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Review

A Systematic Review of the Vertical Green System for Balancing Ecology and Urbanity

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Abstract: Skyrise greenery, including green roofs and vertical gardens, has emerged as an indispensable tool for sustainable urban planning with multiple ecological and economic benefits. A bibliometric analysis was used to provide a systematic review of the functions associated with skyrise greenery in urban landscapes. Key research tools, including the "Bibliometrix" R package and "CiteSpace" 6.2 R4, highlight the depth and breadth of the literature covering skyrise greenery. In 2000–2022, a total of 1474 original journal articles were retrieved. Over this period, there was an exponential increase in the number of publications, reflecting both enhanced knowledge and increasing concerns regarding climate change, the urban heat island, and urbanization. Of the total, ~58% of the articles originated from China, followed by the USA, Italy, Australia, and Canada. The research themes, such as urban heat islands, carbon sequestration, hydrology, and air quality, have been identified as the frontier in this fields. Furthermore, researchers from developed countries contributed the most publications to this domain, while developing countries, such as China, play an increasing role in the design and performance evaluation of vertical greenery. Key benefits identified in vertical green systems (e.g., green roofs and walls) include thermal regulation, sustainable water management, air-quality improvement, noise reduction, and biodiversity enhancement. In addition, several potential future research prospectives are highlighted. This review provides a comprehensive insight into exploring the pivotal role of skyrise greenery in shaping sustainable, resilient urban futures, coupled with sustainable urban planning.

Keywords: green roofs; green walls; skyrise greenery; ecosystem services; urban ecology

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1. Introduction

Escalating urbanization in recent decades, propelled by swift economic progression, has attracted an increasing global interest. Urbanization has been shown to significantly increase the frequency and intensity of extreme weather events, i.e., extreme precipitation events and heatwaves [1–3]. Furthermore, land use changes and urbanization have transformed the landscape patterns of metropolitan areas, since these areas have experienced considerable growth in recent decades. Contemporary urban planning strategies have been explored for reducing land consumption on account of a compact urban development approach [4]. However, these tactics inadvertently exert negative effects on extant green spaces, thereby hampering the delivery of essential ecosystem services [5,6]. As such, in the majority of urban landscapes, an ecosystem service deficit may occur, resulting from the fact that the local demand for ecosystem services often surpasses the available supply [7].

It is crucial to explore sustainable design strategies for multifunctional green infrastructure integrated into urban planning to address urban heat islands, floods, air pollution, and biodiversity loss. More recently, an emergent concept of nature-based solutions (NBSs) has gained increasing popularity, aiming at the enhancement of sustainable urban development through local ecosystem services [8,9]. These services are primarily provided by urban greenery, such as public parks and estate greenery, which facilitates to directly and indirectly enhance human lives [10]. Skyrise greenery or a vertical green system, one of the urban green infrastructures based on the NBS concept, comprises rooftop gardens, building facades, and balconies, which are often termed as "stereoscopic greenery", "vertical green walls", and "roof greenery". Vertical green systems generally fall into two categories: green facades, with vegetation rooted in the ground, and green walls/living walls (GWs), featuring substrate modules or hydroponic sheets attached to structural walls or frames [11]. GW systems are newer and more complex than green facade systems, mainly due to construction and maintenance costs and irrigation complexity. Vertical green systems offer architectural and aesthetic benefits, while also promoting sustainable urban development. They facilitate to mitigate the urban heat island effect, hydrological disturbances, and atmospheric pollution [12]. Additionally, they create a more temperate microclimate, reducing energy consumption and carbon emissions [13].

Vertical green systems have attracted increasing attention from scholar worldwide to review the state-of-the-art knowledge, conduct analyses, employ techniques, and discuss research contributions. Manso et al. [14] provided a summary of the advantages and disadvantages of green roofs and walls, considering benefits at the building scale, city scale, and life cycle financial implications. They highlighted the varied outcomes and provided median qualification. Teotónio et al. [15] meticulously assessed the eco-economic valuation of vertical green infrastructures and elucidated the value spectrum for each green paradigm, spotlighting extant research lacunae. In a geo-specific exploration, Avila-Hernandez et al. [16] examined the energy, thermodynamic, and ecological benefits of green roofs in Mexico. They analyzed various variables, including vegetation types, substrate composition, climatic conditions, and infrastructural design. Cheshmehzangi et al. [17] performed a comprehensive analysis of incentives across 19 urban centers in 113 countries. They identified recurring mechanisms driving the adoption of green roofs and walls within the context of global green infrastructure expansion.

Furthermore, bibliometrics, anchored in quantitative and statistical paradigms, provide a delineation of the prevailing trends in discrete research arenas through citation analyses. For instance, Ying et al. [18] revealed an intricate correlation between green infrastructure scholarship and ecosystem assessments for constructive green edification. "Bibliometrix" is a vanguard open source instrument, tailored for scient metric and bibliometric inquiries. Its computational robustness facilitates rapid analytical throughput, and it efficiently constructs matrices for co-citation, coupling, synergy, and co-word evaluations [19]. On the other hand, "CiteSpace" 6.2 R4 is an avant-garde information visualization software that combines the foundational principles of citation analysis with co-citation techniques. Its primary utility lies in pinpointing and dissecting views in disciplinary research, discerning temporal flux in research hotspots, and elucidating interrelations between emergent research frontiers and foundational knowledge. Through its sophisticated visualization capabilities, it renders the architecture and morphology of disciplinary knowledge palpable [20]. Nevertheless, the comprehensive bibliometric evaluations of ecosystem services subject to green vertical systems still remain scarce.

Given the increasing importance of ecological impacts associated with vertical green systems amid rapid urbanization, this study offers a systematic critical review of the current state-of-the-art progress and future perspectives in the research field of vertical green systems in urban ecological environments. This review utilizes a combined approach of bibliometric analysis and conventional literature review methods. An intriguing dynamism inherent to this domain was manifested via discernible shifts in the compilation of annual publication counts. Figure 1 illustrates the chronological progress of annual publication volumes pertinent to the nexus between skyrise greenery and urban ecosystem services in 2000–2022. This bibliometric review profiles the publication dynamics, knowledge map visualization, and research progression in the field of skyscraper greenery. Furthermore, an alternative approach to describe the connections and networks between specific topics and their published information is addressed. In addition, the research gaps are identified and the potential future research directions are highlighted.

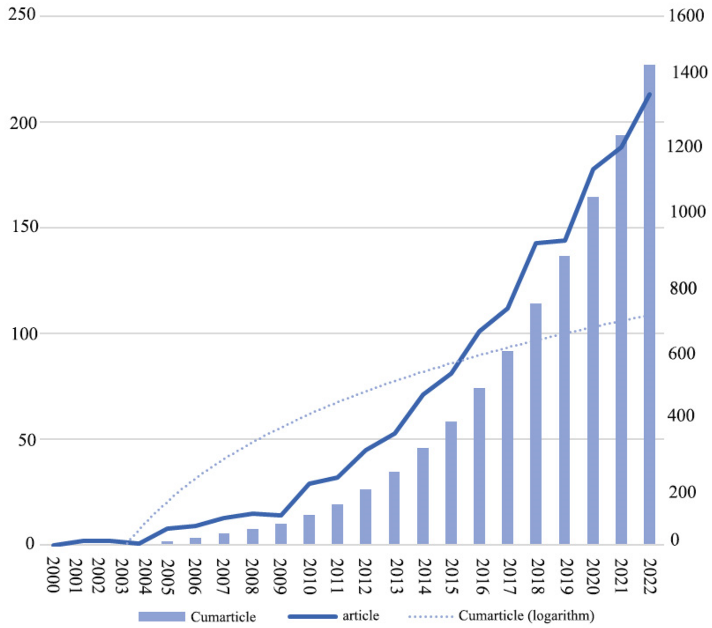

Figure 1. Number of published articles on vertical green systems from 2000 to 2022. The figure indicates the year-to-year values (vertical light-blue bar), the cumulative number (dark-blue line), and the logarithmic value of the cumulative number (blue dotted line).

2. Materials and Methods

2.1. Data Collection

In pursuit of a thorough analysis of the research priorities and emerging frontiers in the vertical greenery domain, the Web of Science (WoS) Core Collection Database (SCI-EXPANDED database) was employed in the present review as the primary library for English literature. In July 2023, a comprehensive literature retrieval was performed, deploying a combination of keywords and Boolean operators within the "Topic" (TS) section of the WoS database. A search within the TS region allowed for a robust and extensive review, encapsulating not only titles, abstracts, and author keywords, but also supplementary index and terms found in each full publication. The specific search queries included: TS = ("skyrise greenery" OR "vertical greenery" OR "green building" OR "super high-rise green" OR "sky gardens" OR "green wall" OR "green roof" OR "skyscraper greenery") AND TS = ("urban ecosystem service" OR "temperature" OR "stormwater management" OR "climate change adaptation" OR "runoff" OR "pollutant" OR "water quality" OR "flood" OR "hydrology" OR "humidity" OR "water management"). The preliminary retrieved results indicate that a total of 1474 original journal articles were retrieved from 2000 to 2022. Unreachable files, which were inaccessible due to copyright restrictions or unavailability through the institutional subscription, were manually eliminated. As such, a total of 1454 manuscripts were obtained, which can be categorized into research and review articles.

