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RECEIVED 02 November 2023

ACCEPTED 18 December 2023

PUBLISHED 08 January 2024

CITATION

Xie C, Liu D and Jim CY (2024) Vicissitudes and prospects of green roof research: a two-decade systematic bibliometric review. *Front. Ecol. Evol.* 11:1331930. doi: 10.3389/fevo.2023.1331930

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Vicissitudes and prospects of green roof research: a two-decade systematic bibliometric review

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Urban green roofs have emerged as an innovative nature-based solution for enhancing urban sustainability and resilience. Based on the Web of Science Core Collection database, the scholarly papers on green roofs published in the past two decades were analyzed quantitatively and visualized using bibliometric techniques. The study scope covered research countries, institutions, main journals, crucial authors, highly cited documents, hot topics, and research frontiers. The 3210 publications mined from the bibliographic database on green roofs have increased progressively in the study period, with a significantly faster pace in recent years. The research subjects changed gradually over time, extending into more disciplines and becoming decidedly multidisciplinary. The notable bibliometric features registered a pronounced spatial concentration of research outputs in a small number of countries, regions, research institutions, journals, and researchers, mainly associated with developed metropolises. The number of publications and citation impacts identified the world's top ten researchers and journals. Well-defined clusters depicted by knowledge graphs indicated a diverse range in the number and strength of inter-node connections for countries, institutions, researchers, and research topics defined by keywords. The research scope focuses on quantifying benefits and costs and optimizing designs to maximize biodiversity, hydrologic, thermal, and energy benefits as urban sustainability and climate-adaptation solutions. Emerging research should enhance biodiversity through optimal plant selection, integrate green roofs with renewable energy systems for sustainability, apply computational tools to enhance designs, evaluate low-cost and locally relevant design options for developing cities, and quantify co-benefits like stormwater reduction and energy savings. Multidisciplinary efforts leveraging simulations, ecosystem services valuation, and participatory community partnerships can advance context-appropriate green roof innovation and evidence-based policymaking to expand adoption in cities worldwide. Quantifying and communicating co-benefits are critical measures to drive wider implementation.

KEYWORDS

green roof, bibliometric analysis, research hotspot, research frontier, nature-based solution, urban sustainability

1 Introduction

Urbanization has accelerated globally since the 1950s, fundamentally transforming landscapes, nature contents and abiotic and biotic processes in urbanized areas (Xu et al., 2011; Taşkın and Saban, 2023). Urban sprawl often brings the proliferation of impervious surfaces like concrete and asphalt to seal previously natural areas. Impermeable roads, sidewalks, parking lots, recreational grounds and buildings prevent rainfall infiltration into the soil, causing most precipitation to runoff (Frazer, 2005). This extensive land sealing significantly alters the urban hydrological cycle, inducing undesirable consequences. The extensive replacement of natural vegetation and soil with impervious cover severely diminishes the ability of urban areas to absorb rainwater (Coutts et al., 2012). This degradation is compounded by climate change, which has brought more frequent and extreme precipitation events in many regions (Mendonça, 2023). The rapid rainwater runoff also curtails the key hydrological function of evaporative cooling, thus contribution to the intensification of the urban heat island effect and associated heat stress impact on human comfort and health (Jim, 2015a). In China, flooding disasters in recent decades have incurred massive financial losses in cities beset by the exigencies of tackling explosive population growth and development (Wang et al., 2021; Peng and Zhang, 2022). Urban green infrastructure presents a promising nature-based solution to offset the negative hydrological effects of urbanization. However, its widespread implementation has

encountered various obstacles in highly urbanized areas (Aparicio Uribe et al., 2022). It is necessary to find innovative solutions to realize the water-smart city goal.

Green roofs have been increasingly recognized as a feasible alternative to ground-level urban greenery (Figure 1). They present effective mitigation measures for stormwater management in the built environment (Berardi et al., 2014; Wang et al., 2023). Retrofitted on existing rooftops, they increase water infiltration and retention, reduce and delay runoff, and improve water quality (Wong and Jim, 2014; Wong and Jim, 2015). In developed cities where rooftops may account for 60% of impervious cover (Li and Yeung, 2014), expanding the rooftop green infrastructure across underutilized roof spaces provides immense potential to alleviate urban flooding with minimal land requirements (McKenzie, 2020). The ecological rehabilitation of roofs through green infrastructure techniques like living roofs and rain gardens offers cities a practical nature-based solution to reverse the hydrological disruptions of urbanization and mitigate climate change impacts (Adem Esmail and Suleiman, 2020). An emerging strategy is integrating nature into the three-dimensional built fabric through innovative and eclectic green space planning (James et al., 2009). With a global rooftop area estimated at over 32 billion m², repurposing roofs as living landscapes could transform cities into natural-cum-cultural entities (Cortinovis et al., 2022).

Rooftop greening provides multifunctional environmental and ecological benefits (Jim et al., 2022). Green roofs can reinforce resilience to climate change impacts (Peng and Jim, 2015). They



FIGURE 1

Structural layers of a modern green roof system and selected examples in China: (A) A typical cross-section of green roof; (B) A residential area in Haikou; (C–E). Office buildings in Shanghai; (F) A government office area in Jinan.

mitigate the urban heat island effect by cooling the substrate, surface and ambient air temperatures (Lee et al., 2013). Rooftop vegetation traps and filters harmful suspended particulate matter, absorbs gaseous air pollutants, and sequesters carbon. They improve air quality and remove greenhouse gases (Zaid et al., 2018). The diverse services qualify green roofs as an integral component of green infrastructure for climate-adaptive and sustainable cities. Beyond environmental benefits, green roofs fulfill aesthetic and psychological functions due to landscape-visual appeals and salubrious venues for outdoor recreation and relaxation (Mesimäki et al., 2017). Some rooftops have been transformed into productive urban farms, blending green space with urban agriculture to yield fresh produce with a minimal transport carbon footprint (Saha and Eckelman, 2017). Recognizing the immense potential of green roofs, many governments have instituted enabling policies, regulations, and incentives to promote adoption (Jim and Hui, 2022; Essuman-Quainoo and Jim, 2023). Such initiatives can render communities greener, healthier, happier, and more resilient (Li and Yeung, 2014; Dobrzańska et al., 2022).

The looming climate change impacts call for enlightened ecological design strategies like green roofs to climate-proof cities (James et al., 2009; Cortinovis et al., 2022). In the past few decades, scientific research on green roofs has flourished, aiming to quantify their multiple functions and benefits across environmental, economic, and social realms (Berardi et al., 2014; Al Sayah et al., 2023). It is an opportune time to synthesize the literature to gain insights into the state of the art, research trends and future directions. Recent advances in sophisticated quantitative software provide powerful and suitable tools to conduct a detailed and systematic bibliometric review. The quantitative data-driven approach can decipher and discover underlying knowledge structures, research hotspots, and emerging directions by mapping the intricate networks between publications, authors, institutions, countries, and concepts (Li et al., 2022). With intensifying challenges to urban sustainability globally (Wachsmuth and Angelo, 2018), applying bibliometric analysis to map the extensive green roof literature can synthesize current understanding and shed light on unanswered questions to advance the research field. The findings will inform strategic priorities for the scientific community, policymakers, and practitioners to expedite green infrastructure implementation in cities worldwide.

