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Review

The Application of Rain Gardens in Urban Environments: A Bibliometric Review

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Abstract: The increasing challenges of urbanization and climate change have driven the need for innovative stormwater management solutions. Rain gardens, as a nature-based solution (NBS), have emerged as a critical component in urban water management, particularly in enhancing hydrological regulation, water quality, and ecosystem services. This bibliometric review examines the application of rain gardens in urban environments, focusing on their roles in stormwater management, pollutant removal, and ecological enhancement. Data from 728 academic papers published between 2000 and 2023 were analyzed using the Web of Science (WoS) Core Collection, employing bibliometric tools such as the "Bibliometrix" R package and CiteSpace. The analysis highlights the increasing global interest in rain gardens, particularly since 2015, with China and the United States leading research efforts. Key findings reveal that rain gardens significantly reduce runoff, improve water quality, and contribute to urban biodiversity. In addition, their integration into public spaces offers landscape esthetics and social benefits, enhancing the quality of life in urban areas. However, challenges remain in optimizing their design for diverse climates and long-term performance. The study underscores the need for further research on plant–soil interactions, pollutant removal mechanisms, and the broader ecological and social contributions of rain gardens. This review provides insights into the evolution of rain garden research and identifies future directions for advancing sustainable urban stormwater management.

Keywords: rain garden; bibliometric analysis; urban hydrology; low-impact development; nature-based solution

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1. Introduction

Global climate change and accelerated urbanization have intensified the challenges associated with urban stormwater management, necessitating the development of adaptive strategies tailored to these evolving conditions. Establishing stormwater management systems that effectively respond to the dual pressures of climate change and urban expansion has emerged as a critical priority in urban planning and environmental protection [1,2]. The adverse effects of urbanization and global warming—such as diminished infiltration rates, decreased groundwater recharge, escalated non-point source pollution, and disrupted hydrological processes—have significantly undermined the resilience of urban ecosystems, thereby posing new challenges to the effectiveness of conventional gray infrastructure [3]. Traditional gray infrastructure, predominantly engineered to mitigate surface flooding and overflow during intense precipitation events, often fails to adapt to the increasing variability and extremity of rainfall patterns driven by global climate change. Consequently, these systems frequently exacerbate flood vulnerability, particularly in densely populated urban areas where the capacity of stormwater infrastructure is insufficient to manage the surge in

runoff volume and intensity [4]. Moreover, such infrastructure typically lacks the capability to address the broader ecological implications of urban flooding and pollution, as its design priorities do not inherently incorporate eco-friendly or sustainable considerations. This limitation underscores the need for integrated, multifunctional stormwater management approaches that can enhance urban resilience by aligning with environmental objectives [5].

To mitigate the challenges posed by climate change and urbanization, numerous countries have adopted nature-based approaches to stormwater management. Notable examples include Sustainable Drainage Systems (SUDS) in the United Kingdom, Low-Impact Development (LID) in the United States, Water-Sensitive Urban Design (WSUD) in Australia, Low-Impact Urban Design and Development (LIUDD) in New Zealand, the Active, Beautiful, Clean (ABC) Watersheds Programme in Singapore, and China's Sponge City Initiative [6]. These nature-based strategies offer a stark contrast to conventional drainage systems, as they facilitate the multifunctional use of urban spaces while promoting sustainable stormwater management practices [7,8]. Among these strategies, rain gardens have emerged as a prominent nature-based solution (NBS) due to their efficacy in stormwater management [9,10].

Rain gardens are particularly effective in reducing surface runoff and mitigating flooding, while simultaneously enhancing water quality through the biofiltration processes facilitated by vegetation and soil. These systems not only attenuate peak flows but also remove pollutants, thereby bolstering the ecological health of urban environments [11,12]. Furthermore, as integral components of urban public open spaces, rain gardens offer additional landscape esthetics and social benefits, contributing to the overall quality of life in high-density urban settings. The integration of these systems within urban infrastructure underscores a shift toward resilient, ecologically harmonious urban planning that aligns with both environmental and community goals.

The study of urban rain gardens has garnered considerable academic attention, particularly in the domains of hydrologic regulation, water quality enhancement, and ecosystem service provision. In response to the burgeoning body of research, several reviews have been published that synthesize the current state of rain garden applications in stormwater management. For instance, Sagrelius et al. [13] assessed the environmental repercussions of design deficiencies within rain garden systems, highlighting the critical importance of optimal design parameters. Shafique et al. [5] underscored the necessity for retrofitting Low-Impact Development (LID) practices in developing urban contexts and provided a global synthesis of the hydrological and water quality performance of rain gardens. Meanwhile, Nasrollahpour et al. [14] examined the role of evapotranspiration in rain garden function, emphasizing key design considerations that influence performance outcomes.

Despite extensive research efforts, there remains a notable deficiency in comprehensive syntheses of the literature concerning urban rain garden applications, along with a scarcity of up-to-date reviews that capture the rapid advancements within this field. As the discipline continues to evolve, there is a critical need for overarching reviews that integrate the latest innovations and methodologies. Traditional literature reviews address this need by adopting a holistic approach that systematically examines the theoretical frameworks, methodologies, and empirical findings of existing studies. In contrast, bibliometric analysis offers a more data-driven and pragmatic alternative, employing statistical algorithms to uncover the intricate interrelationships between scholarly works [15].

Emerging bibliometric tools, such as the open-source "Bibliometrix" R package 4.1.2 and the Java-based knowledge visualization software CiteSpace 6.3 R1, have gained prominence in this analytical context. These tools excel at revealing nuanced research trends and trajectories, making them invaluable for bibliometric and statistical analyses due to their comprehensive capabilities [16,17]. Bibliometrics focuses on the quantitative analysis of knowledge units within a particular field, elucidating the inherent relationships between these units and providing a holistic, data-driven perspective on research dynamics [18]. Bibliometric methodologies typically fall into two main categories: those that treat individual publications as independent statistical entities and those that use the connections

between knowledge units as primary statistical measures through network clustering [19]. The "Bibliometrix" R package, as an emerging open-source tool, is extensively used for bibliometric and statistical analyses owing to its robust features. By analyzing keyword and article networks, this package can identify the most prolific countries, influential authors, and their international collaborations, as well as derive annual publication rates, citation frequencies, and detailed network information from data matrices generated through co-citation, coupling, co-occurrence, and co-word analyses [20,21].

This study presents a comprehensive evaluation of the application of rain gardens in urban contexts, with a specific focus on their multifaceted roles in urban water management, ecological enhancement, and landscape value optimization. By systematically compiling and synthesizing the existing scientific literature, the study aims to advance the understanding of the sustainability and functional dynamics of rain gardens. It delves into the mechanisms by which rain gardens modulate hydrological processes and enhance water quality, while also examining their broader contributions to the urban thermal environment, air quality, and biodiversity. Furthermore, this analysis extends to the exploration of rain gardens as valuable components of urban public open spaces, highlighting their landscape esthetics and social benefits—areas often underrepresented in current research. The study addresses these gaps by integrating insights into the ecological and social dimensions of rain gardens, thereby providing a holistic understanding of their potential as NBS.

2. Materials and Methods

2.1. Data Collection

To elucidate research priorities and identify emerging trends in the field of rain gardens, this review employed the Web of Science (WoS) Core Collection database (SCI-EXPANDED) as the primary repository for English-language scholarly literature. A comprehensive literature search was conducted in July 2024, utilizing the "Topics" (TS) section of the WoS database. The search strategy incorporated a combination of carefully selected keywords and Boolean operators to ensure an extensive and thorough review of relevant publications. The TS searches covered titles, abstracts, author keywords, as well as supplementary indexes and terms associated with each publication, thereby providing a broad yet in-depth overview of the field. The specific search queries were structured as follows: TS = ("rain garden*" OR "rainwater garden*" OR "bioretention" OR "bioinfiltration" OR "biofilter" OR "bioswale") AND TS = (city OR "urban*" OR town) AND TS = (application OR implementation OR use OR performance OR "water management" OR hydrology OR "water quality" OR "*runoff" OR rainfall OR "landscape benefit" OR "landscape value" OR recreation OR leisure OR public) AND TS = ("low impact development" OR "nature-based solution" OR "green stormwater infrastructure" OR "green infrastructure" OR "sponge city" OR "resilient city" OR "water-sensitive urban design" OR "sustainable drainage system" OR "best management practice"). In the Boolean formula, "AND" ensures that all specified keywords appear in the search results, while "OR" retrieves results containing any of the specified keywords, thus broadening the search scope. This approach was used to maximize the comprehensiveness of the search results.