2.2. Bibliometric Methods

Bibliometrics focuses on the analysis of current knowledge units within a specific research area, aiming to elucidate the inherent interrelationships amongst these units in a quantitative fashion, thereby providing both holistic and quantitative perspectives [21]. The bibliometric approaches can be classified into two methodologies: the first method focuses on individual literary entries as separate statistical entities, while the second approach emphasizes network clustering and utilizes inter-knowledge unit linkages as important statistical metrics [22].

Within this context, a bibliometric paradigm was employed in the present study to meticulously conduct the scientific knowledge mapping related to the vertical green system and generate an overview of the underlying knowledge domain. The bibliometric exploration lies in delineating performance indicators and statistically unearthing evolutionary trends, knowledge association status, and research frontiers within a specific research domain. As such, the multifaceted constituents of a research territory, encompassing authors, institutional affiliations, geographies, and publication mediums, are identified. Consequently, this bibliometric analysis enables the identification of current research trends and advancements in vertical green systems, in terms of the merits of vertical greenery, co-citation literary analyses, research epicenters, and avant-garde innovations. Subsequent to procuring a preliminary vista via "Bibliometrix" R package, "CiteSpace" 6.2 R4 was invoked to furnish a more nuanced juxtaposition of divergent research vectors within vertical greenery. This procedural triad encompasses: (1) the integration of text formats into CiteSpace 6.2 R4, accompanied by data de-duplication; (2) precision calibration of pertinent parameters within CiteSpace 6.2 R4, specifying data chronologically from 2000 to 2022, from different aspects, such as titles, abstracts, and keywords; and (3) synthesis of graphical illustrations that manifest the research's current perspective, evolutionary progression, and prospective research horizons.

3. Bibliometric Insights into Skyrise Greenery Investigations

3.1. Dissecting Authorial Relationships

Deeper penetration into scholarly publications reveals the intersection of skyrise greenery and ecosystem services, facilitating the identification of pioneering authors in this research domain. Professor Jim published the greatest number of authored publications, while Professor Rowe had both the longest and the earliest history of publications. Four authors, Professors Irga, Torpy, Garg, and Mei, published the most recent volume of articles. The chronology of published investigations in the field (Figure 2) earmarks professor Rowe as an early adopter, immersing himself into this research domain as early as 2005, with particular emphasis on green roofs. Nevertheless, the scholarly interest and academic endeavors revolving around skyrise greenery and ecosystem services witnessed a considerable surge post-2015, indicating an emergent trend in applying skyrise greenery across expansive urban terrains.

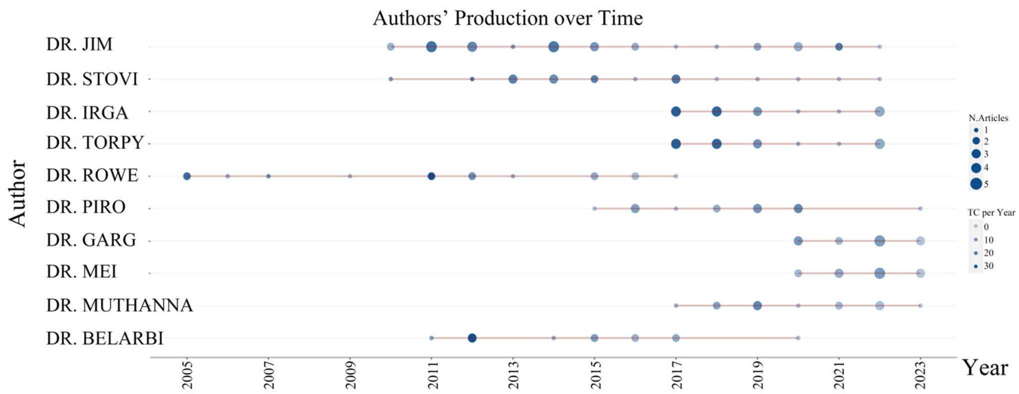

Figure 2. The top authors and the years identified for publication.

Moreover, the "Bibliometrix" R package was further employed to assess the influence of an author's scholarly achievement. Table 1 presents the fractionalization indices surpassing the threshold of 0.5. According to FF indices, Fraser Torpy and Irga Peter belong to the most productive and influential authors, with a notable score of 1.714, followed by Chi Yung Jim at 1.571 and Patrizia Piro at 1.111. It is worth noting that topics such as urban heat island effects and carbon sequestration have emerged as compelling subfields within the domain of skyrise greenery and ecosystem services. For instance, Chi Yung Jim recently expanded his research interests to investigate how green roofs contribute to mitigating urban heat island effects. Furthermore, Fraser Torpy evaluated the potential of skyrise greenery as a means for sequestering carbon dioxide, thereby addressing the increasing concerns about greenhouse gas emissions in urban areas. The shift in the research topics relevant to vertical green systems not only underscore the dynamics of the field, but also signify the potential for future research endeavors [23].

Table 1 presents the most influential authors, main publications, and citation number. The research frontiers include thermal environments, hydrological performance, and air quality. Jim et al. [24] explored the physical attributes, biological mechanisms, and thermal insulation properties of dense green roofs, facilitating the optimization of both the design and thermal efficiency of these green structures. Conversely, Irga et al. [25] embarked on an assessment of particle removal via plant biofilters, and reported that the best filtration efficacy for suspended particulate matter (PM) was observed to be at an airflow rate of 11.25 L/s^{-1} per 0.25 m^2 modular unit. Venturing into the domain of active green wall systems, Torpy et al. [26] scrutinized their capacity to attenuate carbon dioxide in controlled chambers and test cells. Their findings indicated the robust potential of operational active green walls for mitigating carbon monoxide. Meanwhile, an empirical evaluation of rainfall and runoff metrics from the UK Green Roof Test Bed revealed, as per Stovin et al. [27], the implemented roof system achieved a retention rate of 30% of the annual cumulative rainfall. Furthermore, during significant meteorological events, volume retention reached up to 50.2%.

Table 1. Author production and influence.

Source	Articles Fractionalized	Authors' Local Impact (m_Index)	Number of Publications	Citation Frequency	Title of the Most Cited Paper
Jim et al. [24]	17.87	1.571	32	110	Biophysical properties and thermal performance of an intensive green roof.
Stovin et al. [27]	6.57	1.071	19	330	The hydrological performance of a green roof test bed under UK climatic conditions.
Irga et al. [25]	4.38	1.714	17	69	An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system.
Rowe et al. [28]	5.7	0.632	15	388	Green roofs as a means of pollution abatement.
Torpy et al. [26]	4.38	1.714	17	54	Green wall technology for the phytoremediation of indoor air: a system for the reduction in high CO_2 concentrations.
Lundholm et al. [29]	3.41	0.588	12	217	Plant species and functional group combinations affect green roof ecosystem functions.

Table 1. *Cont.*

Source	Articles Fractionalized	Authors' Local Impact (m_Index)	Number of Publications	Citation Frequency	Title of the Most Cited Paper
Piro et al. [30]	3.34	1.111	14	19	Energy and hydraulic performance of a vegetated roof in a sub-Mediterranean climate.
Farrell et al. [31]	2.71	0.818	12	86	High water users can be drought tolerant: using physiological traits for green roof plant selection.
Ma et al. [32]	2.46	1.5	13	34	Experimental and numerical investigations on runoff reduction in and water stress of green roofs with varying soil depths and saturated water contents in dry–wet cycles.

3.2. Pertinent Countries and Their Collaborative Network Dynamics

Furthermore, rapid urbanization and global warming bolstered intra-national, regional, and cross-national collaborations to address skyrise greenery and ecosystem services. The dissection of countries or organizations reveals that China is the principal contributor to this research frontier, with an impressive count of 852 published manuscripts, followed by the USA, Italy, Australia, and Canada, with the publication numbers of 570, 205, 168, and 143 articles, respectively (Figure 3). Of the countries with the highest manuscript production, 80% of publications are identified as being from developed countries. This finding underscores the continued dominance of developed nations in spearheading research initiatives, such as China, India, and Iran.

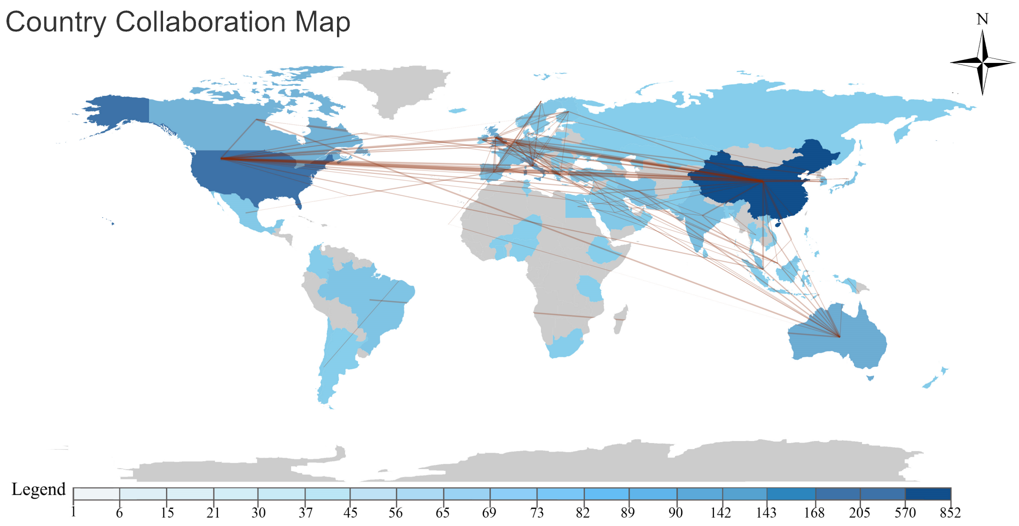

Figure 3. Map of international cooperation among countries. Greater manuscript counts correspond to darker hues; lines connote collaborative relationships between authors from distinct nations.