This study applied bibliometric analysis to examine thoroughly the green roof research field. The quantitative approach pursues several objectives: (1) assess output and citation profiles to gauge the literature's impact; (2) identify influential publications through literature co-citation network analysis; (3) determine key contributing authors, institutions, countries, and journals; (4) elucidate collaboration patterns and their evolution; and (5) to delineate hot topics and research frontiers over the study period. This bibliometric study seeks to uncover publication and authorship trends and emerging research priorities by quantifying research outputs, mapping citation networks, and elucidating collaboration linkages. The goal is to assess green roof literature

objectively to highlight influential works, leading contributors, productive collaborations, and critical knowledge gaps to inform future research directions. Findings will synthesize our current understanding and provide strategic insights to continue advancing the study of green roofs.

2 Data and methods

2.1 Data source

The global literature about green roofs published from 2000 to 2022, held in the core database of the Web of Science (WoS), was exhaustively scanned. The search terms “green roof”, “eco-roof”, “living roof”, and “vegetated roof”, used in the paper title, abstract and keyword list, were used to identify the matching publications. The WoS database supplied comprehensive bibliographic information meeting the research requirements: publication year, language, journal name, paper title, author name, author affiliation, keyword, document type, abstract, citation count, impact factor, and citation impact index. The data harvested on 21 May 2023 were exported in CSV format to facilitate analysis by the bibliometric software. In total, 3210 items were retrieved, which were grouped into four categories: article (reporting original research findings), review, conference proceeding paper, and other type. VOSviewer (version 1.6.19) analyzed the essential attributes and relationships: Co-authorship, Co-occurrence, Citation, Bibliographic coupling, Co-citation, and Theme (van Eck and Waltman, 2010).

2.2 Data analysis and visualization

VOSviewer is a versatile and popular software used for bibliometric network analysis (van Eck and Waltman, 2010). It allows users to construct and visualize networks of various entities (Oyewola and Dada, 2022). The software's quantitative and relationship-focused analysis facilitates understanding the evolution and emerging trends within a research domain (Diwanji, 2022). It can be combined with traditional literature review methods to enhance research analysis (Zare et al., 2017).

The literature data retrieved from WoS was saved in text format for VOSviewer analysis. Knowledge graphs of co-authorship were drawn between authors, institutions, and countries. A node's circle size represented the number of publications, and the inter-node distance indicated the strength of collaboration. Similarly, knowledge graphs were drawn to depict co-occurrence keyword clustering based on the frequency of keyword co-occurrences (Orduña-Malea and Costas, 2021). Each node represented a keyword, and a node's circle size indicated the keyword occurrence frequency (Toledo et al., 2019). The inter-node distance indicated the frequency of keyword co-occurrence, with a shorter distance indicating a higher co-occurrence frequency (Li et al., 2022). Microsoft Excel 2019 analyzed the distribution of publications by years, journals, author institutions, etc., of the retrieved papers and generated charts.

3 Results and discussion

3.1 Temporal distribution of publications

The 3210 publications on green roofs issued between 2000 and 2022 were mined from the WoS database. They included 2831 (88.19%) original research articles, 228 (7.10%) review articles, 65 (2.02%) conference proceeding papers, and 86 (2.67%) other forms of publications such as meeting abstracts, editorial materials, letters, book chapters, etc. (Figure 2).

The temporal distribution of publications can be divided into three phases. (1) The initial incubation phase in 2000–2009 experienced few publications due to the incipient development of the research field characterized by limited understanding of the subject matter. Less than 30 publications were delivered per year, with an average of merely 15.6 per year. (2) The early developmental phase in 2010–2016 witnessed an incremental annual increase, reaching an average of nearly 120 per year, rising from 48 in 2010 to 196 in 2016. The 2015 Paris Climate Agreement (Cléménçon, 2016) could have provided an impetus to studies on green roof benefits for urban temperature regulation, energy savings, and stormwater management. (3) The fast expansion phase in 2017–2022 signified substantial growth to 2000 papers in six years. Against the backdrop of intensifying global climate change, green roof research is increasingly regarded as an important

contributor to environmental and human well-being. Recent green roof studies have concentrated on urban biodiversity, microclimate mitigation, policy development, optimized materials and technology, urban and landscape design tools, real-time environmental monitoring, and mental health benefits (Lee et al., 2013; Li and Yeung, 2014; Liberalesso et al., 2020).

3.2 Bibliometric features

3.2.1 Subject categories

The most researched subject categories reflect the evolution of the green roof field over time (Table 1). Early studies in 2000–2009 focused narrowly on environmental sciences (50, 17.0%), civil engineering (40, 13.6%), construction/building technology (36, 12.2%), and energy (31, 10.5%). In 2010–2016, the inquiries expanded substantially into broader sustainability fields like environmental studies (114, 5.8%), urban studies (110, 5.6%), and green/sustainable science and technology (107, 5.5%). The last few years (2017–2022) witnessed notable and further broadening, with environmental sciences (779, 26.7%) and engineering (281, 9.5%) remaining dominant, but ecology (142, 4.8%) and water resources (249, 8.4%) rising in prominence. The overall trend indicates a maturing field with growing interdisciplinary breadth through diverse lenses spanning the built environment, ecology,

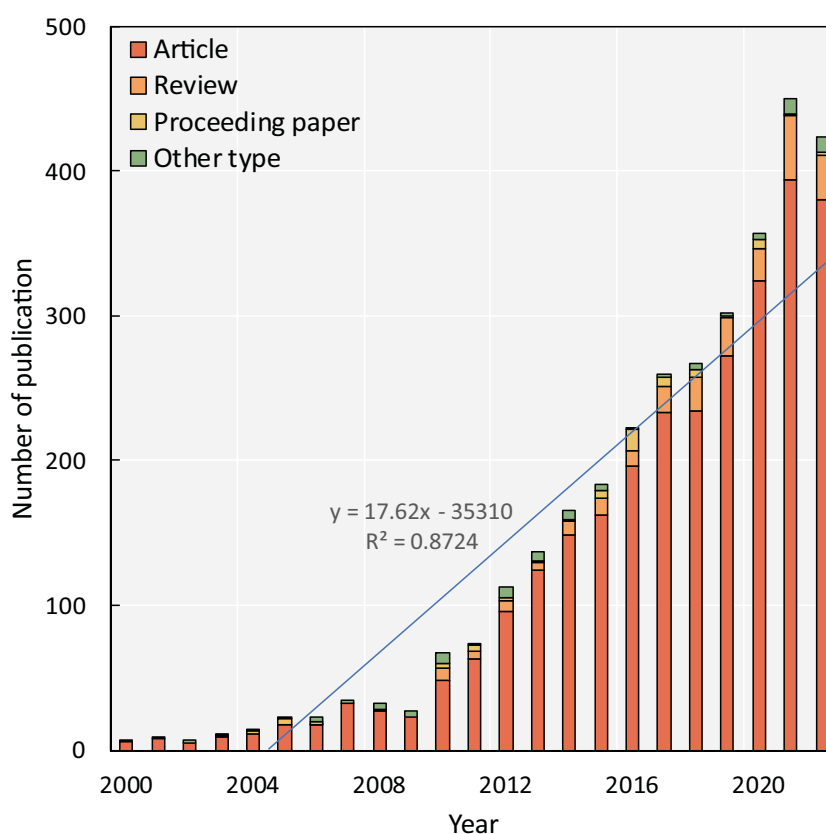


FIGURE 2

The temporal distribution of publications on green roofs from 2000 to 2022. The regression trend line indicates the rate of change in the study period. In the legend, "Article" refers to papers reporting original research on green roofs.