Search results revealed a total of 728 journal articles published between 2000 and 2023, encompassing both research and review articles. This dataset provides a robust foundation for analyzing the evolution of rain garden research, highlighting key developments and the trajectory of academic interest within the domain of sustainable urban stormwater management.

2.2. Bibliometric Methods

In this study, a bibliometric approach was employed to meticulously map the scientific knowledge landscape of rain gardens, offering a comprehensive overview of the field. This approach enabled the identification of performance indicators, evolutionary trends, knowledge linkages, and emerging research frontiers within specific subdomains. The initial analysis was conducted using the "Bibliometrix" R package 4.1.2, followed by a detailed

examination with "CiteSpace" 6.3 R1 to compare various research vectors in the rain garden domain. The methodological steps included (1) importing data into CiteSpace 6.3 R1 and eliminating duplicates; (2) calibrating relevant parameters and conducting a chronological analysis of datasets from 2000 to 2023; and (3) generating detailed visualizations to illustrate current research perspectives, evolutionary trajectories, and prospective research directions. Within CiteSpace, the g-index is utilized to determine the number of nodes—representing articles, authors, or journals—included in a network visualization, contingent upon the analysis type. The scale factor k is a critical parameter in network analysis that influences the selection of nodes by setting a threshold for the g-index. This allows control over the network's density and ensures that only the most influential nodes are included. Following a series of trials, a value of k = 5 was adopted to strike an optimal balance between comprehensiveness and clarity, preventing the network from becoming too dense while still capturing key patterns. This approach has been used in similar studies to optimize the readability of network visualizations [6]. For network optimization, Pathfinder algorithms and pruning of sliced networks were employed. Network decomposition and clustering techniques were used to delineate research frontiers, prioritize keywords, and identify research hotspots and pivotal nodes in the evolution of the field. Co-citation analysis was utilized to pinpoint the core literature, key research areas, and their prevailing trends, thereby highlighting the most impactful contributions to rain garden research. Additionally, the keyword emergence function was applied to identify cutting-edge research themes, facilitating predictions of future research directions [22].

3. Results

3.1. Publication Development Trends

Figure 1 depicts the annual trends in the number of publications and citation frequencies within the analyzed corpus. The review identified a total of 728 articles published across 73 academic journals, with an average citation count of 27.57 per paper. Scholarly contributions on rain gardens were nearly absent until 2004. From 2004 to 2014, academic output remained relatively limited, with fewer than ten publications per year. Since 2015, rain garden research has experienced significant growth, with a notable focus on the integration of nature-based solutions into urban stormwater management strategies. The United States and China have led these efforts, driven by the LID approach and Sponge City initiatives, respectively. This period has seen an increase in the application of hydrological models, such as SWMM, to optimize rain garden design for various urban environments. Furthermore, research has emphasized the role of rain gardens in enhancing urban biodiversity and mitigating urban heat island effects, indicating a shift toward multifunctional green infrastructure solutions. The trajectory of this research is expected to continue upward as cities worldwide face increasing challenges related to climate change and urbanization.

The period from 2019 to 2023 was particularly prolific, accounting for 451 papers, or 61.9% of the total literature analyzed. The year 2023, in particular, witnessed an unprecedented peak in citation frequency, reaching a total of 3349 citations. This escalation in academic output aligns with the increasing global emphasis on addressing extreme weather events and urban flooding, underscoring the critical need for optimized urban stormwater management systems in the face of climate change. The consistent upward trend in research activity highlights the expanding recognition of rain gardens as vital components of sustainable urban infrastructure. Given the ongoing global challenges associated with climate resilience, this trajectory of academic contributions is expected to persist, further advancing the development of innovative solutions in urban stormwater management.

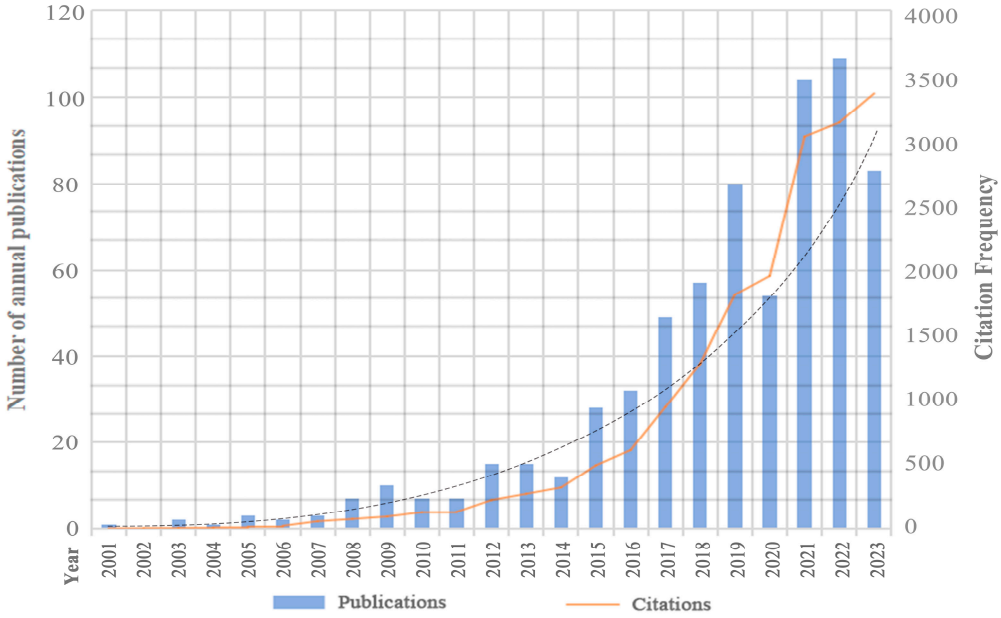


Figure 1. Annual trends in the number of publications (left vertical axis) and frequencies (right vertical axis), with the horizontal axis representing the year and the dashed line indicates the growing trend in the number of citations.

3.2. Author and Country Analysis

An in-depth examination of scholarly publications is essential for identifying pioneering authors within the field of rain garden research. Li Jiake stands out as the most prolific author, while Davis Allen P. holds the distinction of the longest publication history, having contributed to the field since 2008. The chronology of published works in this domain, illustrated in Figure 2, reflects these trends. A notable surge in academic interest and scholarly output related to the application of rain gardens in urban settings has been observed post-2015, suggesting that the deployment of them is gaining traction as a response to the increasing frequency of extreme weather events and the challenges of high-density urban environments.

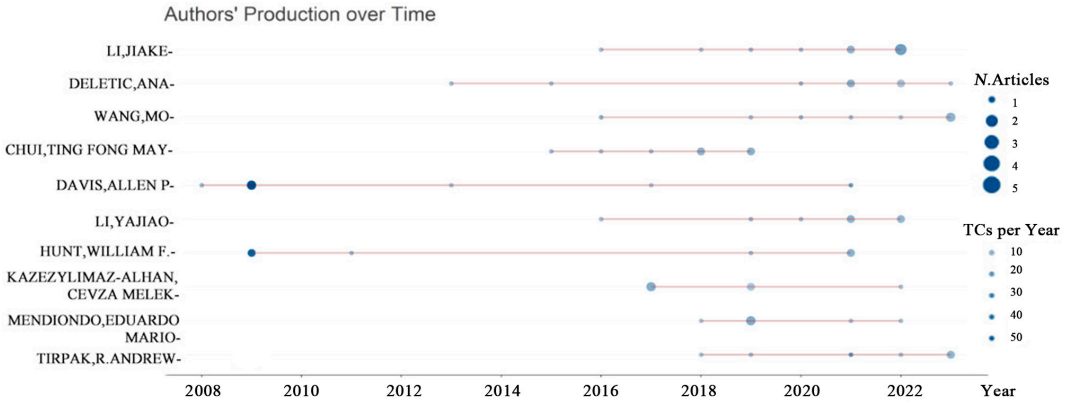


Figure 2. Top authors and their publication years (TCs mean Total citations; "N.Articles" mean "No. of Articles").

Table 1 details the top ten authors identified through author co-citation analysis, providing metrics such as impact index, citation frequency, number of publications, and the year of first publication in this field. Li Jiake from China holds the highest local impact index of 1.111, having published 12 papers that have collectively garnered 198 citations since his initial publication in 2016. Conversely, Davis from the United States leads in

citation frequency, with 1178 citations across seven publications since 2008. This analysis effectively highlights authors who have made substantial contributions to the field, as indicated by the frequency of co-citations of their work.

Table 1. Author production and influence.