Figure 3 illustrates the international collaborative efforts of skyrise greenery research. China's collaborative ties extend most broadly, fostering collaborations with researchers from developing nations and amplifying their research contributions within this field. This observation underscores the pivotal role of international collaborations in augmenting research capacities and enhancing the quality of research derived from developing countries (Figure 3). Data on international collaborations stipulate a correlation between the research frontiers and the national policy framework. Since the advent of the reform and opening up, especially in the late 1990s, urban greenery endeavors in China have reaped significant dividends [33]. Within Asia, China pioneers the urban greenery research, particularly in the realm of green infrastructure [9]. Moreover, the exacerbated effects of urban climate fluctuations and rapid urbanization in developed nations may promote investments into urban greenery research as a mechanism to navigate these pressing challenges [23].

3.3. Delving into Dominant Research Themes

The directional comprehension of the evolution of skyrise greenery and its consequential effects on ecosystem services can be attained via an elementary bibliometric analysis. Nevertheless, a network structure evaluation can provide a more comprehensive understanding of the central research motifs and emergent tendencies in this research field. Employing the function of Bibliometrix R package for network structure analysis, word cloud visualizations and author keyword lists were generated, as illustrated in Figures 4 and 5. By harmonizing the author keyword cloud depiction with the author keyword inventory, it is possible to discern the conspicuous research motifs within this realm. The keyword "performance", recurring 408 times, was on the top list of skyrise greenery research. Most investigations revolve around the regulatory operations of ecosystem services, as exemplified by high-frequency keywords, such as "runoff" (203 instances), "temperature" (201 instances), and "quality" (153 instances).

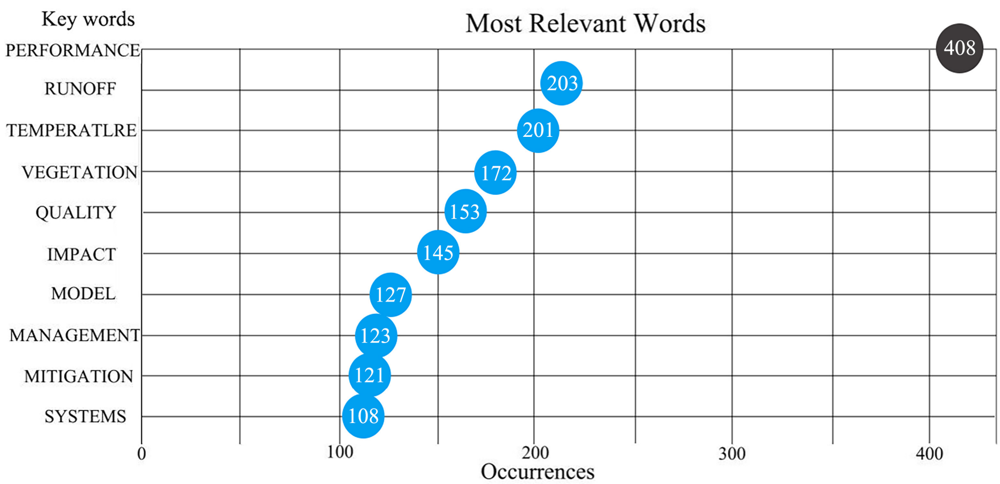

Figure 4. The list of the most relevant keyword.

Figure 5. Word clouds of the topics identified from the titles, abstracts, and keywords of skyrise greenery-related literature retrieved from Scopus for different periods between 2000 and 2022.

Keyword extraction and classification can unveil the research frontiers, dynamics, and tendencies in skyrise greenery research. Upon homogenizing several synonymous keywords, the "Co-Occurrence View of Keywords" attribute of CiteSpace 6.2 R4 was employed to analyze aggregating circumstances in skyrise greenery research. In the "Co-Occurrence View of Keywords" generated by CiteSpace 6.2 R4, nodes symbolize harvested keywords, and the size of the node typeface denotes their frequency. Lines interconnecting two keywords represent a co-occurrence, and the line thickness reflects the intensity of co-occurrence, while the line color denotes the inaugural co-occurrence instance of the keywords. Figure 6 presents the literature co-citation network associated with skyrise greenery. A total of 19 keywords are identified as high-frequency terms, such as green roofs, green buildings, facades, green walls, temperature, thermal performance, runoff, and quality, suggesting their close interrelation and consolidated research field. Figure 7 illustrates the time-series distribution of research hotspots. The cluster labels were automatically assigned, facilitating the genesis of 16 keyword clusters by CiteSpace 6.2 R4. The historical span of keywords exhibits the distribution of the initial occurrence and co-occurrences of keywords within a cluster and among clusters. Nodes denote keywords, while lines interlinking keywords symbolize a mutualistic relationship.

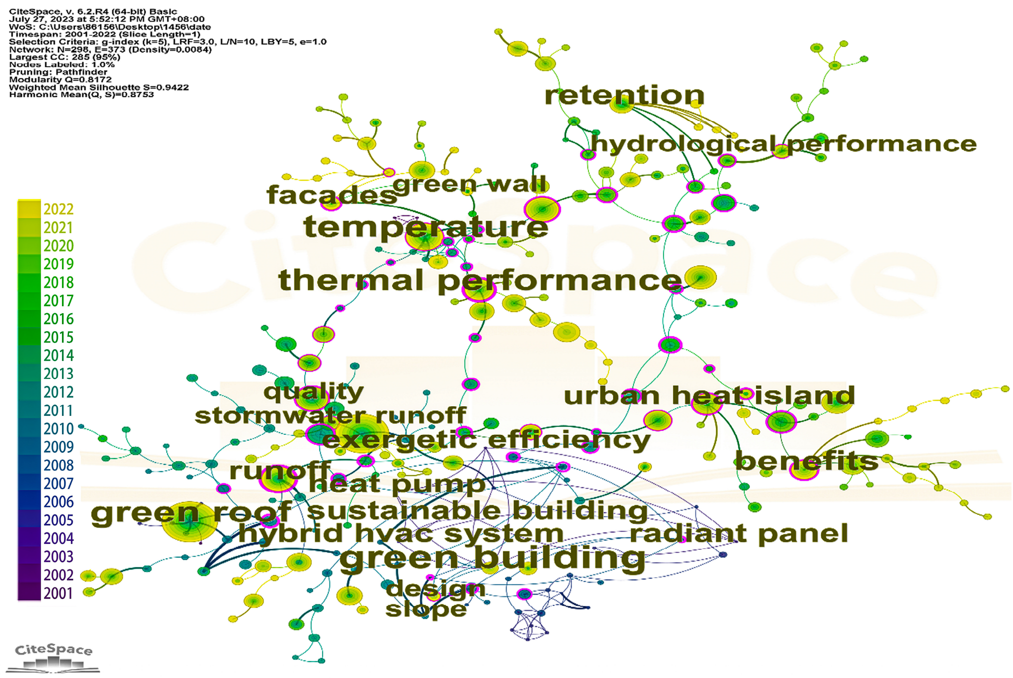

Figure 6. Literature co-citation network associated with skyrise greenery.

In light of climatic perturbations and urban ecological degradation, the paradigm of skyscraper greening anchored in the broader framework of urban green infrastructure has emerged as a focal point of contemporary environmental discourse [34]. The interpretative findings derived from an investigation utilizing Bibliometrix's keyword cloud, word frequency enumeration, and "Co-Occurrence View of Keywords" through CiteSpace indicate the cardinal points of research interest. The primary green infrastructure is identified as green walls and green roofs, with a subsidiary emphasis on green facades and green buildings. Beyond the exploration of skyrise greenery, the research spectrum extends to assess hydrological performance, air quality, thermal performance, and biodiversity. Furthermore, the crux of the research content is largely dependent on parameters such as stormwater runoff, ambient temperature, plant selection, choice of construction materials, and the urban heat island phenomenon.

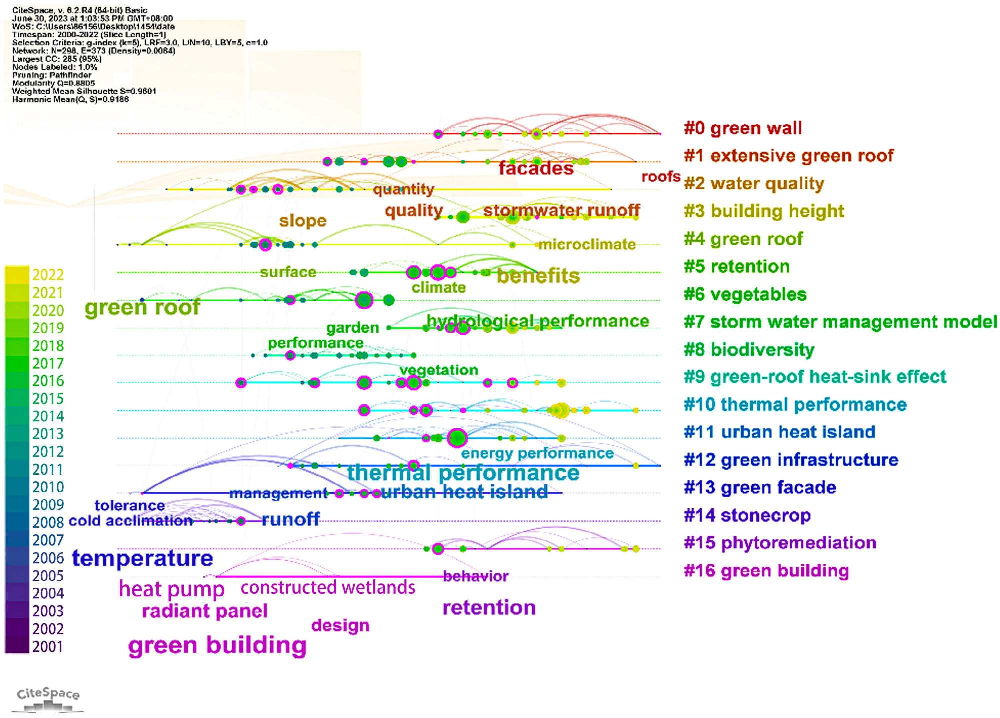

Figure 7. Time-series distribution of research hotspots.