TABLE 1 The top ten research subject categories of publications on green roofs from 2000 to 2022.

Subject category	2000–2009	2010–2016	2017–2022	Total
Environmental science	50	368	776	1194
Engineering civil	40	260	281	581
Construction building technology	36	212	282	530
Energy fuels	31	225	262	518
Engineering environmental	38	220	256	514
Water resource	30	157	249	436
Green-sustainable science and technology	4	107	310	421
Environmental studies	15	114	247	376
Ecology	35	183	142	360
Urban studies	15	110	110	235
Total	294	1956	2915	5165

hydrology, climate resilience, and sustainability realms (Peng and Jim, 2015). The importance recently accorded to urban studies signals recognition of green roofs' potential to address sustainability challenges in cities (James et al., 2009; Dorst et al., 2019). As knowledge accumulates across domains, a more holistic systems perspective will be critical to leverage fully green roofs for regenerative and climate-adaptive urban design.

3.2.2 Main research countries, regions and institutions

The United States and China generate the most green roof publications, jointly accounting for over one-third of the total (Table 2). Italy ranks third, followed by major English-speaking countries: UK, Australia, and Canada. Western European nations known for green technology, like Germany and France, also make it to the top ten. Regarding research impact, the USA and UK have the highest total citations, mean citations per article, and h-index. However, normalizing for publication volume, Australia and the

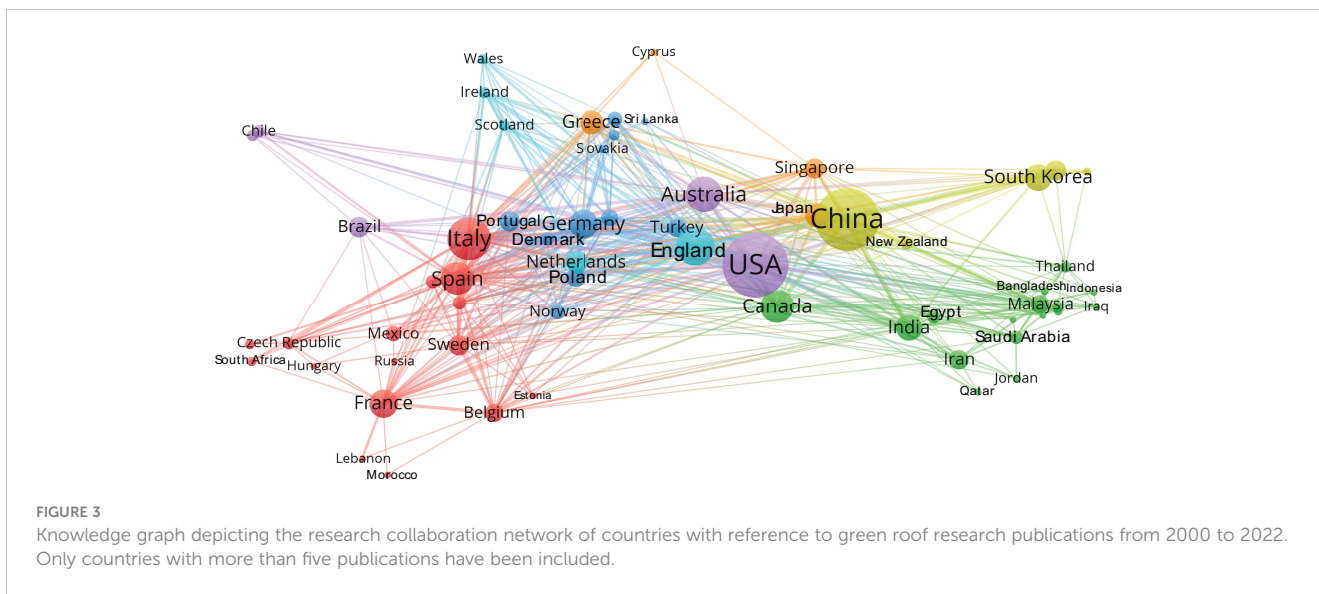
UK have the highest field-weighted citation impacts. This result indicates that Australia is proportionally more influential in green roof research (Irga et al., 2017). Beyond quantity, the data reflects a global distribution of top green roof knowledge clusters extending from Western Europe to North America and Asia-Pacific. With urbanization and climate change challenges becoming more acute worldwide, international collaboration will be essential to advance green roof research. Context-specific studies are needed to understand how regional differences in climate, building types, policies, and culture shape green infrastructure adoption (Chen and Gou, 2022).

The color patterns and proximity of country nodes indicate the strength and direction of their relationships (Figure 3). The diagram excludes countries with less than five publications and limited research capacity. Seven clusters are differentiated, indicating distinct regional research clusters in green roof technology and knowledge sharing. The Asia-Pacific region forms a prominent yellow cluster, indicating close collaborations between China, South

TABLE 2 The top ten countries that published the most papers on green roofs from 2000 to 2022.

Country	Publication	Percent	Total citation	Mean citation	h-index ^a
USA	626	19.94	31,049	49.60	90
China	596	18.99	15,577	26.14	59
Italy	276	8.79	10,958	39.70	54
England	218	6.94	12,057	55.31	60
Australia	186	5.93	10,367	55.74	52
Canada	162	5.16	6783	41.87	44
Spain	157	5.00	4523	28.81	33
Germany	126	4.01	3502	27.79	32
France	118	3.76	3735	31.65	34
South Korea	105	3.35	2031	19.34	27

^aThe h-index is a metric that measures the productivity and citation impact of the publications of a scholar or research group; it is defined as the maximum number h such that a scholar or research group has published h papers with each cited at least h times (Hirsch, 2005).



Korea, Taiwan (China), and Southeast Asian countries. This pattern reflects rapid urbanization and the emerging green building initiatives in the region. North and South America also show tight integration, with the USA playing the bridging role to connect research across the Americas. Western Europe constitutes a densely interconnected red cluster, with countries like Italy, France, Spain, Belgium, and Sweden benefiting from proximity and shared policies and standards under the European Union umbrella. The British Isles represent a somewhat insular but highly productive light-blue cluster, while Germany anchors research in Northern Europe. The Middle East, South Asia, and Africa form a loosely connected green cluster marked by geographic dispersion, relatively weak links, and fewer specialized research institutes. Japan and Singapore in orange have strong research capabilities but less regional integration. Figure 3 illustrates how geographic, cultural, and political factors exert lingering impacts on

knowledge generation, clustering, and diffusion patterns. Targeted cooperation between hubs can strengthen the universal dissemination of green roof expertise while tailoring applications to local contexts (Appio et al., 2019).