Author	Authors' Local Impact (m_Index)	Citation Frequency	Publication Number	Year First Published
LI JIAKE	1.111	198	12	2016
TIRPAK R. ANDREW	0.857	152	6	2018
LI YAJIAO	0.778	151	8	2016
KAZEZYILMAZ-ALHAN CEVZA MELEK	0.625	114	6	2017
CHUI TING FONG MAY	0.600	232	7	2015
WANG MO	0.556	178	8	2016
DELETIC ANA	0.500	144	8	2013
ENGEL BERNARD A.	0.385	920	5	2012
DAVIS ALLEN P.	0.353	1178	7	2008
HUNT WILLIAM F.	0.313	899	6	2009

A detailed review of the literature from these influential authors was conducted. Table 2 presents the most cited articles authored by these key contributors, summarizing their research focus and findings. This analysis aims to delineate the principal themes and research trajectories in the study of rain gardens. By exploring the thematic interconnections among leading researchers, this assessment enhances understanding of the knowledge architecture of the field and identifies emerging research frontiers, including hydrologic regulation, water quality enhancement, and ecological benefits.

Table 2. Primary literature of key authors.

Source	Country	Research Content	Conclusions
Davis et al. [23]	USA	The current status of bioretention technology applications is discussed, and future needs are analyzed.	Bioretention technologies are effective in reducing runoff and improving water quality, but pollutant removal mechanisms need to be improved.
Guo et al. [24]	China	Effect of runoff infiltration on nitrogen and phosphorus contents of rain garden soils and their relationship with enzyme activities.	Runoff infiltration affects the nitrogen and phosphorus content of the soil, which in turn affects the ecological function of the rain garden.
Li et al. [25]	China	Evaluating the impacts of rain gardens on hydrology and water quality in urbanized areas using SWMM (Stormwater Water Management Model) modeling.	Demonstrate that rain gardens have significant ecological benefits and water quality improvement in urban stormwater management.
Fletcher et al. [26]	Australia	An overview of recent advances in urban runoff reuse in Australia.	Challenges remain, such as complexity of water quality management and high system maintenance costs.
Wang et al. [27]	China	Analyzed the cost-effectiveness of bioretention systems in the context of climate change and urbanization scenarios.	The design and implementation of bioretention systems need to take into account regional climate and urbanization to achieve optimal benefits

Geographically, rain garden research involves 524 research institutions across 55 countries, with the United States and China emerging as the leading contributors, producing 337 and 191 papers, respectively, accounting for 46% and 26% of the total. In addition, Singapore, with 45 publications, has positioned itself as a leader in the field due to its pioneering efforts in the Active, Beautiful, Clean (ABC) Waters Programme, which emphasizes the use

of nature-based solutions such as rain gardens to enhance urban water management and ecological sustainability [28]. In addition to the dominant contributions from China and the United States, other regions, such as Australia (68 articles), Canada (45 articles), and South Korea (28 articles), have also made significant contributions. Additionally, countries like the UK, Brazil, and India have conducted important research on urban rain gardens, addressing specific climate challenges such as droughts and heavy rainfall. This inclusion demonstrates the global effort in utilizing nature-based solutions to mitigate urban water management issues under diverse climate conditions. These contributions predominantly originate from esteemed academic and research institutions within these nations, underscoring their pivotal roles in this field. Among the countries with the highest research output, approximately 80% of the publications are from developed nations, underscoring the sustained dominance of developed countries such as the United States, Australia, and Singapore in spearheading rain garden research initiatives. This pattern highlights the significant research capacity and resources available in developed regions, which continue to drive advancements in the study and implementation of nature-based solutions for urban stormwater management. The prominence of these nations in the field reflects not only their academic prowess but also a broader commitment to addressing the environmental challenges posed by urbanization and climate change.

Figure 3 depicts the patterns of international collaboration in rain garden research, where each node represents a country or region, and the node size reflects the number of publications [29,30]. The United States and China are particularly prominent, followed by Australia, Canada, Singapore, and the United Kingdom, underscoring a robust trend of international cooperation in this field. China, in particular, has developed the most extensive collaborative network, actively partnering with researchers from developing countries and significantly amplifying their contributions to the domain. This extensive network of international collaborations emphasizes the critical role of cross-border partnerships in enhancing research capacity and quality, particularly in developing nations [31]. Moreover, the escalating challenges associated with urban flooding and rapid urbanization in developing countries are likely to further drive investment in urban rain garden research as an effective strategy to mitigate these pressing environmental issues.

3.3. Delving into Dominant Research Themes

By examining the network structures, this analysis facilitates a comprehensive understanding of the core themes and emerging trends within this research domain [32,33]. The extraction and categorization of keywords elucidate the dynamic forefront of urban rain garden research. After standardizing synonyms, the aggregation patterns within this field were analyzed using the "Keyword Co-occurrence View" function of CiteSpace 6.3 R1. In the resulting "keyword co-occurrence view", nodes represent keywords, with font size indicating the frequency of occurrence. Connecting lines signify co-occurrences between keywords, with line thickness reflecting the strength of these connections and color denoting the time of first co-occurrence. The analysis reveals that nine keywords, including "low-impact development", "green infrastructure", "hydrology", "runoff", and "performance", are high-frequency terms, highlighting concentrated research areas and strong interconnections.

"Low-impact development" emerges as the most frequent keyword with 236 occurrences, followed by "green infrastructure" with 176 occurrences, and "performance" with 175 occurrences. Keywords with the highest betweenness centrality include "low-impact development" (0.29), "best management practice" (0.24), and "removal" (0.18), indicating their pivotal roles in the research network. These findings suggest that rain gardens, as a tool of low-impact development, are intrinsically linked to urban stormwater management, with simulation and performance evaluation through modeling being prevalent research approaches [34]. Notably, stormwater management models such as SWMM, STORM, and MOUSE are frequently employed in these evaluations. Furthermore, keywords like "hydrology" and "runoff" are not only highly frequent but also exhibit significant between-

ness centrality, reaffirming their critical importance in the field. These topics consistently emerge as key issues across various analytical metrics, underscoring their central role in the ongoing research discourse surrounding rain gardens and their application in urban environments. In urban planning for green infrastructure, geoprocessing tools such as Geographic Information Systems (GISs) have been widely used to assess the suitability of sites for rain garden implementation. These tools enable precise mapping of surface runoff patterns, land slopes, and soil permeability, which are critical for identifying optimal locations for rain gardens. Several studies, including those by Rosa et al. [35] and Alves et al. [36], utilized GISs to model hydrological processes and forecast the performance of rain gardens under different rainfall scenarios. GISs also play a pivotal role in integrating rain gardens into larger urban systems, enabling planners to visualize how green infrastructure can interact with surrounding land uses and existing stormwater networks (Figure 4).