4. Research on the Regulation of Urban Ecosystem Services by Skyrise Greenery

4.1. Thermal Environment

As urban green infrastructures facilitate the mitigation of the urban heat island effect, vertical greenery and green roofs have attracted increasing attention. As illustrated in Figure 8, a stringent screening of the literature yielded 1242 articles with the subject of the thermal performance of skyrise greenery. The highest number of publications was derived from China (723), followed by the USA (385), Italy (230), Australia (147), and the United Kingdom (97).

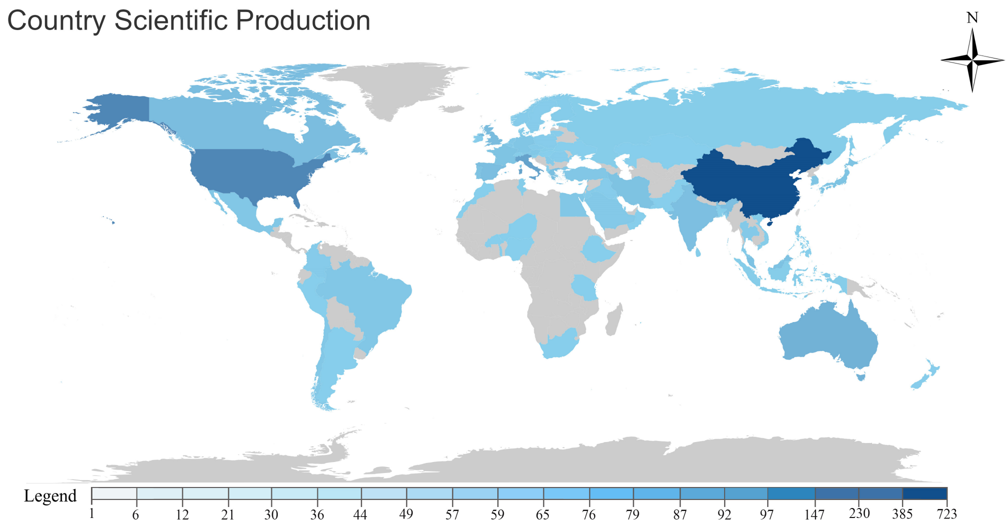

Figure 8. Geographical distribution of publications relative to the thermal environment in vertical green systems between 2000 and 2022.

Figure 9 delineates the co-occurrence network of keywords associated with thermal environment in skyrise greenery research. The most frequently cited keywords are "green roof" and "green building". Other keywords related to thermal environments with a high frequency were "heat island effect", "urban heat island", "temperature", "climate", and "energy saving". Figure 10 depicts the co-occurrence clusters of these keywords. This wide-ranging set of keywords serves as a valuable resource for exploring research trends within this domain. In addition, some keywords, along with their respective clusters, such as "vertical greening system", "green roof", "urban heat island", "thermal comfort", and "performance analysis", imply the research frontiers of vertical green systems.

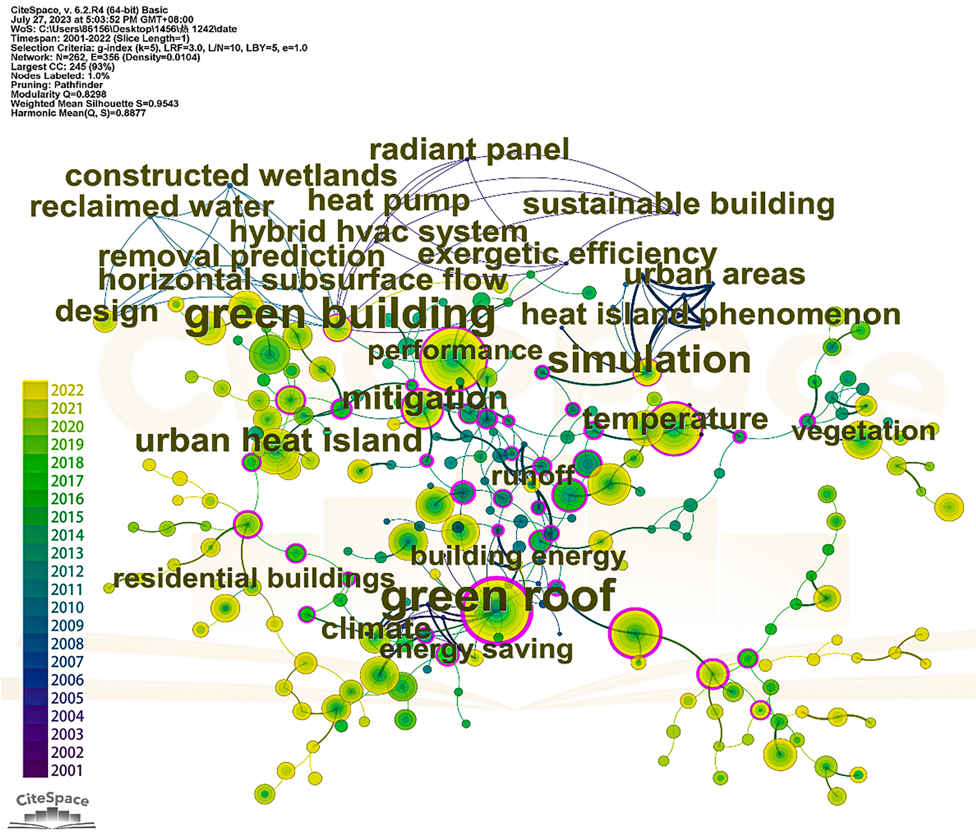

Figure 9. Literature co-citation network of thermal environments in the research domain of vertical green systems.

To identify the most influential research theme in each cluster, pivotal articles with significant citation counts were selected and analyzed, as delineated in Table 2. This methodology facilitates a holistic overview of the predominant research motifs inherent to each cluster. For instance, in Cluster 0, Klein and Coffman [35] assessed the effectiveness of green roofs in ameliorating the thermal milieu harnessing various metrics, such as radiation balance, air temperature, relative humidity, and buoyancy fluxes from dual meteorological stations. Conversely, in Cluster 9, Zhen and Zou [36] evaluated both the direct and indirect thermal effects of plants on building facades, utilizing in situ temperature and humidity measurements with theoretical explorations. In these clusters, the environmental and ecological benefits associated with thermal performance (e.g., shading, evapotranspiration, and insulation) were achieved mainly through green roofs and vertical greening, respectively. The investigation of keyword frequencies can facilitate academics in pinpointing paramount research epicenters relevant to thermal performance. Particularly, two primarily research topics were emphasized in the literature spanning 2000 to 2022 on the thermal environment, i.e., the merits of skyrise greenery and the crucial determining factors affecting modulating efficacy. A succinct description of these research nexuses is carried out in subsequent sections.

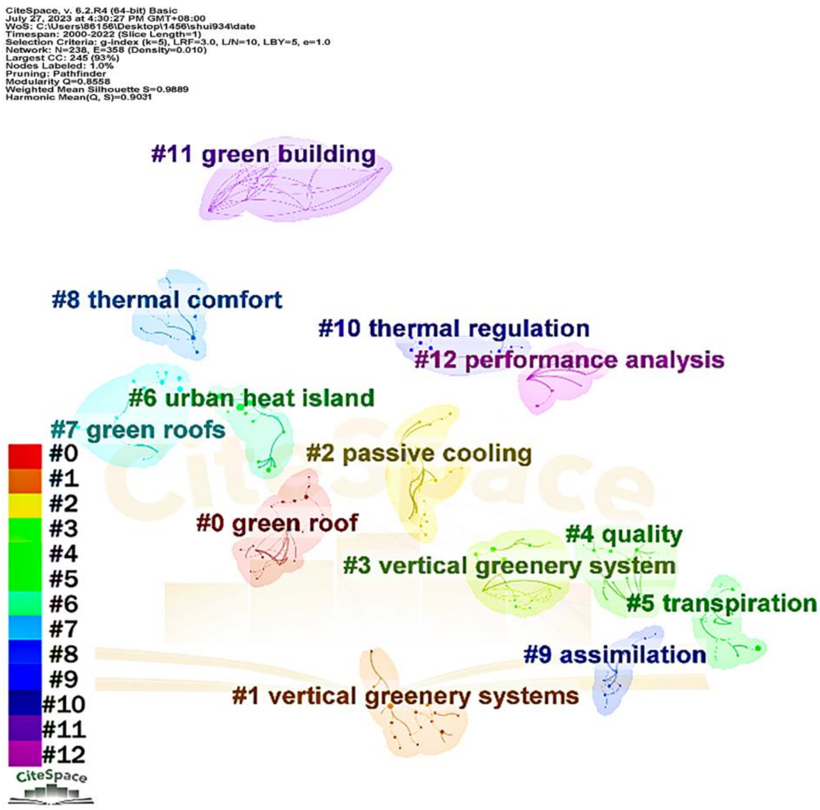

Figure 10. Cluster of keywords related to the thermal environment.

