches to maximize water-use efficiency. The integration of hydroponic irrigation systems with

hydrogel-infused substrates has been shown to reduce water consumption by up to 60%, making it a viable solution for skyscraper greenery in desert climates [14]. Additionally, drought-resistant species such as *Agave americana* exhibit superior survivability in arid conditions, demonstrating enhanced physiological adaptations to low-water environments [14]. In temperate cities such as London, where seasonal temperature fluctuations necessitate adaptive solutions, modular green walls commonly incorporate deciduous climbers such as *Parthenocissus tricuspidata*. These species provide dynamic thermal regulation, offering shading during summer while permitting increased solar gain in winter, effectively reducing building heating demand by approximately 12% [60]. Such region-specific adaptations underscore the necessity of customized design strategies that align with climatic constraints to optimize energy efficiency and plant longevity.

Beyond environmental and regulatory factors, social acceptance and public perception play a fundamental role in shaping the adoption and widespread implementation of VGSs. Urban greenery initiatives are often evaluated not only on their ecological contributions but also on their visual and aesthetic integration within the built environment. Public attitude surveys conducted in Tokyo and Berlin indicate that 65% of urban residents prioritize aesthetic appeal over ecological functionality when assessing the desirability of green infrastructure projects [77]. This finding highlights the necessity for designers to balance ecological benefits with architectural aesthetics, ensuring that vertical greenery is perceived as an enhancement to urban landscapes rather than an intrusive structural element. Furthermore, landmark projects such as Milan's *Bosco Verticale* have demonstrated the capacity of skyscraper greenery to increase public engagement with urban biodiversity, reinforcing the potential of the VGS as an educational and cultural tool in addition to its environmental benefits.

Finally, economic viability remains a crucial determinant of the feasibility of vertical greenery, as high upfront installation costs often present financial barriers to adoption. The capital expenditure required for VGS installation varies considerably, with modular panel systems averaging USD 300 per square meter, while customized hydroponic systems can exceed USD 1000 per square meter, making return on investment a critical consideration for developers and policymakers [13]. Despite these significant initial costs, skyscraper greenery has been shown to yield long-term economic benefits, particularly through energy savings and carbon credit incentives. Empirical studies indicate that VGSs can reduce cooling energy consumption by 15–25%, contributing to substantial cost savings over the building's operational lifespan [13]. Furthermore, the emergence of carbon trading markets has introduced new financial mechanisms for monetizing CO₂ sequestration, with carbon credits valued between USD 50 and USD 100 per ton of CO₂ captured, effectively shortening the payback period for skyscraper greenery investments to approximately 8–15 years [13]. These findings emphasize the importance of integrating financial incentives and policy-driven subsidies to enhance the economic attractiveness of vertical greening systems.

3.3.5. Future Research Prospects

(1) Standardizing Carbon Sequestration Measurement and Lifecycle Assessments

One of the most pressing gaps in skyscraper greenery research is the lack of standardized carbon sequestration methodologies. Current studies employ diverse measurement techniques, ranging from biomass sampling to gas exchange analysis, leading to fragmented and non-comparable datasets. Future research must establish harmonized protocols that integrate real-time IoT sensors for continuous CO₂ monitoring and dynamic lifecycle assessment frameworks to track emissions throughout installation, maintenance, and decommissioning phases.

(2) Addressing Socio-Economic and Policy Barriers

Given the diverse environmental conditions in high-density urban centers, skyscraper greenery must be customized for different climatic zones, and could enhance energy efficiency while maintaining structural integrity. Future studies should conduct comparative field trials across multiple climate zones to develop regionally optimized plant–substrate combinations.

(3) Financial incentives and interdisciplinary collaboration

While skyscraper greenery offers long-term energy savings and ecosystem benefits, high upfront costs and extended payback periods remain major deterrents for large-scale adoption. Public–private partnerships and carbon credit mechanisms under global agreements like the Paris Agreement could financially incentivize investment in skyscraper greenery, particularly in low-income regions. Additionally, interdisciplinary collaboration is essential: material scientists should focus on developing lightweight, recyclable substrates to minimize structural loads; urban planners and ecologists must design biodiversity-inclusive systems that align with public preferences.

(4) Enhancing Long-Term Resilience and Durability

Most existing research fails to examine the long-term performance of skyscraper greenery beyond five-year observation periods. Several critical uncertainties remain, including the impact of biofilm accumulation on photosynthetic efficiency and performance fluctuations under extreme climatic events. Future research should explore anti-fouling coatings to prevent microbial growth and maintain plant health; modular, climate-adaptive designs that can be retrofitted to respond to shifting urban microclimates; and multi-decade simulation models to forecast long-term ecological benefits and structural stability.

4. Conclusions

This review underscores the critical role of skyscraper greenery in addressing the interconnected challenges of urbanization and climate change. By enhancing carbon sequestration and delivering a range of environmental, social, and economic benefits, skyscraper greenery has emerged as a vital component of sustainable urban development. The bibliometric analysis conducted reveals a consistent growth in scholarly interest and identifies key research hotspots, including thermal regulation, ecosystem services, and urban biodiversity enhancement. Despite these advancements, significant gaps persist, particularly concerning standardized assessment methodologies and the systematic integration of skyscraper greenery into broader urban sustainability frameworks. Future studies could extend this work by integrating urban heat island mitigation and resilience frameworks, thereby bridging the gap between carbon-centric and multifunctional NBS applications. These findings highlight the necessity of interdisciplinary research to fully realize the potential of skyscraper greenery as an effective nature-based solution to urban sustainability challenges.

To unlock the full potential of skyscraper greenery, coordinated efforts across research, policy, and practice are imperative. Technological innovation must be complemented by robust stakeholder engagement and evidence-based policymaking to promote global adoption and optimization. A comprehensive, holistic approach is essential to address existing challenges, including high-altitude environmental stressors, structural limitations, and economic feasibility. By leveraging these concerted efforts, skyscraper greenery can play a transformative role in creating resilient, low-carbon urban environments that harmonize with natural ecosystems. This vision underscores the importance of skyscraper greenery as a cornerstone of sustainable urban development in the face of escalating global environmental challenges.

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