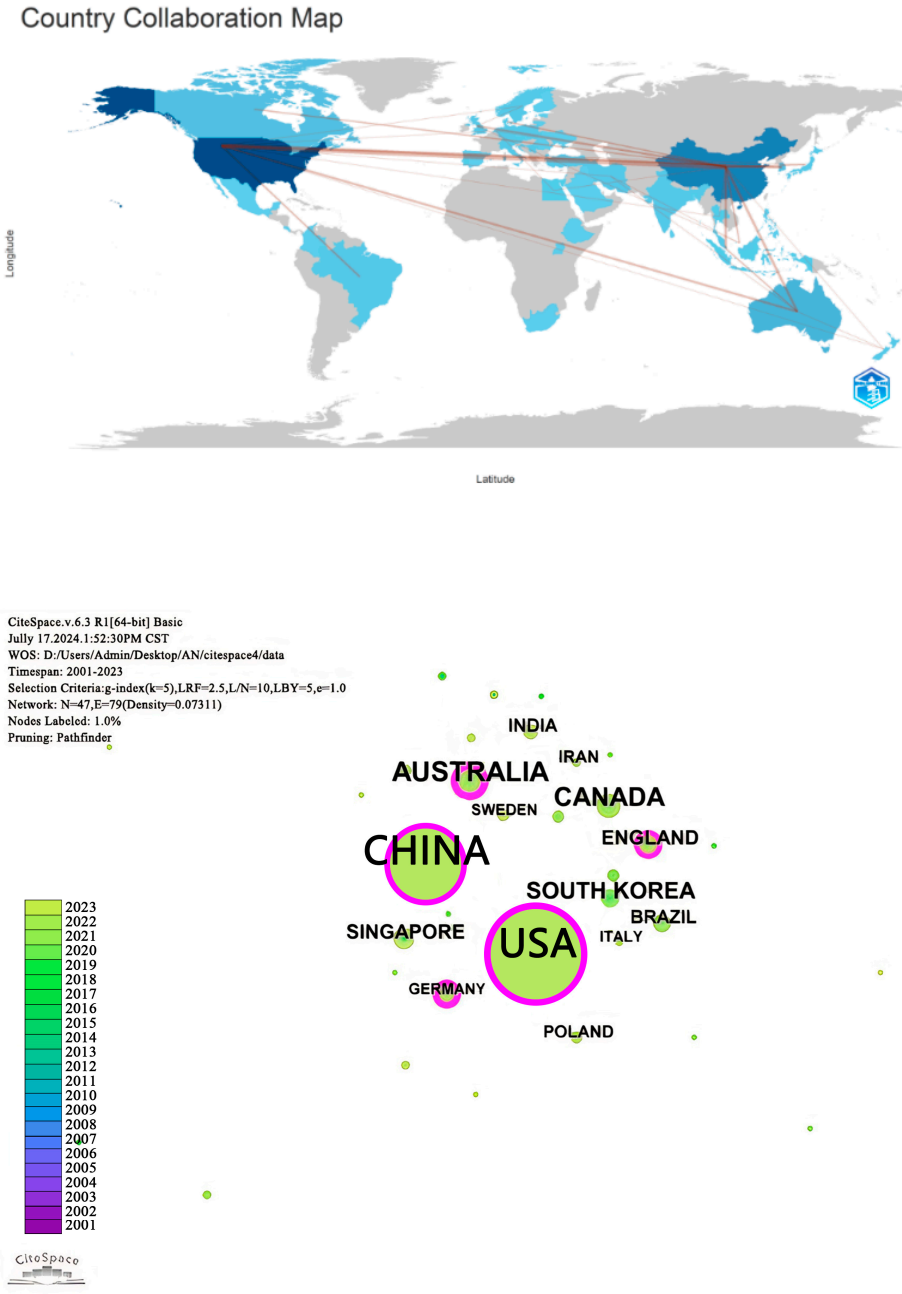


Figure 3. Countries of authorship for rain garden-related studies, 2000–2023.

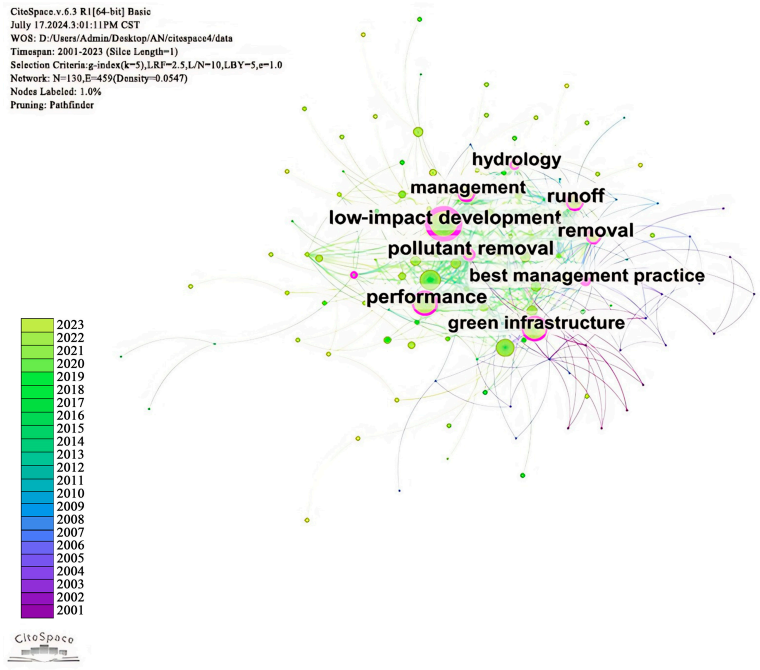


Figure 4. Keyword co-occurrence network diagram.

Figure 5 presents the time series distribution of research hotspots in the field of rain gardens, with cluster labels automatically generated by CiteSpace 6.3 R1, resulting in eight distinct keyword clusters: Cluster #0 (using bioretention), #1 (plant selection), #2 (green stormwater infrastructure), #3 (urban stormwater runoff), #4 (watershed hydrology), #5 (evaluation model), #6 (green infrastructure), and #7 (urban stormwater management). The temporal distribution of these keywords illustrates their initial occurrences and co-occurrences within and across clusters. In this visualization, nodes represent keywords, while the connecting lines indicate reciprocal relationships, reflecting the intricate web of interconnected research themes. The results underscore the role of rain gardens as a form of green stormwater infrastructure that optimizes urban water management, effectively addressing challenges posed by urban runoff. Key design considerations highlighted include plant selection, integration of bioretention systems, and the development of robust evaluation models.

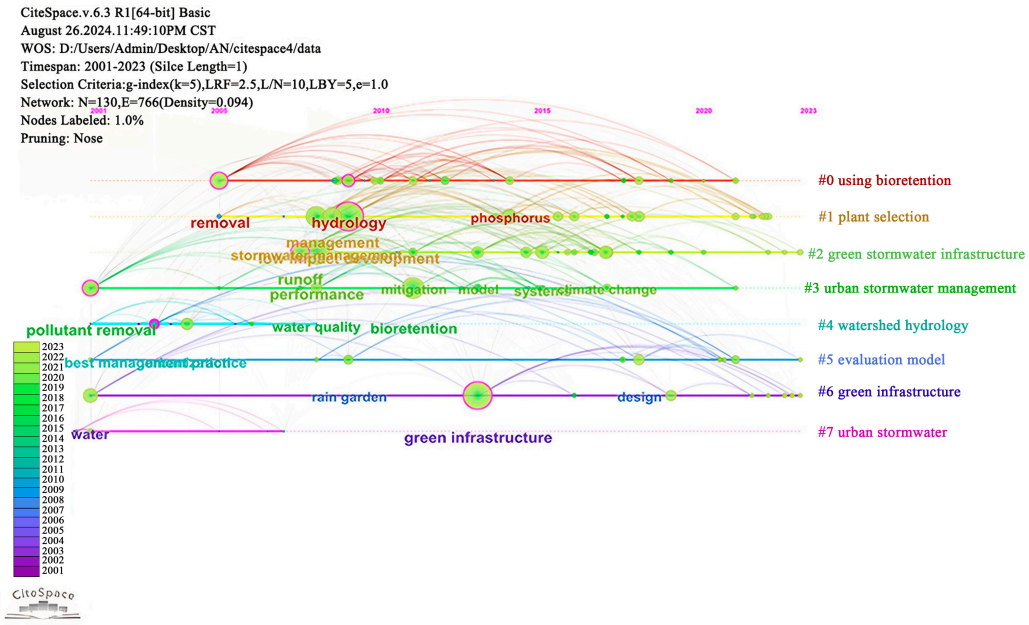


Figure 5. Time series distribution of research hotspots related to rain gardens.

4. Discussion

4.1. The Role of Rain Gardens in Urban Stormwater Management

Clustering techniques in bibliometrics are extensively utilized to identify key research topics and author groups, offering valuable insights into the structure and dynamics of academic fields. Wang et al. [37] explored the application of clustering to analyze visualizations of author collaborations and keyword co-occurrences, providing a framework for understanding the interconnectedness of research themes. As depicted in Figure 6, each numbered node represents a distinct research topic, with node size proportional to the number of publications in that area. Lines between nodes indicate co-citation relationships, highlighting connections between different research areas [38].