Table 2. Adaptation to the hot environment of skyscraper greening (Note: Selected articles in this table).

Source	Country	Research Content	Research Conclusion	Cluster
Klein and Coffman [35]	U.S.A	Radiation balance, air temperature, relative humidity, and buoyancy flux of the green roof were monitored at two weather stations.	The albedo of the green roof was still about twice as high as that of the dark roof surface, and the albedo of gray concrete roof tiles was significantly lower than that often used to simulate the effect of a cold roof.	#0 Heat Flux
Saadatian et al. [37]	Malaysia	An overview of the application of green roof strategies.	Discusses various types of green roofs, components of green roofs, economic revenues, and technical attributes, and synthesizes the advantages and disadvantages of green roofs in terms of energy use.	#3 Vegetation Envelope
Marçal et al. [38]	Brazil	Thermal sensory perceptions of users of two public squares in the semi-arid region of Paraíba, northeastern Brazil, were observed.	The strong correlation between thermal sensations and measured discomfort indices emphasizes the importance of open spaces, with trees as the most effective way to mitigate heat in urban areas.	#8 Indoor Thermal Environment
Zhen and Zou [36]	China	The direct and indirect thermal benefits of growing creepers on buildings in four life stages were evaluated.	Gradually decreasing as the life stage progresses, the cooling gain in the green phase is up to 8 °C and the insulation benefit in the wilting phase is still about 1 °C compared to a concrete wall.	#9 Thermal Performance Measurement

4.1.1. Green Roofs and Green Walls: Promising Tools for Urban Heat Management

The substantial benefits of green infrastructure for mitigating the urban heat island effect have been documented by numerous studies [23]. The thermal benefits of skyrise greenery for buildings include shading, evapotranspiration, and insulation.

In general, skyrise greenery can modulate urban climates through increasing shading in urban areas, absorbing solar radiation, and alleviating the increasing heat stress. The natural cooling effect of plant evapotranspiration is an effective way to mitigate the urban heat island effect. Mayrand et al. [39] indicated that, during summer, the average surface temperature of a green roof (without any insulation material) in southern Italy was around 12 °C lower than a conventional roof. Even in the winter, the temperature difference between traditional roofs and green roofs was considerable, nearing 4 °C. Particularly, when green walls and green roofs are combined, the temperature reduction is much more predominant, and the vegetation on green roofs and living walls exert a more significant impact on the surface of the structure [6]. In addition to reducing the temperature of the roof surface, previous researchers have also studied potential shading and solar radiation absorption using greenery systems. Feng et al. [40] revealed that the thermal losses by roofs in the summer and winter were reduced by approximately 70–90% and 10–30%, respectively. Studies by Mazzali et al. [41] and Vox et al. [42] suggested that, over a 95-month observation period, a green roof can reduce heat gain and loss by 26% and 22%, respectively. Fioretti et al. [43] demonstrated that plant leaves insulated against solar radiation and created moist airflows in the surrounding environment, thereby reducing the temperature of the building surface.

Furthermore, in addition to enhancing outdoor thermal condition, previous studies revealed that green roofs and green walls can facilitate to reduce the energy consumption associated with building heating and cooling [44]. In Xiangtan, China, Yang et al. [45] evaluated the impacts of vertical greenery and green roofs on the working temperature inside air-conditioned rooms. The results showed that the working temperature of rooms with vertical greenery systems and green roofs was lower than that of rooms without these systems. The indoor working temperature was dropped by an average of 0.4 °C, with the maximum reduction reaching 2.1 °C when vertical greenery systems and green roofs were used [46]. In summary, from a thermal perspective, green roofs and green walls not only create more "humane" outdoor conditions, but also benefit indoor thermal conditions.

4.1.2. Optimizing the Cooling Capacity of Green Roofs: The Influence of Substrate and Plant Choice

Addressing the response to climate change within urban landscapes necessitates the strategic deployment of green roofs and walls, integrating green infrastructure and nature-centric resolutions [47]. However, the variances in the thermodynamic behaviors of vertical greenery systems are multifactorial and contingent on elements such as botanical attributes, substrate composition, and architectural envelopes.

Specific plant taxa incorporated into green roofs and walls exert a profound influence on the surface temperature of the respective structures. In a study conducted by Sternberg et al. [48], the surface temperature of plant-covered structures was reduced by 16 °C compared to their plant-deficient counterparts, with *Sedum* spp. contributing to a decrease of 13 °C. Moreover, abundant plant canopy coverage offers expansive shaded regions, enhancing foliar density to bolster cooling capacity. In general, plant species characterized by voluminous canopies are commonly selected in vertical green systems, as evidenced by a high leaf area index (LAI) [46]. As such, plant species featuring a dense leaf structure and extensive canopy coverage can significantly augment the thermal insulation efficacy of buildings.

Furthermore, the insulation characteristics of buildings may be significantly impacted by the thickness of the substrate utilized in green roofs and walls. Permpituck and Namprakai [49] revealed that green roofs with thicknesses of 59 cm and 96 cm reduced heat transfer by 31% and 37%, in addition to lowering energy consumption by 10% and 20%, respectively. Paulo Cesar Tabares-Velasco [50] revealed that substrate moisture content was the most important determinant of evapotranspiration rates and that the average heat flux of the green roof with plants was reduced by 25% compared to unplanted roofs, thus highlighting the pivotal role of substrate water content and thickness in building cooling. Perez et al. [51] revealed the vertical greenery system in Tokyo could lower wall surface temperature by 5 °C to 8 °C. Moreover, the hydric content of soil within the substrate also plays a crucial role, reducing the ambient temperature via the mechanism of evapotranspiration. Variations in soil hydric content between 30% and 60% alleviated heat storage by 24% [52].

The architectural envelope, a delineating barrier segregating the interior and exterior of a building, plays a vital role in energy saving. Comprising a multitude of functional components in a top-down arrangement, green roofs may consist of vegetation (e.g., landscaping materials), a growing medium (e.g., substrate and soil), drainage materials (e.g., moisture retention), root barriers, waterproof membranes, and insulation layers [53]. By contrast, green walls frequently employ climbing plants anchored directly to the wall (e.g., utilizing aerial roots, leaf tendrils, and adhesive pads) or species with indirect support structures (e.g., metal wires, nets, and trellises) [42]. Owing to their stratified composition, green roofs and walls can efficiently augment the insulative properties of the architectural envelope.

Furthermore, the amalgamation of architectural design with green infrastructure appears to be an effective strategy for mitigating the challenges posed by urban heat islands and climate change. The implementation of such strategies not only enhances the energy performance of buildings, but also contributes to sustainable urban development through enriching urban biodiversity. However, to optimize the application of vertical greenery systems, comprehensive studies are required to identify the most effective combinations of plant species and substrates, tailored to specific local climates and building characteristics. Future research should focus on optimizing these parameters to maximize the cooling effect and reduce energy consumption, contributing to urban sustainability in line with the objectives of the United Nations Sustainable Development Goals.

4.2. Urban Hydrological Environment

The inherent urban characteristics, marked by impervious surfaces combined with increasing anthropogenic activities, impose a significant adverse effect on urban hydrological administration. This impediment often hampers the large-scale incorporation of green infrastructure for effective stormwater regulation [54]. The interplay between green infrastructure and the hydrological environment has attracted increasing interest from academics and global policy designers. In the context of low-impact urban development, green roofs and walls serve as essential tools, providing sustainable, nature-aligned strategies for alleviating urban stormwater vulnerability. Through a precise screening process, the bibliometric analysis indicated an aggregation of 934 scholarly articles subject to hydrological research. As delineated in Figure 11, the preponderance of publication contributions originates from China (519), followed by the United States (438), Australia (122), Italy (110), the United Kingdom (103), and Canada (99).

A vivid representation of the co-occurrence network related to horological key terms is illustrated in Figure 12. Keywords such as “management”, “performance”, “runoff”, “rainwater runoff”, “water quantity”, “water quality” and “hydrology” appear to be frequently used in hydrological research. Figure 13 outlines the clustering patterns of these shared keywords, such as, “water quality”, “hydrological performance”, and “rain and flood management”. The frequency and clustering patterns of these keywords offer a discerning insight into the frontiers and advancement of this research sphere.