The distribution of research forte in green roofs may be echoed by the inter-institution cooperative network, with frequent activities signifying strong research capabilities (Table 3; Figure 4). The Chinese Academy of Sciences published the most papers with 59, followed by the University of Hong Kong with 52. However, the University of Sheffield had the highest total citations (4,308) and mean citations per paper (86.16). Table 3 displays the percentage of total publications, h-index, and countries of the institutions. The data denote the global distribution of research strength, with high output from China and major impacts from the UK, France, USA, and Australia.

No one institution dominates green roof research (Figure 4). Rather, the expertise is distributed across top global cities like Hong

TABLE 3 The top ten institutions that published the most papers on green roofs from 2000 to 2022.

Institution	Publication	Percent	Total citation	Mean citation	h-index	Country
Chinese Academy of Sciences	59	1.88	1677	28.42	21	China
University of Hong Kong	52	1.66	2207	42.44	30	China
University of Sheffield	50	1.59	4308	86.16	30	England
Centre National De La Recherche Scientifique	48	1.53	1051	21.90	21	France
Arizona State University	47	1.50	2554	54.34	28	USA
Arizona State University Tempe	46	1.47	2584	56.17	28	USA
Indian Institute of Technology System	46	1.47	1532	33.30	19	India
National University of Singapore	42	1.34	2536	60.38	26	Singapore
University Of New South Wales Sydney	39	1.24	1016	26.05	21	Australia
Saint Mary's University Canada	38	1.21	2036	53.58	22	Canada
Udice French Research Universities	38	1.21	1221	32.13	18	France
University of Melbourne	38	1.21	2251	59.24	21	Australia

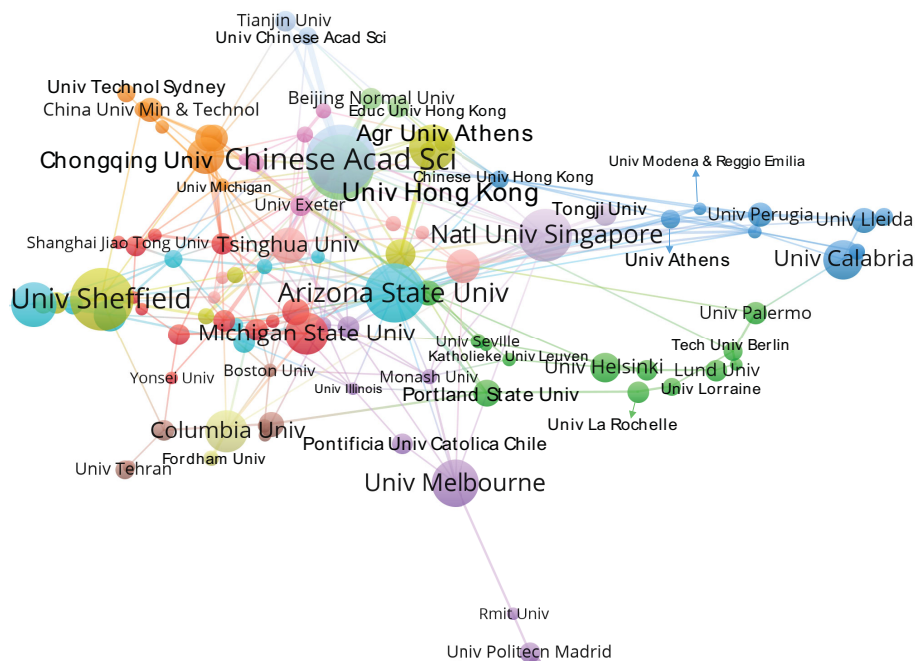


FIGURE 4

Knowledge graph depicting institutional cooperations involving more than ten publications on green roofs from 2000 to 2022.

Kong, Paris, London, Singapore, and Melbourne, which are pioneers of green roof study (Shmelev and Shmeleva, 2019). The research institutions are grouped based on geographical proximity and shared regional expertise in green roofs. The red and light-blue clusters reflect the strong North American hubs, with major US universities at their core. The green and blue clusters represent European centers of excellence, with the green one anchored in Northern Europe and the blue in Southern Europe (Mediterranean region). The strength of Asia-Pacific is seen in the red and orange clusters, which are associated with leading Chinese, Korean, Hong Kong, and Australian universities. The yellow cluster bridges Western Europe and North America, reflecting the lingering trans-Atlantic association. While geography is the main grouping criterion, some universities are prominent connectors between regions. The Swedish University of Agricultural Sciences, Arizona State University, and the University of Hong Kong are present in multiple clusters. The clustering patterns demonstrate time-honored geographic coherence, with universities leveraging regional knowledge sharing while a few globalized institutions cross-pollinate and hybridize ideas between hubs. Identifying and learning the modus operandi of these networking universities could help improve global collaboration.

Therefore, international collaboration is essential to advancing green roof research in the face of urbanization and climate change challenges. Researchers can enhance the growth and dissemination of green roof expertise worldwide by leveraging regional knowledge sharing and fostering cooperation between clusters.

3.2.3 Journal citation analysis

The top 10 journals publishing green roof research extend across a broad interdisciplinary territory and signify an applied focus on sustainable buildings and infrastructure (Table 4).

The journal *Energy and Buildings* has published the most green roof articles (179, 5.7%), which is logical given green roofs' coupling with the building envelope and abilities to reduce building energy use and improve indoor thermal comfort. *Sustainability and Building and Environment* rank next, indicating the technology's role in urban sustainable development. *Ecological Engineering*, and *Urban Forestry & Urban Greening* emphasize green roofs' ecological benefits, while *Water* highlights the stormwater management applications. Major international companies like Elsevier and MDPI publish the leading journals. Most publishers originate from Europe (Switzerland, Netherlands, Germany), followed by North America.

Regarding the three-year impact, *Landscape and Urban Planning* and *Urban Forestry & Urban Greening* have the highest journal citation indicator (JCI) at around 2, reflecting green roofs' expansion beyond engineering into urban ecology and planning. However, engineering-focused journals like *Energy and Buildings* still account for a large share of citations. As green roof research integrates concepts and insights across scientific domains, the publications have decidedly diversified beyond applied engineering into environmental, social, and economic sustainability fields (Berardi et al., 2014; Peng and Jim, 2015; Irga et al., 2017; Wachsmuth and Angelo, 2018). However, knowledge translation and collaboration between cognate disciplines covering engineering, ecology, climatology, and urban planning remain essential to advancing green roof understanding and deployment in cities worldwide.

3.2.4 Key authors

A visual review found 9091 authors associated with 3210 articles. The most frequently published author was C.Y. Jim from the Education University of Hong Kong (previously affiliated with

TABLE 4 The top ten journals that published the most papers on green roofs from 2000 to 2022.