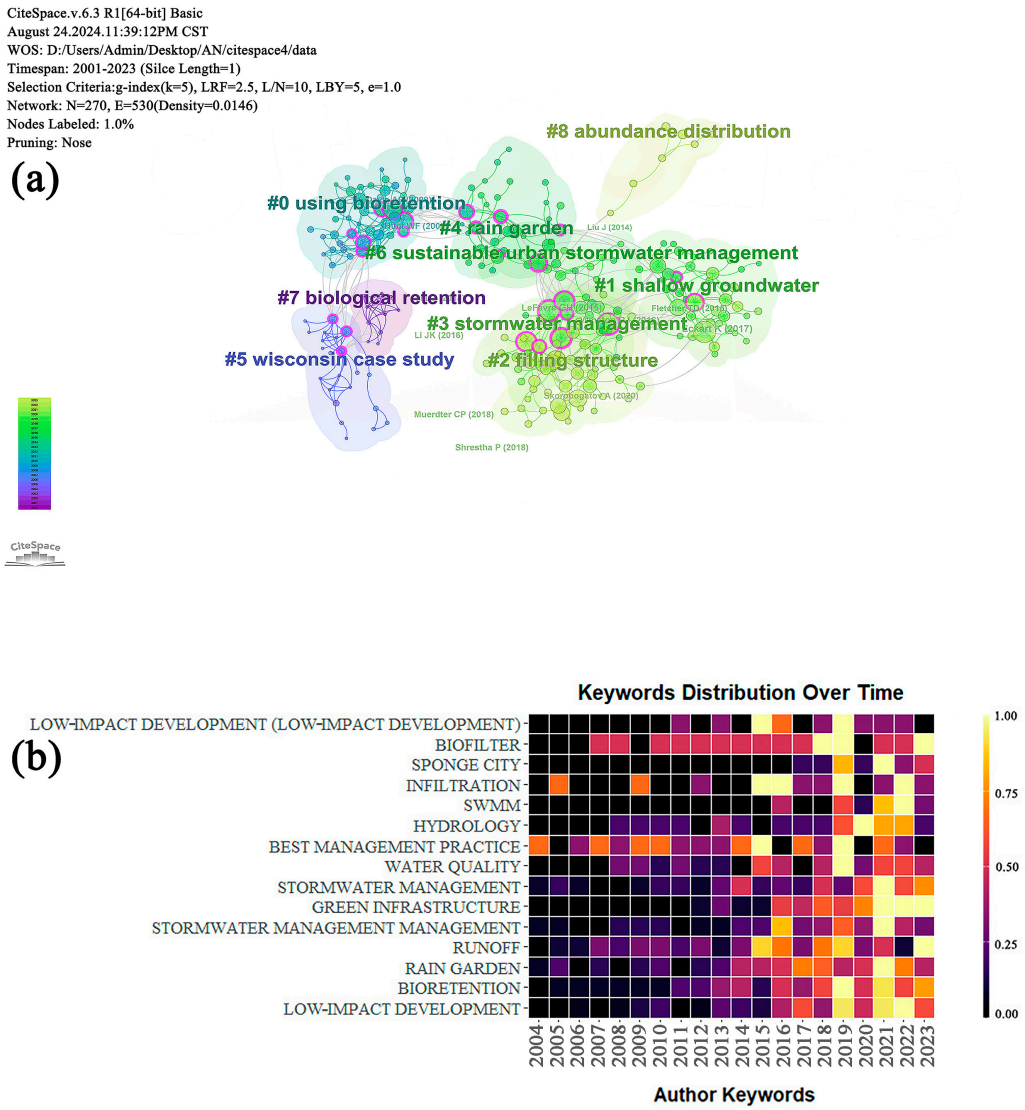


Figure 6. (**a**) Literature co-citation network analysis of rain gardens in urban stormwater resource management. Different colors represent various clusters, with numbers indicating cluster IDs. Nodes within a cluster represent co-cited papers, with node size reflecting citation frequency. Connecting lines represent co-citation relationships. (**b**) Time series distribution of keywords related to rain gardens in urban water management, 2004–2023. Larger values on the right axis indicate higher keyword prominence in the literature.

To investigate the co-citation clustering of the literature pertaining to rain gardens in urban stormwater management, Boolean retrieval formulas were employed by using the query TS = (“rain garden*” OR “rainwater garden*” OR “bioretention” OR “bio in-

filtration" OR "biofilter" OR "bioswale") AND TS = (city OR "urban*" OR town) AND TS = ("water management" OR hydrology OR "water quality" OR "*runoff" OR rainfall). This approach facilitated the visualization and analysis of the relevant literature. The cluster analysis identified key research hotspots within urban water management concerning rain gardens, including themes such as "stormwater management", "shallow groundwater", and "bioretention", underscoring the role of rain gardens in enhancing water quality and hydrologic management.

To deepen the understanding of pivotal studies within each cluster, highly cited articles were selected for detailed analysis and summarization, providing an overview of the roles and limitations of urban rain gardens in stormwater management. For example, Davis et al. [23] in Cluster #0 and Hatt et al. [39] in Cluster #7 collectively demonstrate that bioretention techniques, such as rain gardens, are effective in reducing runoff and improving water quality, though there are ongoing challenges related to stability and long-term effectiveness. Furthermore, Bratieres et al. [40] in Cluster #0 illustrate that optimized biofiltration systems can achieve substantial reductions in nutrient levels, such as nitrogen and phosphorus (Table 3).

Table 3. The role of rain gardens in urban water resources management (Note: Articles most frequently cited in this cluster).

Source	Country	Research Content	Conclusions	Cluster
Davis et al. [23]	USA	Current application practices of bioretention technologies and their future development needs are summarized.	Bioretention technologies effectively reduce runoff and enhance water quality, but their stability and overall effectiveness require further improvement.	#0 using bioretention
Ahiablame et al. [41]	USA	Evaluated the effectiveness of low-impact development (LID) practices in managing urban stormwater.	LID practices are very effective at reducing urban runoff and enhancing water quality.	#3 stormwater management
Bratieres et al. [40]	Australia	Assessed the effectiveness of bioretention systems in removing nutrients and sediments.	Enhanced biofiltration systems have demonstrated outstanding effectiveness in removing nutrients like nitrogen and phosphorus.	#0 using bioretention
Hatt et al. [39]	Australia	The hydrologic performance and pollutant removal capabilities of bioretention systems were assessed.	Stormwater biofiltration systems provide significant runoff reduction and pollutant removal under field conditions.	#7 biological retention
Davis et al. [42]	USA	The effectiveness of bioretention systems in managing urban stormwater is examined.	Bioretention systems reduce runoff volume and remove pollutants under laboratory conditions.	#7 biological retention

Figure 6 illustrates the increasing prominence of key research topics in urban rain garden studies over time, with the values on the right axis showing a notable upward trend in citation frequency. This surge in citations, particularly for the high-frequency keywords "green infrastructure" and "biofiltration technology", underscores the growing significance of these topics in urban stormwater management research, establishing them as central themes in the field. In addition, stormwater management models such as the SWMM (Storm Water Management Model) model are widely applied in urban rain garden research to evaluate the performance of green infrastructure under various hydrological scenarios. The SWMM model can simulate the hydrological processes involved in stormwa-

ter management, including rainfall, surface runoff, infiltration, and evapotranspiration, and assess the effectiveness of rain gardens in reducing peak flows and improving water quality [43]. For instance, Li et al. [25] applied SWMM in an urbanized area in Xi'an, China, to assess rain garden impacts across different storm events, demonstrating their significant ecological benefits. Similarly, Jang et al. [44] utilized SWMM to conduct sensitivity analysis, identifying key factors influencing rain garden performance in stormwater management.

Compared to traditional stormwater management techniques, which primarily rely on gray infrastructure such as storm drains and detention basins, rain gardens provide superior performance in both reducing surface runoff and improving water quality. Traditional systems are often limited in their ability to filter pollutants and mitigate the ecological impacts of urbanization. In contrast, rain gardens enhance water infiltration, reduce peak flows, and remove contaminants such as nitrogen, phosphorus, and heavy metals through bioretention process. Several studies have demonstrated that rain gardens are more effective at removing nutrients and sediments from stormwater runoff, thus contributing to both hydrological regulation and ecosystem health [45–47]. In the context of global climate change and accelerating urbanization, the role of rain gardens in urban flood mitigation has become increasingly vital. The average annual growth rate of publications in this area is 28.61%, reflecting the heightened research focus on leveraging such green stormwater infrastructures to address the challenges posed by urban runoff and flooding. The findings of these studies reinforce the critical function of rain gardens in mitigating runoff from impervious surfaces, enhancing stormwater infiltration and promoting groundwater recharge [11]. As urban areas continue to expand and climate conditions become more unpredictable, the importance of rain gardens in sustainable urban water management is expected to grow, further cementing their status as a key strategy in urban resilience planning [48,49].

To elucidate the mechanisms and principles by which rain gardens optimize urban stormwater management, an extensive review and synthesis of the literature across various research clusters were conducted. The findings indicate that in terms of water quality improvement, rain gardens are shown to effectively remove suspended solids, heavy metals, nutrients, and organic pollutants from urban runoff through a combination of physical, chemical, and biological processes, with soils and plants playing integral roles in these functions [50]. Mehring et al. [51] highlighted the significant influence of soil invertebrates on plant growth, water infiltration rates, and retention and removal of pathogens, nutrients, heavy metals, and other pollutants, suggesting that biotic interactions within soil systems are critical to the performance of rain gardens. Further research by Björklund and Li [52] expanded on this by emphasizing the role of soil macrofauna in enhancing plant growth and water infiltration, as well as in pollutant removal. In the same year, Yuan et al. [53] noted the limited quantification of vegetation type effects on the hydrological performance of rain gardens, advocating for prioritizing the categorization and structural diversity of plantings within vegetated stormwater management facilities. Moreover, rain gardens significantly contribute to urban hydrology improvement and flood mitigation by reducing surface runoff, enhancing stormwater infiltration, and delaying peak flood flows [54]. These functions not only reduce the immediate impacts of flooding but also support the long-term sustainability of urban water resources.