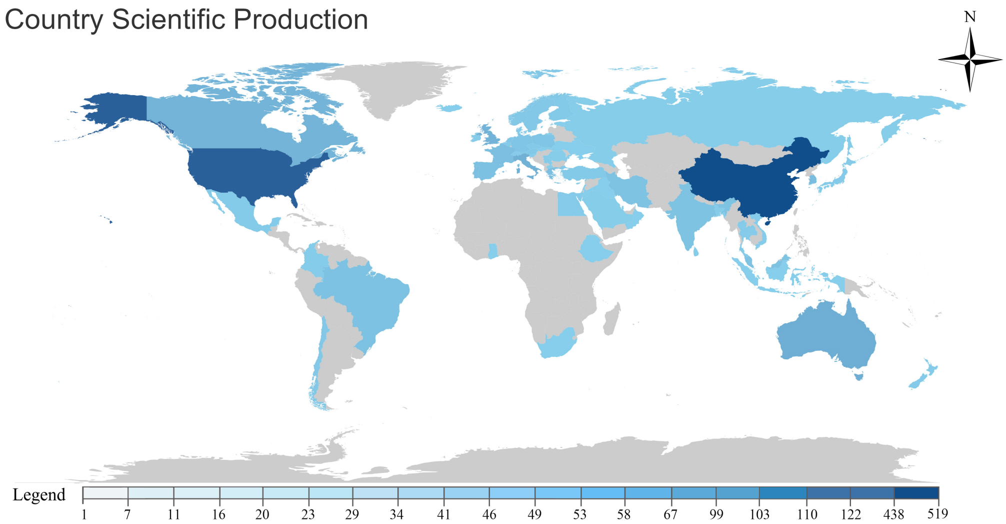

Figure 11. Country production of research sources on skyrise greenery, water environment regulating services published between 2000 and 2022.

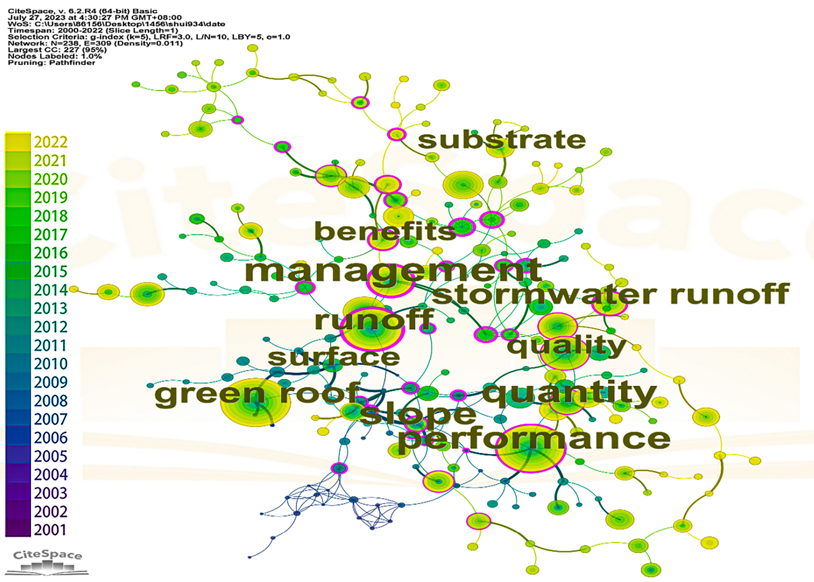

Figure 12. Literature co-citation network of skyrise greenery research relative to stormwater management coupled with ecological regulating services.

Table 3 presents frequently cited articles related to stormwater management in skyscraper greenery research. In cluster 1, titled "Pollution Abatement", Stovin and Peng [55] employed the SWMM Green Roof module to simulate observed runoff from an expansive green roof, and evaluated the hydrological performance of green roofs via calibrated soil parameters. Pęczkowski et al. [56] investigated the stormwater runoff vulnerability and water quality associated with green roof systems in Lower Silesia, and implied the nuanced variability in runoff retention and its subsequent delays, which was not only dependent upon the surface typology, but also significantly influenced by substrate moisture content and precipitation intensity. Notably, although the preponderance of scholarly endeavors gravitates toward viewing green roofs as quintessential instruments for stormwater modulation, the rainwater retention capacities of green walls are still comparatively underexamined. An analytical dissection of hydrological studies spanning from 2000 to 2022 can be classified into two paramount categories: (1) the instrumental role of green infrastructure in regulating runoff dynamics; and (2) its consequential reverberations on water quality. An incisive exposition of these pivotal themes is proffered in the ensuing sections.

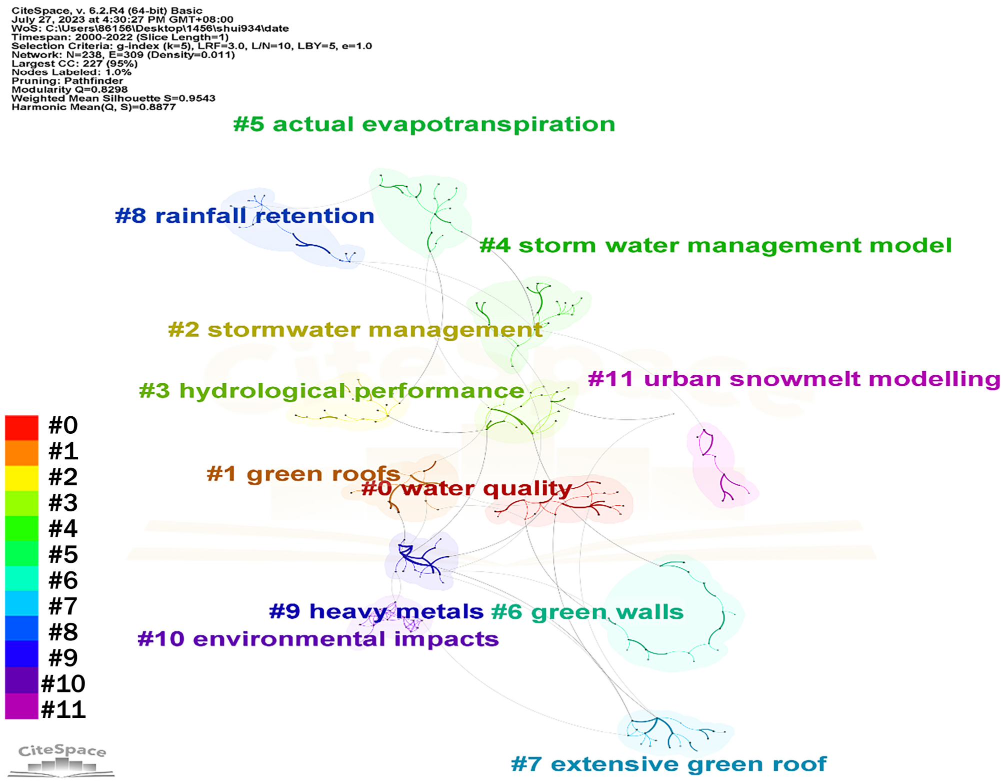

Figure 13. Cluster of keywords related to stormwater management.

Table 3. The frequently cited articles related to the skyscraper green water environment.

Source	Country	Research Content	Research Conclusion	Cluster
Peng and Stovin [55]	UK	Study to validate the ability of the stormwater management model (SWMM) module to represent the hydrologic performance of large green roofs in response to actual rainfall events.	The results from the green roof test bed and the SWMM green roof module were compared to demonstrate that the model can represent the hydrology of green roof runoff after calibration.	#1 Pollution Abatement
Szota et al. [57]	Australia	Simulated rainfall experiments were conducted on the green roof module to compare the rainfall retention capacity of vegetated and non-vegetated substrates with different WHCs and PAWs, and in relation to substrate storage capacity.	the PAW of the substrate is a better indicator of vaporization and retention than WHC.	#2 Water Supply
Pęczkowski et al. [56]	Slovakia	Study of runoff and water quality from the lower Silesian green roof system in the area of the Wroclaw–Slojec agricultural and hydrometeorological station for the period from 2012 to 2016.	The maximum retention performance index calculated for the experimental green surface was as high as 65% relative to rainfall and 49% relative to the control surface (substrate vs. perlite).	#4 Water Retention
Stovin et al. [27]	UK	Study investigates the hydrological performance of a full-size, large-area green roof in Leeds, UK.	Green roofs are effective in retaining rainfall from the precipitation events analyzed.	#3 Hydrologic Performance

4.2.1. Vertical Greenery: An Emerging Approach for Mitigating Rainwater Runoff

With respect to the low-impact development (LID) approach, the efficacy of runoff reductions through vegetated rooftops was reported to be in the range of 33%–81% across varied precipitation events [58]. Within the climatic particularities of Connecticut's (USA) humid continental milieu, extensive green roof incorporation yields an average precipitation retention of 34%, spanning both regular and isolated meteorological perturbations [59]. Palla et al. [60] provided an empirical affirmation of vegetative rooftops' pivotal role in moderating runoff inception in the University of Genoa (Italy), with a median volume retention and peak attenuation of 94% and 98%, respectively. Notably, previous studies indicated that an average delay of 17.9 min associated with stormwater runoff could be achieved through green roof establishment [61,62].

Nevertheless, although vertical greenery systems can be considered as promising and sustainable strategies for stormwater management, the existing research has predominantly focused on l LID strategies, such as green roofs, bio-retention ponds, rain gardens, and vegetated swales [63], overlooking vertical greenery as a viable low-impact development solution. Despite the predominance of surface areas of green walls over rooftops in urban landscapes, research exploring the potential of vertical greenery in rainwater management remains disappointingly sparse [64]. As urban areas continue to grow and the scramble for limited horizontal surface areas escalates [65], the potential of vertical surfaces for mitigating rainwater runoff and promoting evaporation has become ever more significant [1]. As such, scholarly community would benefit from future research on enhancing stormwater management capabilities through green walls coupled with green roofs to maximize rainfall retention and water-quality enhancement.