Journal	Publication	Percent	Publisher	Country	Total citation ^a	IF ^b	JCI ^c
Energy and Buildings	179	5.70	Elsevier Science	Switzerland	9424	6.7	1.19
Sustainability	165	5.26	MDPI	Switzerland	2258	3.9	0.68
Building and Environment	157	5.00	Pergamon-Elsevier Science	UK	9248	7.4	1.22
Ecological Engineering	133	4.24	Elsevier	Netherlands	6193	3.8	0.71
Urban Forestry & Urban Greening	121	3.85	Elsevier	Germany	3997	6.4	1.72
Water	102	3.25	MDPI	Switzerland	1286	3.4	0.67
Science of the Total Environment	91	2.90	Elsevier	Netherlands	2832	9.8	1.67
Journal of Cleaner Production	77	2.45	Elsevier Sci	USA	2094	11.1	1.53
Landscape and Urban Planning	66	2.10	Elsevier	Netherlands	8258	9.1	2.26
HortScience	65	2.07	American Society of Horticultural Science	USA	1429	1.9	0.58

^aThe total citation value reported here counts only the citations of green roof papers published in a given journal throughout the study period.
^bA journal's impact factor (IF) is calculated by dividing the number of citations to articles published in the previous two years by the total number of citable articles published in the same period. The IF values in Table 4 were extracted from WoS in June 2023.
^cThe Journal Citation Indicator (JCI) is a metric that compares all journals in the WoS database by their relative citation impact, with 1.0 set as the global average baseline. A journal with a JCI above 1.0 has a higher-than-average citation impact. Conversely, a journal with a JCI below 1.0 has a lower-than-average citation impact. The JCI data in Table 4 were extracted from WoS in June 2023.

the University of Hong Kong), with 52 total publications (Table 5). Applying Price's Law (Li et al., 2022), the key contributors in green roof research were determined by the formula $m_p = 0.749 \sqrt{n_{pmax}}$, where m_p is the minimum number of papers published by core authors during the period, and n_{pmax} is the number of papers by the author with the highest output. The calculation yielded $m_p = 5.30$, identifying 1549 core authors with ≥ 6 publications. Table 5 lists the top ten authors with > 20 publications. These researchers are affiliated with institutions in China, Canada, the USA, UK, and Australia. Researchers from China have published extensively with high citation impact, including C.Y. Jim from Hong Kong. Other prolific authors are from Canada, the USA, UK, and Australia, including Jeremy Lundholm, Bradley D. Rowe, Virginia Stovin, and Claire Farrell. These researchers have collectively published over

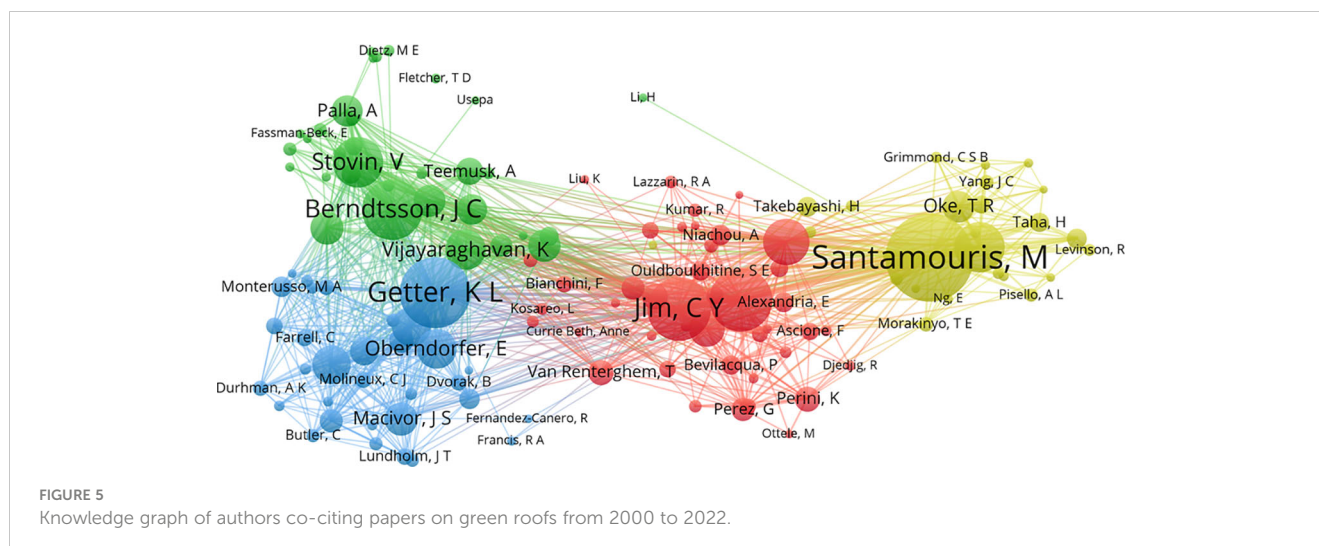
150 articles, each with an h-index ranging from 15 to 27, indicating significant global expertise and influence in this research area.

VOSviewer generated the authors' co-citation network knowledge graph, visualized in Figure 5, with each node representing one author. This diagram depicts the interconnected authorship in the research field. It shows the tangled and complicated linkages between authors, forming four prominent author clusters, each with a single or a few lead authors.

The red cluster includes scholars such as C.Y. Jim, D.J. Sailor, and U. Berardi. They are mainly committed to research on thermal performance, energy impacts, hydrology, microclimate effects, ecosystem services, cost-benefit analysis, policy development, and optimized integration of green roofs in urban environments (Sailor, 2008; Peng and Jim, 2013; Berardi et al., 2014). The authors have

TABLE 5 The top ten authors that published the most papers on green roofs from 2000 to 2022.

Author	Publication	Institution	Country	h-index
Jim, C.Y.	52	Education University of Hong Kong and University of Hong Kong	China	27
Lundholm, Jeremy	32	Saint Mary's University	Canada	18
Rowe, D. Bradley	27	Michigan State University	USA	21
Stovin, Virginia	25	University of Sheffield	UK	19
Farrell, Claire	23	University of Melbourne	Australia	15
Nektarios, Panayiotis A.	23	Agricultural University of Athens	Greece	13
Mat, Santamouris	23	University of New South Wales Sydney	Australia	17
Sailor, David J.	20	Portland State University	USA	17
Garg, Ankit	20	Shantou University	China	8
Ntoulas, Nikolaos	20	Agricultural University of Athens	Greece	12



contributed significant insights into the multifunctional benefits of green roofs in varied climate-building-green roof permutations through field studies, modeling, and interdisciplinary analysis.

The green cluster includes J.C. Berndtsson, V. Stovin, K. Vijayaraghavan, N.D. Vanwoert, M. Shafique, and others. Their research focuses on green roof water and plant relationships, including stormwater and hydrology functions, moisture retention, drought tolerance, water quality improvements, plant dynamics, rooftop agriculture, thermal performance, and energy modeling (Berndtsson et al., 2008; Castleton et al., 2010; Vijayaraghavan and Raja, 2014). Their findings provide important insights into optimizing green roof performance through plant selection, substrate design, irrigation strategies, and integration with stormwater systems.