4.2. The Role of Rain Gardens in Urban Ecological Benefits

Urban rain gardens play a significant role in terms of eco-efficiency by improving the microclimate and air quality and enhancing urban biodiversity. Through the careful selection of native and adaptive plant species, they provide habitats that support various forms of wildlife, including pollinators and small urban fauna, contributing to the resilience of urban ecosystems [55,56]. Utilizing the Boolean search equation TS = ("rain garden*" OR "rainwater garden*" OR "bioretention" OR "bio infiltration" OR "biofilter" OR "bioswale") AND TS = (city OR "urban*" OR town) AND TS = ("ecological environment" OR "ecological benefit" OR "air quality" OR "city heat island effect" OR biodiversity OR "biological

diversity"), a high-frequency co-citation analysis was conducted to examine the literature on the ecological enhancements facilitated by rain gardens. The analysis revealed that "pollutant removal efficiency" in Cluster 1 and "air quality" in Cluster 2 are central themes within this research focus (Figure 7).

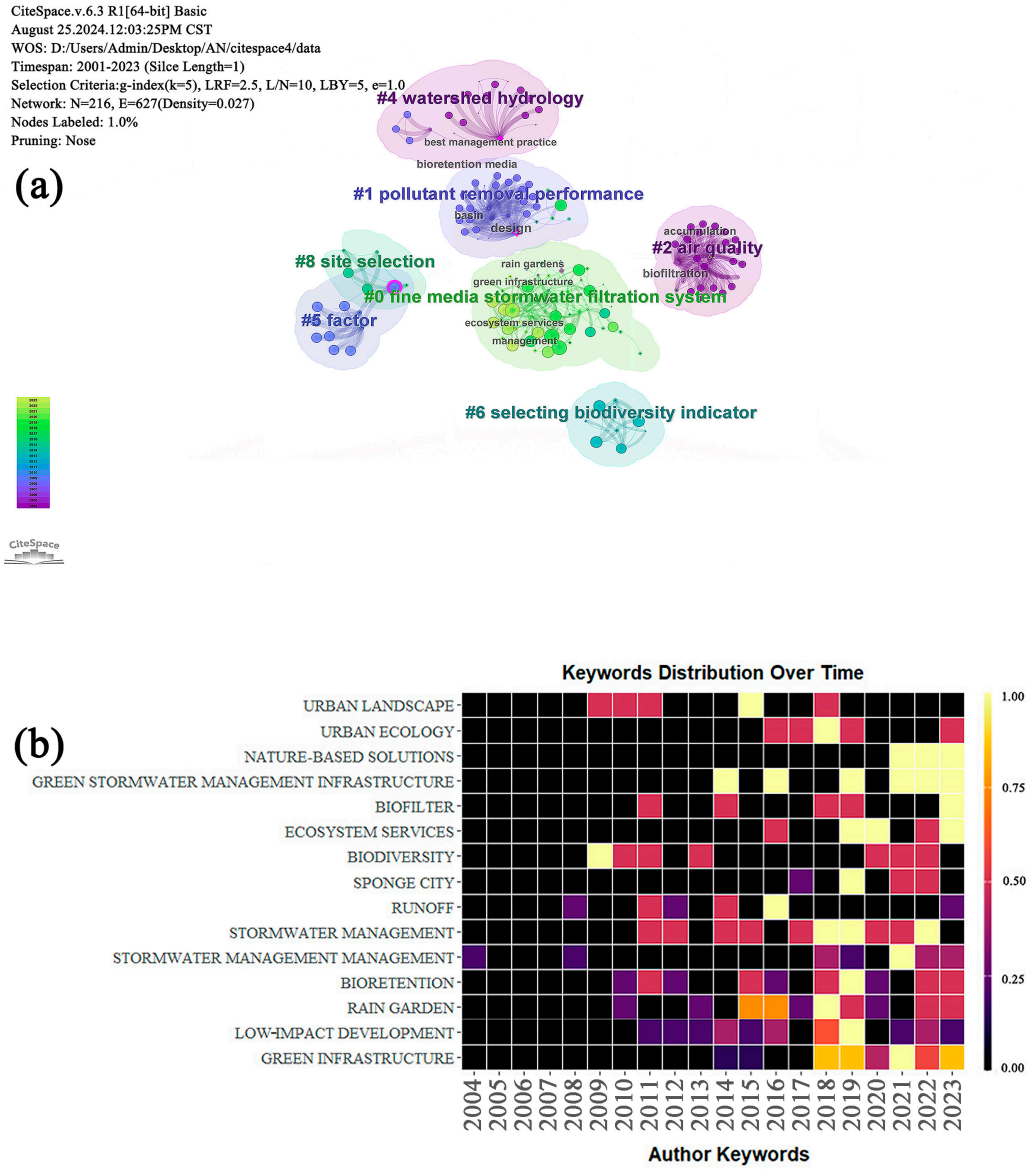


Figure 7. (**a**) Literature co-citation network analysis of rain gardens and their ecological benefits. Different colors indicate clusters, with node size reflecting citation frequency. (**b**) Time series distribution of keywords related to the ecological benefits of rain gardens, 2004–2023. Larger values indicate higher keyword prominence.

To further substantiate these findings, a review of global case studies was undertaken to evaluate the use of rain gardens in enhancing urban ecological efficiency (Table 4). For instance, Kazemi et al. [57] from Australia investigated terrestrial invertebrates as biodiversity indicators by comparing six bioretention basins with six corresponding paired green spaces in Melbourne, divided into two subgroups. Their findings indicate that transitioning from conventional urban green spaces to bioretention basins can significantly enhance urban biodiversity. Similarly, Kasprzyk et al. [58] from Poland demonstrated that the introduction of rain gardens in Gdansk significantly improved stormwater management, reduced pollution, increased biodiversity, and supported sustainable urban development. Furthermore,

high-frequency keyword analyses indicate that recent research has increasingly focused on the impacts of climate change, a trend that has intensified over time. This highlights the critical role of regulatory services, such as pollutant removal and climate amelioration, as catalysts for advancing research in this domain [12]. These insights underscore the multifaceted ecological benefits of rain gardens, positioning them as vital components in the broader strategy of enhancing urban resilience and ecological health.

Table 4. Case studies of rain gardens in urban ecosystem optimization.

Source	Country	Research Content	Conclusions
Kazemi et al. [57]	Australia	A study of street-scale bioretention basins in Melbourne and their impact on local biodiversity.	Melbourne's street bioretention basins enhance local biodiversity.
Kazemi et al. [59]	Australia	A study of streetscape biodiversity in Australian urban environments and the role of bioretention drains in it.	Bioretention drains significantly increased the biodiversity of the streetscape in the Australian urban environment.
Morash et al. [60]	USA	Focuses on the role of rain gardens in capturing pollutants, increasing biodiversity, and enhancing ecosystem resilience.	Rain gardens significantly increase pollutant capture rates, enhance biodiversity, and increase ecosystem resilience in residential neighborhoods.
Kasprzyk et al. [58]	Poland	The technical solution of introducing rain gardens and the benefits they bring is explored using the city of Gdansk, Poland, as a case study.	The introduction of rain gardens has significantly improved stormwater management in Gdańsk and enhanced biodiversity.
Shreewatsav, M et al. [61]	India	Exploring how rainwater runoff can be used as a resource to enhance urban green infrastructure on the Karnataka Nice Highway.	Effective management of stormwater runoff can contribute to the improvement of green space construction and ecological restoration around highways, thus promoting environmental sustainability.

4.2.1. Improve the Urban Microclimate

The urban heat island (UHI) effect is a prevalent and exacerbating issue associated with urbanization, particularly during summer when temperatures in city centers significantly exceed those in surrounding suburban and rural areas [62]. In addition to their primary role in regulating the urban water cycle, rain gardens offer significant potential to enhance urban evapotranspiration, thereby contributing to the mitigation of the UHI effect [63]. They facilitate cooling through processes such as evapotranspiration and shading, which collectively help to moderate urban microclimates.

A study by Ma et al. [64] demonstrated that rain gardens can improve thermal comfort and urban livability in hot environments by lowering surface temperatures and stabilizing microclimates. These gardens reduce ambient temperatures and create more comfortable conditions for urban residents. Ge et al. [65] further explored the benefits of rain gardens, revealing that complex, multi-layered planting designs can expand areas of moderate temperatures and higher humidity, thus significantly enhancing the subjective perceptions of these green spaces among the public. The study highlighted the importance of diverse and strategically layered vegetation in optimizing microclimate benefits. Specifically, vegetation in rain gardens contributes to microclimate regulation by releasing water vapor through transpiration, which increases air humidity and lowers surface temperatures [66]. This cooling effect is further augmented by the shading provided by plant canopies, which reduce the amount of direct solar radiation reaching the ground [67]. These combined effects are particularly impactful during nighttime, as rain gardens can cool urban environments more rapidly through sustained transpiration, thereby reducing the intensity of the UHI effect during critical periods.