4.2.2. Green Roofs and Walls: Nature's Solution for Urban Water Pollution Control

The fast urbanization progress coupled with consequent anthropogenic activities tends to increase the types and concentrations of various contaminants in stormwater runoff [66]. Addressing this concern, a vertical green system is an important component of sustainable stormwater management. Particularly, flora and the associated root matrix contained in vertical green walls and green roofs may function as biofilters, enabling the adsorption, sedimentation, and filtration of both organic and inorganic contaminants. Particularly, the "rhizosphere effect", which refers to biochemical and physical changes that occur in soils around plant roots, can significantly affect microbial community composting and structure, as well as element cycling via plant secretions and the microenvironment [67]. As such, the rhizosphere effect is extremely important for regulating nutrient (N and P) cycling in stormwater runoff.

Liu et al. [68] evaluated the efficacy of rainwater biofilters through a green roof installation in the elimination of TSS, nitrogen, and phosphorous in Melbourne, Australia, and reported that the practices reduced TN, TP, and TSS by 0.30 to 34.20%, 0.27 to 47.41%, and by 0.33 to 53.59%, respectively, highlighting the integral contribution of vegetation to contaminant removal in biofilter-mediated systems. Correspondingly, Barron et al. [69] examined the performance of contaminant removal under a bi-modal rainwater–graywater biofilter scheme with varying operational modes in a distinct Australian trial, and revealed a remarkable attenuation of TSS (>83%) and BOD5 (>86%), along with certain heavy metals (e.g., lead > 96%). Nevertheless, if the contaminant concentration in rainwater is significantly lower than that in the green roof substrate, pollutants are likely to be discharged into the effluent.

The intricate structural composition of green roofs, synergized with the metabolic functions of resident flora and soil microbiota, plays a pivotal role in attenuating pollutants from stormwater runoff. Monterusso et al. [70] reported that phosphorous efflux from a prototypical green roof at Michigan State University was closely associated with specific vegetation systems, and the highest concentrations were associated with Crassulaceae plants (stone bamboo family). Harper et al. [71] revealed substantial reductions in both phosphate and nitrate during the nascent operational phase of a green roof system, with observed decreases in phosphate and nitrate loads by 5 mg L^{-1} and 10 mg L^{-1}, respectively. In addition, although a vertical green system can potentially enhance the quality of urban runoff, soil constituents and fertilizers have emerged as paramount determinants influencing nutrient concentrations in leachate from green roofs. The exogenous introduction of fertilizers may inadvertently exacerbate the prevalence of elements such as nitrogen and phosphorus in stormwater runoff. As such, the lack of consistency of previous research on the assessment of the environmental impact of leachate from green roofs on receiving waters has generated unfavorable views on the use of these systems. Thus, topics, such as the (lack of) consideration of the use of fertilizers in the research on green roofs, have resulted in ambiguous conclusions and misinterpretations that compromise the future use of green roofs.

4.3. The Role of Vertical Green Systems in Enhancing Air Quality

The quality of ambient air is a paramount concern for human health, as it bears a profound correlation with various respiratory diseases [26]. The investigation on the influence of terrestrial green infrastructure on air quality has been quite thorough; however, scholarly examinations of the impact of vertical greenery on air quality are rather limited. Terrestrial green spaces and vertical greenery manifest distinct aerodynamic conditions, soil milieu, and background pollutant concentrations, exerting disparate effects on air quality [72]. In relation to water and thermal environment regulatory services, a relatively meagre number of studies addressing the role of vertical greenery in air-quality control have been sourced from the literature. Most articles on this subject originate from the United States (131 papers), China (116 papers), Australia (59 papers), Iran (28 papers), and Germany (24 papers) (Figure 14).

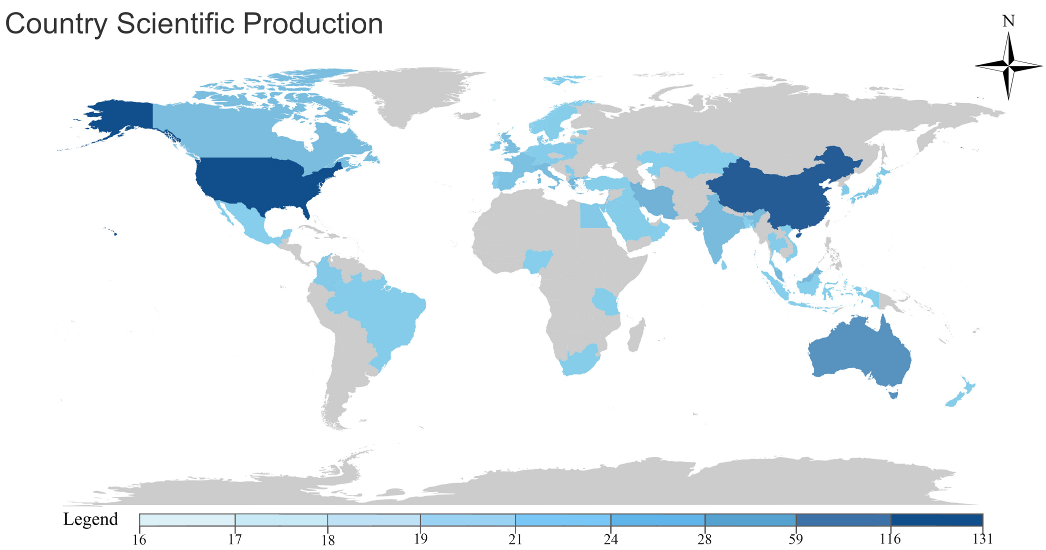

Figure 14. Country production rate of research sources on skyrise greenery air-quality-regulating services published between 2000 and 2022.

The articles focusing on the intersection of vertical greenery and air quality were subjected to a keyword analysis, categorized using CiteSpace 6.2 R4 software (Figure 15). "Indoor air quality", "air quality", and "air pollution" were observed as the high-frequency keywords. The analysis indicated the top-three themes in this research domain: (1) vegetation filters; (2) urban vegetation; and (3) particulate matter. This finding indicates the research prominence of the function of vegetation in mitigating air pollution particulates (Figure 16). Both vertical urban greenery and terrestrial green vegetation can function as natural filters, removing particulate pollutants from the atmosphere.

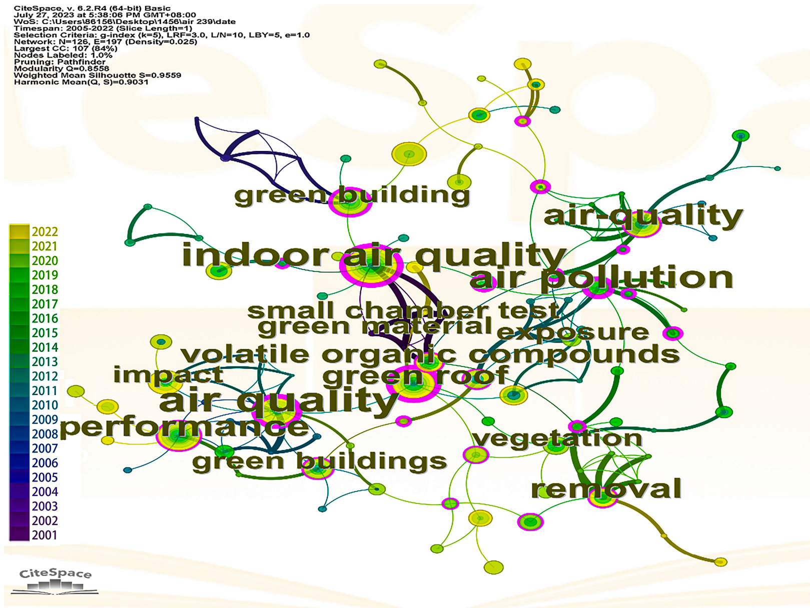

Figure 15. Literature co-citation network of skyrise greenery research focusing on air-quality-regulating services.

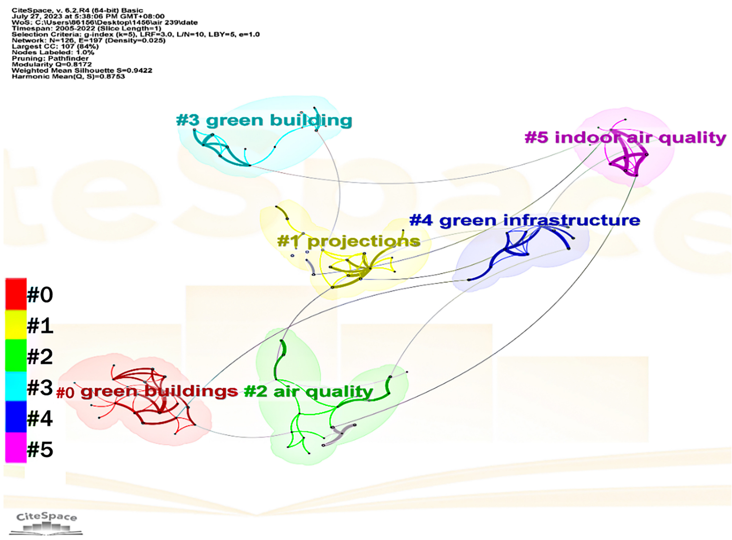

Figure 16. Clustering of keywords related to air quality.

Table 4 presents the most frequently cited articles related to skyscraper greening and air quality. Utilizing vegetation as a natural solution for atmospheric pollutant filtration can not only refine air quality, but also enhance the urban living experience. For instance, as delineated in cluster 5, "Volatile Organic Compounds" (Table 4), planted green systems demonstrate augmented air purification capacities through VOC filtration, PM filtration, and CO_2 reduction, as well as enhanced humidity and temperature [73]. In cluster 6, "Active Green Wall", a meticulous analysis of airflow dynamics within active green wall modules reveals that substrate saturation facilitates a more pronounced airflow through the conventional green wall substrate, resulting in air purification [74]. Contrarily, green roofs exhibit a much more attenuated influence on air-quality enhancement compared to green walls.