The blue cluster includes K.L. Getter, E. Oberndorfer, D.B. Rowe, A. Nagase, JS Macivor, and others. Their studies concentrate on biodiversity, habitat creation, plant dynamics, animal populations, thermal performance, energy modeling, moisture retention, and ecosystem services (Lundholm et al., 2010; Nagase and Dunnett, 2010; Rowe et al., 2012). Their results offer useful hints into optimizing green roof vegetation, substrates, and strategies to maximize ecological and energy benefits in urban areas.

The yellow cluster includes M. Santamouris, H. Akbari, T.R. Oke, H. Takebayashi, A. Synnefa, and others. They focus mainly on thermal performance and energy impacts of green roofs, including mitigating urban heat islands, energy savings, microclimate effects, heat flux, evapotranspiration, and cooling potential (Takebayashi and Moriyama, 2007; Santamouris, 2014; Akbari et al., 2016). Their work provides important quantitative insights into optimizing green roof design for maximum energy efficiency and climate change mitigation in urban areas.

3.2.5 Highly cited publications

Urban green roof research has expanded rapidly in the past 15 years, led by teams in North America, Europe, Asia, and Australia (Table 6). Highly cited studies in journals like *Landscape and Urban Planning*, *BioScience*, and *Solar Energy* demonstrate the crucial green roof benefits of mitigating the urban heat island through

evaporative cooling, increased albedo, and shading (Santamouris, 2014), reducing building energy use by lowering cooling demands (Sadineni et al., 2011), retaining stormwater through absorption by vegetation and substrates (Mentens et al., 2006; Dietz, 2007; Czemieli Berndtsson, 2010), and providing wildlife habitat to support biodiversity (Oberndorfer et al., 2007). Additional studies show that integrating green roofs into urban planning can optimize sustainability benefits (Norton et al., 2015). This growing literature establishes that thoughtfully designed green roofs can help cities mitigate climate change impacts, manage stormwater, reduce energy use, support biodiversity, and advance resilience goals (Su et al., 2023). Further research can continue optimizing green infrastructure performance and integration.

3.3 Research hotspots

The growing body of green roof research has demonstrated the versatile abilities to provide sustainability benefits in urban areas (Berardi et al., 2014; Peng and Jim, 2015; Cortinovis et al., 2022), including mainly stormwater management, urban heat island mitigation, energy savings, and biodiversity enhancement (Figure 6). As cities worldwide increasingly recognize green roofs and walls as critical components of resilience and climate adaptation strategies, targeted research will be essential to augment adoption and ensure the realization of full green roof potential to create livable, sustainable, and regenerative urban environments. The following paragraphs discuss four key research hotspots.

- (1) The red cluster is centered around the hydrologic functions of green roofs. The five top keywords are: green roof, green infrastructure, low-impact development, stormwater management, and sustainability (Figure 6). Green roofs are increasingly recognized as a critical green infrastructure and low-impact development solution to mitigate the harmful hydrologic impacts of urbanization (Mentens et al., 2006; Raimondi and Becciu, 2021). Many

TABLE 6 The top ten cited publications on green roofs from 2000 to 2022.

Author	Year	Journal	Country/First institution	Topic	Citation
Wolch et al.	2014	Landscape and Urban Planning	USA/University of California Berkeley	Environmental Science & Ecology	1964
Bowler et al.	2010	Landscape and Urban Planning	UK/UK Centre for Ecology & Hydrology	Environmental Sciences & Ecology	1447
M. Santamouris	2014	Solar Energy	Australia/University of New South Wales Sydney	Energy & Fuels	977
E. Oberndorfer et al	2007	BioScience	Canada/Independent researcher	Life Science & Biomedicine	779
S.B. Sadineni et al	2011	Renewable & Sustainable Energy Reviews	USA/University of Nevada Las Vegas	Science & Technology	728
M.E. Dietz	2007	Water Air and Soil Pollution	USA/University of Connecticut	Environmental Science	658
Berndtsson	2010	Ecological Engineering	Sweden/Lund University	Environmental Sciences & Ecology	641
BA. Norton et al	2015	Landscape and Urban Planning	UK/University of Derby	Environmental Science & Ecology	582
J. Mentens et al	2006	Landscape and Urban Planning	Belgium/Katholieke Universiteit Leuven	Environmental Science & Ecology	564
Alexandria and Jones	2008	Building and Environment	UK/Cardiff University	Construction & Building Technology	559

studies using field experiments, laboratory tests, and computational models have demonstrated green roofs' significant hydrologic functions: stormwater retention, peak flow reduction, and water quality improvement through enhanced infiltration, evapotranspiration, and filtration (Alves et al., 2023). Field studies also quantified

relationships between vegetation type, substrate depth, drainage layer design and water retention (Nagase and Dunnett, 2010; Sims et al., 2016). While most studies focused on individual green roofs, larger-scale modeling showed that widespread green roof installation combined with rainwater harvesting and detention practices could

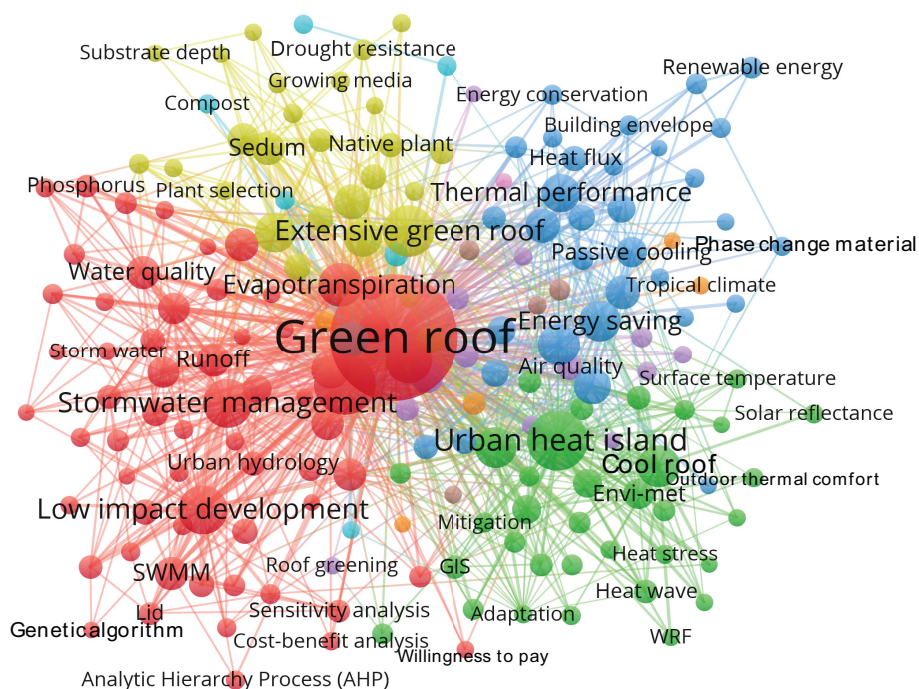


FIGURE 6 Knowledge graph depicting keyword co-occurrence and clustering of green roof research publications from 2000 to 2022.

significantly reduce urban flooding and meet “sponge city” objectives in China (Liao et al., 2017). However, fulfilling such benefits is beset with challenges, including the lack of cost-benefit analysis, financial incentives, and difficulties in retrofitting existing buildings, resulting in limited green roof adoption (Peng and Jim, 2015).