The ability of rain gardens to regulate urban microclimates plays a crucial role in enhancing the overall quality of life for urban residents by improving thermal comfort and

reducing the adverse health effects associated with extreme heat events [68]. This research underscores the importance of strategic rain garden design and optimization, emphasizing the need for tailored planting strategies that maximize evapotranspiration and shading. By examining microclimate patterns and the associated perceptions of rain gardens, these studies explore the potential of rain garden design as a pivotal strategy in addressing the challenges of urban climate change. As cities continue to expand and temperatures rise, the role of rain gardens in moderating urban microclimates and contributing to urban resilience becomes increasingly vital, offering a sustainable solution to mitigate the UHI effect and improve urban livability.

4.2.2. Enhancement of Urban Biodiversity

Biodiversity serves as a critical indicator of the health and resilience of urban ecosystems [69]. In urban areas, biodiversity is often linked to the extent and quality of existing natural land [70], but vegetation-based interventions such as rain gardens have shown considerable potential in enhancing biodiversity in otherwise fragmented environments [71–73]. Rain gardens create vital habitats and foraging grounds for species such as insects, birds, and other urban wildlife, thereby supporting ecosystem resilience and functional diversity. These ecosystems are essential in providing shelter, food sources, and reproductive grounds, which ultimately bolster the health and sustainability of urban biodiversity [74]. This enhancement not only improves urban ecological integrity but also contributes to broader biodiversity conservation and restoration efforts. The strategic selection of plant species within rain gardens can optimize their ecological functions, allowing them to play a more substantive role in promoting urban biodiversity and supporting the establishment of ecological networks [75,76]. For instance, the use of native and regionally adapted plants can attract local wildlife, support pollinator populations, and provide food sources and nesting sites, which are crucial for the survival of various species in urban landscapes. The incorporation of plant species with varied structural and functional traits can further enhance habitat complexity, increasing the ecological value of rain gardens as part of urban green infrastructure.

To illustrate the contributions of rain gardens to ecosystem services, Table 4 presents case studies that highlight the role of them in enhancing urban biodiversity. Kazemi et al. [59] demonstrated that such bioretention facilities significantly increased biodiversity within streetscapes in Australian urban environments, thereby promoting ecological resilience. Similarly, in Case #3, Morash et al. [60] found that rain gardens in residential neighborhoods not only enhanced biodiversity but also improved pollutant capture rates, contributing to the overall resilience of urban ecosystems. Moreover, rain gardens serve as critical ecological habitats with the capacity to provide shelter for endangered species and facilitate their reproduction and dispersal. Through the optimization of plant selection and habitat design, they can effectively connect fragmented urban green spaces, forming biological corridors that promote gene flow, species dispersal, and overall ecosystem stability [77]. This connectivity is essential for the persistence of urban wildlife populations, as it mitigates the effects of habitat fragmentation and provides pathways for species movement across urban landscapes.

4.2.3. Improvement of Air Quality

Air quality issues remain a significant challenge in urbanized areas, particularly in regions affected by high traffic volumes and industrial emissions [78]. Over the past two decades, extensive research has explored the role of phytoremediation—using plants to mitigate air pollution—in urban environments [79,80]. Rain gardens, with their rich vegetative cover, are strategically positioned near urban roads and corridors, making them effective in enhancing urban air quality. The vegetation within rain gardens not only sequesters carbon dioxide but also captures suspended particulate matter (such as PM2.5 and PM10) and adsorbs harmful gases, including sulfur oxides and nitrogen oxides [81–83].

Studies have demonstrated the efficacy of rain gardens in reducing various air pollutants. For instance, Dabbous and Kumar [84] reported a nearly 37% reduction in the concentration of ultrafine particles in the air following the establishment of planted bioretention systems (BRSs). Similarly, Deshmukh et al. [85] found that dense roadside vegetation contributed to significant reductions in ultrafine particles (50%), black carbon (27%), NO2 (20%), and CO (19%). Further, Maher et al. [80] highlighted that vegetation in bioretention systems, including rain gardens, was effective in reducing indoor PM10 concentrations by up to 60%. These findings underscore the feasibility and efficacy of phytoremediation as a strategy to mitigate human exposure to various air pollutants.

Several studies have focused on optimizing the design of rain gardens to enhance their capacity for air pollution removal. Muerdter et al. [86] suggested selecting plant species with high leaf area density, particularly in locations adjacent to vehicular roads and in the downwind direction, to effectively reduce concentrations of particulate matter and gaseous pollutants. In contrast, Chen et al. [87] emphasized the role of local wind conditions, noting that wind patterns play a more significant role in reducing particulate matter concentrations than the specific characteristics of the plant species used. This insight points to the importance of considering environmental factors such as wind direction and speed when designing rain gardens for air quality improvement.

The capacity of rain gardens to improve urban air quality is particularly pronounced in areas with high traffic flow and intense industrial emissions, where the removal of pollutants can have substantial public health benefits [61,88]. By incorporating diverse plant species that maximize pollutant capture through a high leaf area index and optimizing placement in relation to prevailing wind conditions, rain gardens can serve as a critical component of urban phytoremediation strategies [89]. Future designs of rain gardens should prioritize the strategic matching of plant communities to local environmental conditions, thereby enhancing their effectiveness in air purification [10,90]. As cities continue to grapple with air quality issues, the integration of rain gardens into urban infrastructure represents a promising, nature-based solution for improving urban air quality and contributing to overall environmental sustainability.

4.3. The Role of Rain Gardens in Enhancing Urban Landscape Value

Rain gardens are a vital component of green stormwater infrastructure, contributing not only to optimized stormwater management and enhanced ecological benefits but also to the esthetic and social value of urban landscapes [91–93]. To investigate the contribution of rain gardens to urban landscape value, a bibliometric analysis was conducted using the Boolean search equation TS = ("rain garden*" OR "rainwater garden*" OR "bioretention" OR "bio infiltration" OR "biofilter" OR "bioswale") AND TS = (city OR "urban*" OR town) AND TS = ("landscape benefit" OR "landscape value" OR recreation OR leisure OR public). The co-citation clustering results, depicted in Figure 8, reveal that clusters focusing on "value" (Cluster #2) and "public acceptance" (Cluster #4) hold prominent positions within the literature, highlighting the importance of these themes in rain garden research.

Within these clusters, studies emphasize the multifaceted benefits of rain gardens in urban settings. For instance, Addas [94] underscores the critical role of rain gardens in enhancing the value of urban landscapes from a multidimensional perspective, integrating ecological, esthetic, and social functions. This research illustrates how rain gardens contribute to the creation of visually appealing and functionally resilient urban spaces, thereby enhancing the overall quality of urban life. Similarly, Kazemi et al. [57] explored the integration of rain gardens into garden bed-type green spaces within Australian neighborhoods, demonstrating their potential to create ecologically resilient and esthetically pleasing urban streetscapes. At the streetscape scale, these integrations not only improve the visual quality of urban areas but also promote ecological functions such as biodiversity enhancement and microclimate regulation. By blending functional stormwater management with esthetic and recreational benefits, rain gardens contribute to the development of sustainable and livable urban environments. These installations significantly enhance the

visual diversity and appeal of urban landscapes while simultaneously improving urban functionality and residents' quality of life through their unique designs and diverse plant configurations [95]. Unlike traditional hardscapes, rain gardens incorporate natural forms and seasonal dynamics, introducing vibrancy and variability into the urban environments. By integrating a variety of plant species and landscape elements, rain gardens transform rainwater runoff into esthetically pleasing and functional features that enhance the urban experience [96]. Moreover, the inclusion of walkways, seating areas, and observation points within rain garden designs encourages residents to use these spaces for leisure and social interaction, fostering community engagement. Studies have shown that rain gardens, with their ecological and esthetic values, are widely appreciated by citizens, contributing to the social vibrancy of public spaces and promoting stronger community ties through shared experiences in green spaces [97,98]. Such social benefits are critical for the sustainable development of modern cities, as they enhance public support for green infrastructure initiatives and contribute to a robust social foundation for urban governance.