Table 4. The most frequently cited articles related to skyscraper greening and air quality.

Source	Country	Research Content	Research Conclusion	Cluster
Allen et al. [73]	USA	Simulated indoor environmental quality (IEQ) conditions in "Green" and "Conventional" buildings and evaluated the impacts on an objective measure of human performance: higher-order cognitive function.	On average, cognitive scores were 61% higher on the green building day and 101% higher on the two Green+ building days than on the conventional building day ($p < 0.0001$). VOC and CO_2 were independently associated with cognitive scores.	#0 Indoor Environment
Pettit et al. [74]	Australia	Assessed the capacity of replicate active green walls to filter NO_2 at both ambient temperatures.	Consider active green walls (i.e., VOC filtration, PM filtration, CO_2 reduction, enhanced humidity and temperature, and biophilic benefits) as phytoremediation agents for a limited number of pollutants.	#5 Volatile Organic Compounds
Abdo et al. [75]	Australia	A detailed assessment of airflow through an active green wall module.	More air will pass through a typical green wall substrate, and hence become cleansed, when the substrate is saturated more than when it is dry.	#6 Active Green Wall
Patton et al. [76]	USA	Evaluated effects of ventilation, occupant behaviors, and overall building design on PM mass concentrations.	The building design and occupant behaviors that either produce or dilute indoor PM are important factors affecting residents' exposure to PM in residential green buildings.	#2 Green Plants

4.3.1. Green Roof and Green Walls Act as Natural Air Filters

It is noteworthy that the vegetation in green roofs play a dual role: direct pollutant attenuation and microclimate moderation. In general, air pollution control in vertical green systems can have both direct and indirect impacts [77]. Direct impacts involve plants consuming or increasing pollutants in the air via absorption, blocking, and discharging them through their structures. Many studies have shown that green roofs can reduce CO, CO_2, SO_2, and NO_2 while increasing the concentrations of volatile organic compounds (VOCs) [28]. Plants assimilate gaseous pollutants through stomatal absorption, a process extensively discussed in the literature [78]. Moreover, the morphology of leaves and their surface roughness plays a vital role in PM accumulation [79]. Weerakkody et al. [80] quantitatively analyzed the PM interception capacity of different tree species, and found substantial variation in PM levels based on species and leaf characteristics. Similarly, Safikhani et al. [81] underscored the significance of plant species selection in urban greening initiatives, according to their air-purifying characteristics. Additionally, the branches of plants can participate in the absorption of gaseous pollutants (e.g., CO_2) via photosynthesis, the cornerstone of a plant's survival and growth. This biochemical process can be viewed as a powerful pollution mitigation strategy harnessed by nature.

Plants serve as intrinsic moderators of microclimates, thereby indirectly mitigating air pollution [82]. The thermoregulatory function of plants in vertical green systems diminish the adverse effects caused by air temperature, potentially curtailing the air conditioning demand, thereby attenuating energy consumption [77]. They mitigate ambient air temperatures and enhance evaporative cooling, decelerating photochemical reactions that compromise air quality [81]. In addition, vertical green systems can indirectly affect ozone levels by emitting VOCs or removing NO_x, which are key precursors of ozone [83].

4.3.2. Optimize Green Roofs and Green Walls to Absorb Pollutants: Plant Selection

The scientific community has increasingly recognized the significance of species selection in the implementation of vertical green systems [84,85]. Dzierżanowski et al. [86] indicated that different plant species exhibit substantial variances in their PM accumulation and filtration abilities. Iligan and Irga [87] further corroborated these findings in a recent study, which underlined the importance of choosing proper tree species to optimize air purification in urban skyrise greenery projects. Similarly, Song et al. [88] provided significant insights into the distribution, morphology, and elemental composition of PM on leaves, and revealed that the regions with the highest density of furrows on leaf surfaces exhibited the highest PM deposition. Likewise, Viecco et al. [79] also reported that leaf surface roughness was a significant determinant of PM accumulation.

4.4. Regulation of Other Ecosystem Services

While the significant impact of skyrise greenery systems on thermal and water environments has been widely recognized, their roles in providing other ecosystem services deserve further attention. Among those functions, the capacity and function of green walls and roofs regarding noise pollution reduction and biodiversity promotion are particularly noticeable, which deserves further exploration. These greenery systems can provide a physical barrier against noise, reducing ambient noise levels in urban environments and affecting the transmission of sound into building interiors [1]. For instance, Van Renterghem et al. [89] reported that tree belts in southeast Nebraska could decrease noise levels in the range of 5–8 decibels (dB), and the noise reduction capability was proportional to the breadth of these tree belts. Jaafar et al. [90] installed eight distinct vertical greenery systems in Singapore's Hort Park to assess their impacts on reducing noise pollution, and revealed a positive correlation between greenery coverage and sound-absorption coefficients. Although these research findings indicate that augmenting greenery coverage can significantly enhance noise mitigation, various factors, such as climate, roof height, vegetation types, soil matrix features, human activity intensity, pollution transport characteristics, and photochemical reaction intensity, may substantially influence air quality [72].

Furthermore, green roofs and green walls can also provide additional habitats for a variety of species, such as insects, birds, and microbes, facilitating the potential for amplifying biodiversity in urban areas that is often overlooked in urban planning [84]. They are effective in transforming otherwise empty vertical and horizontal spaces into viable habitats, thereby contributing to the biodiversity within the confines of urban spaces [39]. Greg et al. [91] found that green roofs in Berlin were hosting several rare and endangered plant species, thus significantly contributing to urban biodiversity conservation. Wooster et al. [92] indicated that green roofs can support a diverse community of invertebrates, birds, and plants, which in turn provide essential ecosystem services, such as pollination and natural pest control.

The integration of green roofs and walls into other green infrastructures, to create ecological corridors within urban areas, has a profound impact on the propagation of biodiversity in cities [93]. Such corridors can significantly increase the range and movement of urban wildlife, thereby enhancing urban biodiversity and promoting a healthier urban ecosystem. A greater appreciation and application of these benefits (i.e., noise pollution reduction and biodiversity promotion) facilitates the enhancement of urban living environments. As urbanization progresses, the importance of these ecosystem services will only increase [94], providing an impetus for future research and the application of greenery systems in urban settings.

5. Future Research Prospects and Conclusions

Existing studies have identified a range of vertical green system services and values. However, there are still several knowledge gaps.

(1) Bibliometric investigations reveal that some knowledge gaps remain in the performance metrics of skyrise greenery under evolving climatic and hydrological paradigms, resulting from fast urbanization processes. Alterations in land utilization and climatic dynamics can pivot urban green space planning. Furthermore, although previous studies indicated that green roofs are an effective means for mitigating the urban heat island effect, the application of model simulation for elucidating the heat

transport mechanisms associated with roof material, plant-growing substrates, vegetation species, and soil microbial community still remains scarce. Moreover, the design of innovative vertical green systems should be tailored on account of individual cooling or insulation performances. In addition, the quantification of energy saving and cost effectiveness should be considered along with their ecological benefits for regulating the thermal environment.

(2) With multiple environmental benefits, vertical greenery has been proved to be a promising approach for stormwater management. However, the lack of consistency on previous research results on the assessment of the environmental impact of leachate from green roofs on receiving waters has generated unfavorable views. As such, themes such as the (lack of) consideration of the use of fertilizers on green roofs and the assessment of the sour-sink effect, may lead to ambiguous conclusions and misinterpretations. Furthermore, designing verdant facades and green roofs necessitates a holistic evaluation of stormwater management functionalities. To maximize the significant role of greenery in reducing stormwater runoff and enhancing water quality, the combination of different components in vertical green systems should be optimized, such as vegetation species, soil substrates, and microbial structure.

(3) In addition to technological perspectives, the conceptualization and formulation of skyrise greenery also mandates a contemplation of the societal, economic, and public health dimensions. Bibliometric outcomes accentuate the imperative for enriched research in this domain. For instance, when subjected to skyrise greenery design, the Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) should be considered for better understanding the holistic economic and ecological footprints of such systems. As such, fiscal interventions or incentives may be a requisite for such implementations. Sociologically, enhancing the perceptions and public participation in relation to skyscraper greening projects are also necessary. Future studies should be conducted based on an interdisciplinary approach, taking social, economic, engineering, and ecological aspects into overall consideration.

(4) Future deliberations should explore the influence of legislative frameworks and governance edifices on the facilitation or impediment of skyrise greenery implementations. This entails the creation of malleable policies and regulations to buttress Green Stormwater Infrastructure (GSI), as well as formulate policy incentives to foster GSI adoption. Using Singapore as a case study, a profound national policy supporting skyrise greenery implementation is conducive to optimizing GSI's holistic dividends.

(5) Skyrise greenery harbors latent potential for urban biodiversity conservation and air pollutant mitigation. Incorporating principles of landscape ecology into skyrise greenery can attenuate air pollution while amplifying urban biodiversity. However, value assessments for vertical green systems often ignore the trade-offs and complementarity between different services. In addition, given the severe impacts of climate change induced by greenhouse emissions, the significant contribution of plants to CO_2 mitigation and sequestration through photosynthesis should be identified in future research.

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