- (2) The green cluster highlights the cooling functions of green and cool roofs. The five top keywords are: urban heat island, cool roof, climate change, Envi-met, and urban greening. Green and cool roofs can mitigate urban heat islands (Figure 6) (Singh et al., 2020). Researchers have increasingly adopted the cooling effects of green roofs and high albedo of “cool roofs” to mitigate the urban heat island (Takebayashi and Moriyama, 2007; Lee et al., 2013; Santamouris, 2014). Many studies have used field measurements, remote sensing data, and microclimate models to assess green and cool roofs’ air-cooling benefits (Jim, 2015b; Vahmani et al., 2016). Extensive green roof installation can increase carbon stocks in Thessaloniki by 2.5 times based on high spatial resolution remote sensing data. The dynamic energy simulations found up to 5% heating and 16% cooling energy consumption reduction in some blocks (Karteris et al., 2016). However, widespread green and cool roof adoption is hindered by high costs and difficulties in retrofitting existing buildings (Shafique et al., 2018). Some studies combined green and cool roofs to tap their synergistic effects (Tewari et al., 2019). Several studies emphasized integrating urban heat island mitigation strategies with city planning using geospatial tools to strategically locate green and cool roofs to optimize cost-benefit (Norton et al., 2015). Future research can provide stronger economic incentives, develop lower-cost solutions for existing buildings, and leverage GIS analysis to identify priority areas for green and cool roof implementation to maximize urban heat island mitigation.
- (3) The blue cluster concentrates on green wall functions of energy conservation and thermal comfort. The five top keywords are: green wall, energy saving, thermal performance, thermal comfort, green building, and energy efficiency (Figure 6). Green walls, also known as living walls or vertical gardens, can furnish energy-saving and thermal comfort benefits in buildings (Irga et al., 2017; Liberalesso et al., 2020). Green walls can reduce heat flux through building envelopes and lower energy consumption for cooling due to added thermal insulation properties (Perini et al., 2011). For example, heat flux through a green wall can reduce internal heat gain and electricity consumption compared to a blank wall (Andrić et al., 2019). Additionally, green walls can passively cool indoor environments through evaporation from plants and growing media (Perini et al., 2011; Norton et al., 2015). This cooling effect improves occupants’ thermal comfort by moderating indoor temperatures (Daghighi, 2015). Furthermore, green walls can reduce life-cycle energy consumption and carbon emissions compared to

conventional walls by factoring in operational energy savings (Ottelè et al., 2011). However, some studies note that green walls may increase environmental impacts due to material use and maintenance (Liberalesso et al., 2020). Therefore, potential tradeoffs with other impacts highlight the need for holistic sustainability assessments (Manso et al., 2021).

- (4) The yellow cluster is associated with the cost-effectiveness of extensive green roofs. The top five keywords are: extensive green roof, vegetative roof, urban ecology, biodiversity, and *Sedum* (Figure 6). Green roofs offer an effective nature-based solution in urban areas (Dorst et al., 2019). Extensive green roofs with shallow substrate depth are well-suited for retrofitting existing buildings. Hardy, low-maintenance succulent species such as *Sedum* were often planted (Rowe et al., 2012; Vijayaraghavan and Raja, 2014). Even in small or modular applications, extensive green roofs can enhance urban biodiversity by providing habitats for plants, insects, birds and other wildlife not typically found in built-up areas (Lundholm et al., 2010). Modeling studies of large-scale green roof deployment indicate that increased connectivity between patches can significantly improve habitat availability and species dispersal across metropolitan regions (Braaker et al., 2014). While upfront costs are rather high, life-cycle assessments (LCA) show that extensive green roofs’ energy savings and ecological benefits can render them competitive over their lifespan vis-a-vis conventional roofs (Clark et al., 2008; Tighnavard Balasbaneh et al., 2024). Green roofs exemplify ecological design innovations that can increase biodiversity, restore critical ecosystem functions, and foster more sustainable and resilient cities.

3.4 Research frontiers

As green roofs continue to gain popularity as a nature-based solution in cities, ongoing research is pushing the frontier to improve understanding and unlock their full potential. The data analysis identified the following five notable research frontiers.

- (1) Enhancing biodiversity and habitat provision. Some studies explore optimal plant selection and traits to support more diverse flora, fauna, and pollinators. An emerging trend investigates leveraging green roofs to enhance urban biodiversity and habitat provision. Thoughtful plant selection and trait-based design can transform rooftops into thriving ecosystems for birds, bees, butterflies and other wildlife (Williams et al., 2014). Strategically selecting native plants, sedums, alliums, and other taxa that provide critical food and nesting resources, ensuring flowering and fruiting times can spread across seasons to optimize foraging opportunities (MacIvor and Lundholm, 2011). Modeling tools and databases with plant trait details

can enable more systematic selection for adaptive characteristics like drought tolerance and heat resistance, which will become increasingly important under climate change (Lundholm et al., 2010; Butler et al., 2012).

Critical research gaps remain regarding detailed plant-pollinator interactions, competition dynamics between native and invasive species, and reconciling aesthetic preferences with biodiversity goals (Williams et al., 2014). Green roofs can be integrated with green walls, parks, and other urban green infrastructure through ecological network modeling and spatial optimization techniques. The outcomes can provide exciting opportunities to augment biodiversity benefits across cities or metropolitan regions.

(2) Integrating green roofs with renewable energy systems. Incorporating solar photovoltaic panels, geothermal heat pumps, rainwater harvesting, and other systems with green roofs can maximize sustainability. An emerging research focus integrates green roofs with renewable energy technologies to maximize urban sustainability benefits (Manso et al., 2021; Liu et al., 2023). For example, green roofs are increasingly combined with building-applied photovoltaics (BAPVs) to form a symbiotic system that can enhance solar panel efficiency while mitigating the urban heat island effect (Santamouris, 2014). (Cruz Torres et al., 2023). Green roof-based rainwater harvesting systems can capture water for irrigation or non-potable building uses while reducing stormwater runoff volumes (Vijayaraghavan and Raja, 2014). Looking ahead, integrated optimization methodologies leveraging computational modeling can develop complementary configurations and sizing of green roof-renewable energy systems tailored to specific climates and building types (Daghighi, 2015; Sims et al., 2016; Morakinyo et al., 2017). More work is needed on long-term performance characterization, life-cycle cost analysis, and interactions between vegetation and renewable systems from an energy standpoint (Ottel  et al., 2011). Another research opportunity lies in policy and incentive structures to encourage joint adoption and cover incremental costs of integration (Irga et al., 2017; Wachsmuth and Angelo, 2018). Innovative studies can investigate how cities increasingly adopted zero-carbon goals, and climate resilience measures can foster combined green roof-renewable energy systems.