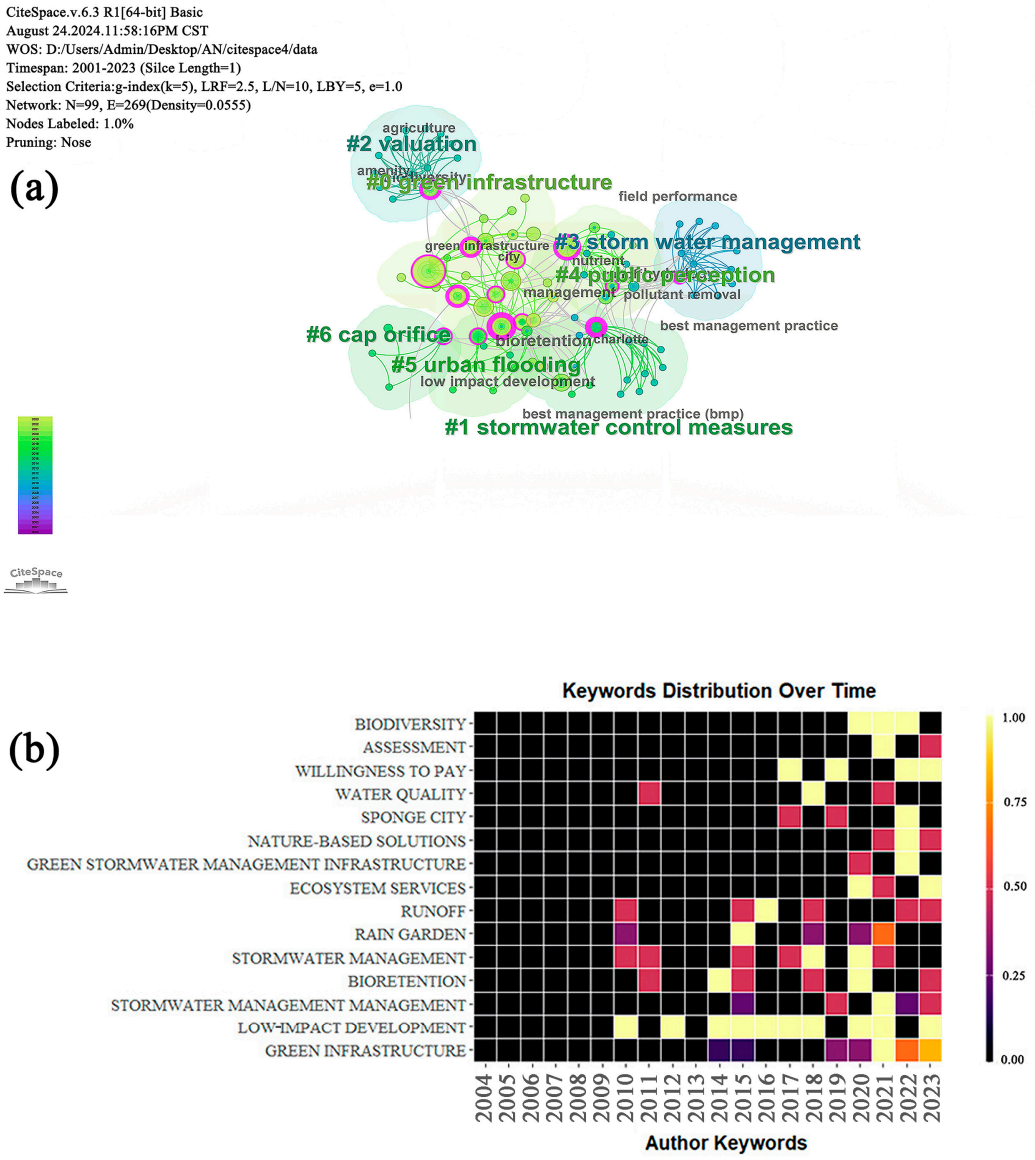


Figure 8. (**a**) Literature co-citation network analysis of rain gardens and their impact on urban landscape value. Different colors indicate clusters, with node size reflecting citation frequency. (**b**) Time series distribution of keywords related to the landscape value of rain gardens, 2004–2023, with larger values representing greater importance.

The integration of rain gardens into urban landscapes thus extends beyond mere environmental management, contributing to the esthetic enrichment, social vitality, and ecological sustainability of cities. By bridging the gap between green infrastructure and public amenity, rain gardens play a pivotal role in the evolution of urban spaces that prioritize both ecological health and human well-being. As cities continue to evolve, the strategic incorporation of rain gardens into urban planning frameworks will be essential for creating resilient, vibrant, and sustainable urban environments [99].

4.4. Future Research Perspectives

The findings of this review indicate that rain gardens are increasingly being implemented as a form of green infrastructure in urban settings to address the challenges associated with rapid urbanization. Over the past two decades, rain gardens have garnered significant attention for their roles in biofiltration, pollutant removal—including nitrogen, phosphorus, and heavy metals—and in stormwater management modeling, such as the use of SWMM. Despite these advances, current rain garden designs face substantial limitations, particularly in terms of their adaptability to diverse climatic conditions and their long-term performance [100]. The efficacy of rain gardens can vary significantly depending on local climatic conditions, land use, and environmental stressors. Key factors influencing long-term performance include soil permeability, plant selection, and pollutant load management. Soil permeability directly affects water infiltration rates, while appropriate plant species selection ensures that vegetation is resilient to local climatic conditions. Additionally, ongoing maintenance—such as regular plant pruning, monitoring for soil compaction, and pollutant removal—plays a crucial role in maintaining the garden's ability to manage stormwater effectively over time. To ensure the sustainability of rain gardens, it is essential to establish robust maintenance programs that focus on preserving plant health and soil function while periodically assessing pollutant buildup.

In the realm of urban stormwater management, there remains a dearth of research on the hydrological interactions between plant species and the medium within rain gardens, particularly concerning their impact on stormwater runoff attenuation. Additionally, there are notable gaps in understanding the specific roles that plants play in the removal of various pollutants [101]. The pollutant removal efficiency of rain gardens is highly variable, largely influenced by their adsorption and phytoremediation capacities. Thus, more in-depth research is required to refine the design of rain gardens and optimize their water purification processes to achieve maximum efficacy. Investigations into the synergistic effects of plant–medium interactions and the selection of plant species tailored to specific pollutant removal needs will be critical for advancing the performance of rain gardens [102].

Furthermore, studies on the ecological benefits of rain gardens remain underexplored, particularly regarding the roles of soil fauna and plant communities in rain garden functionality. Existing research often neglects the contributions of soil fauna, which play crucial roles in enhancing plant growth, water infiltration rates, and pollutant removal [51,52]. Future research should focus on the biodiversity within rain gardens and its impact on their ecological functions, exploring how the integration of diverse plant communities can enhance ecological outcomes. Pairing plant species with complementary traits could improve urban ecological benefits and provide enhanced ecosystem services for urban residents.

While the ecological benefits of rain gardens are increasingly recognized, their social benefits as urban public open spaces are often overlooked. As essential components of green infrastructure in high-density urban environments, rain gardens have the potential to provide not only environmental advantages but also significant social value. Future designs of rain gardens should embrace a multifunctional approach, where they serve not only as stormwater management tools but also as inviting public spaces that integrate seamlessly into the urban landscape [103,104]. This approach would enhance the attractiveness and landscape value of rain gardens, fostering greater public engagement and support for green infrastructure initiatives.

5. Conclusions

The application of rain gardens in urban environments has proven to be an effective nature-based solution for managing stormwater, improving water quality, and contributing to urban ecological and esthetic value. These systems reduce surface runoff and mitigate flooding through biofiltration processes, effectively enhancing water quality by removing pollutants. As multifunctional components of urban landscapes, rain gardens also offer ecological benefits, such as improving biodiversity and contributing to the urban thermal environment. This bibliometric review demonstrates a significant increase in global research interest in rain gardens, particularly in high-density urban areas where traditional grey infrastructure often fails to adapt to increased stormwater volumes due to urbanization and climate change.

Rain gardens, as part of green stormwater infrastructure, not only address the technical challenges of urban water management but also enhance the visual and social aspects of urban spaces. This combination of environmental, social, and ecological functions positions rain gardens as a critical component of sustainable urban development strategies. However, challenges remain in optimizing their design for diverse climates and ensuring long-term performance. Key issues include variations in soil permeability and plant species' adaptability to different environmental conditions. For example, regions with high rainfall may require fast-draining soil media to prevent waterlogging, while arid regions may need drought-tolerant plants and deeper infiltration zones. Further research into the synergistic roles of plant species, soil media, and environmental conditions is crucial for advancing the field. Developing modular designs that can be adapted to local climate conditions will also help address these challenges. Future studies should focus on enhancing the efficiency of pollutant removal in rain gardens, with particular emphasis on understanding plant–soil interactions and their role in optimizing water filtration processes. Additionally, there is a growing need to explore the broader ecological benefits of rain gardens, such as their contributions to urban biodiversity and resilience. Beyond environmental impacts, future research should also assess the social benefits of rain gardens, including their potential to foster community engagement and improve the esthetic and recreational value of urban spaces.

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