(3) Using computational tools and simulations. Applying machine learning, 3D modeling, and tools like EnergyPlus can optimize green roof design and forecast benefits. This development signifies a growing role for advanced computational tools and simulations in green roof design and performance optimization (Tsang and Jim, 2011; Wei et al., 2022). For example, machine learning techniques can improve plant species combination and trait selection and enhance stormwater retention, urban cooling, and biodiversity in different climates (Olivieri et al., 2013;

Aparicio Uribe et al., 2022). 3D modeling can enable virtual prototyping to refine factors like substrate composition and depths, drainage layers, and layouts to balance green roof benefits and engineering constraints (Appio et al., 2019; Shmelev and Shmeleva, 2019). Whole building energy modeling platforms like EnergyPlus can integrate green roof modules to raise the simulation accuracy of impacts on building heating and cooling loads (Sailor, 2008; Cortinovis et al., 2022). As green roofs are increasingly adopted as urban resilience solutions, computational and simulation tools can integrate evaluation of performance, economics, and synergies with other technologies like solar PV (Cruz Torres et al., 2023). However, some knowledge gaps need attention, such as improving the model representation of complex soil-plant-atmosphere interactions, integrating site-specific parameters, and validating against field data (Zare et al., 2017). Multidisciplinary datasets can be enlisted to develop computational co-design frameworks to optimize green roof configurations. The findings can fulfill multiple objectives like energy savings, stormwater reduction, and urban heat island mitigation (James et al., 2009; Zare et al., 2017). Advanced simulations and digital design tools can pump-prime innovations and fine-tune green roof performance.

(4) Focus on appropriate technology for developing countries. Low-cost local materials like compressed earth blocks and passive cooling techniques can be evaluated for social and climate resilience. An important emerging research focus involves evaluating and optimizing green roof design for developing countries. Due to constraints in resources and technical capacity, recent work explores low-cost, locally available materials such as compressed earth blocks and recycled aggregates rather than importing components (Molineux et al., 2009). Green roofs requiring little maintenance for developing regions can be designed using native, drought-tolerant plants (Nagase and Dunnett, 2010; Butler et al., 2012). Innovative passive cooling techniques can integrate wind towers and solar chimneys with green roofs to enhance natural ventilation and indoor thermal comfort (Daghighi, 2015; Morakinyo et al., 2017). Beyond conventional rooftops, community-based greening of dwellings in informal settlements can place green sheets on corrugated metal sheet roofs. Such socially-relevant methods can offer social and environmental co-benefits and climate resilience for vulnerable urban populations (Kimemia et al., 2020). However, ensuring local community participation and addressing structural barriers related to the lack of incentives or supporting policies is equally important. Costs and technical capacity can be reduced through locally available materials and plants. Thus, green roofs combined with down-to-earth passive cooling techniques could provide much-needed indoor cooling. More applied research partnerships between universities and communities can focus on context-appropriate solutions

and multiple co-benefits for social inclusion and environmental justice.

- (5) Quantifying green roof co-benefits in cities. This field has attracted increasing research attention. For example, LCA studies have estimated cumulative energy savings and carbon sequestration benefits from reduced building heating and cooling loads (Peng and Jim, 2015; Cruz Torres et al., 2023). Economic valuations have reckoned cost savings from avoided stormwater infrastructure expansion and substituting it with retention and detention functions of green roofs (Alim et al., 2022). The air quality improvement brought by green roofs can generate public health benefits, as indicated by reduced asthma attacks. This important function of removing particulate matter and gaseous pollutants can be quantified (Singh et al., 2020). Social science methods can measure the mental health value of green roof access for urban residents and workers (Lee et al., 2015). Emerging co-optimization tools can explain tradeoffs between maximizing green roof outcomes like energy savings versus stormwater reduction and biodiversity enhancement (Lundholm et al., 2010; Ma et al., 2023). However, variability in monetization techniques and inconsistent valuation assumptions remain challenging, and demand continued research. Developing widely accepted metrics and standardized methods is crucial for green roof applications. Overall, comprehensive performance quantification and benefit monetization can strengthen the economic case for policy incentives like green roof mandates. It also opens innovative funding opportunities to subsidize or promote green roof installation, such as payment for ecosystem services schemes (Calderón-Argelich et al., 2021).

In addition, a major challenge in green roof research is the lack of accurate quantification and accounting of carbon reduction and sink enhancement benefits. In the complex urban carbon cycle, Green roofs involve natural carbon sequestration through plants and substrates and artificial pathways related to artificial materials, components, installation, and maintenance (Zaid et al., 2018; Dong and He, 2023). This “natural-artificial” duality leads to difficulties in measuring green roofs’ net carbon footprint (Dorst et al., 2019; Cortinovis et al., 2022; Liu et al., 2023). The complex interactions between biotic and abiotic urban carbon fluxes of green roofs require detailed assessment, monitoring and modeling to systematically map carbon pools and flows (Karteris et al., 2016; Zare et al., 2017; Aparicio Uribe et al., 2022). However, limitations in current LCA methods have generated uncertainties about the magnitude of green roof carbon impacts. To enable robust accounting, future efforts must improve LCA protocols tailored to urban ecosystems with a hybrid natural-artificial carbon cycling regime. It is necessary to develop integrated measurement and modeling frameworks to capture the holistic carbon footprint of green roofs across biotic and abiotic components. A more accurate

quantification can offer stronger evidence of carbon benefits to promote adoption.

3.5 Implications and limitations of the study

This study on green roofs has identified several areas for future study, policymaking, and practical applications to enhance urban sustainability. Longitudinal studies covering a certain period can assess the long-term sustainability and resilience of green roof ecosystems. Additionally, comparative studies that evaluate different green roof configurations under diverse climatic conditions can offer valuable insights for optimizing design strategies. Exploring the socioeconomic benefits of green roofs can permit a more comprehensive understanding of their overall value and contributions to the community. Policymakers can leverage our findings to develop supportive policies, incentives, and regulations, highlighting the potential of green roofs as a sustainable urban solution. However, our study indicates that further research is required to assess their economic feasibility and scalability. Professionals involved in green roof design, installation, and maintenance can use our results to make informed decisions regarding plant selection, substrate composition, and maintenance practices. Our findings can guide practitioners in tailoring green roof designs to match site conditions and maximize their environmental benefits in specific urban contexts. Lastly, sharing case studies and best practices from successful green roof projects can facilitate knowledge transfer, foster collaboration among practitioners, and advance professional practice standard.

The reliance on bibliometric data as the primary source of analysis is a limitation of our study. Although bibliometric analysis provides valuable insights into the trends, patterns, partnerships, and scholarly impact of research in the field, it is important to note that it does not capture the full scope of green roof research. The exclusion of non-indexed or non-academic literature, such as gray literatures or reports from industry practitioners, may have resulted in an incomplete representation of the field. Future studies could incorporate a broader range of sources, including non-traditional forms of literature, to gain a more comprehensive understanding. Another limitation is related to potential language biases. Our study focused primarily on English-language publications and excluded relevant research in other languages. This language bias could affect the generalizability and inclusiveness of our findings. Future studies could overcome this constraint by conducting multilingual searches and incorporating research published in various languages to provide a more globally representative view of green roof research. Furthermore, it is important to acknowledge that our study is based on a specific time frame, covering two decades of research. As such, our findings may not have captured the latest developments in the field. Green roof research is a rapidly evolving field characterized by constantly emerging new study directions, technologies, and methodologies. To address this omission, future

research could consider conducting more frequent systematic reviews or employing real-time data collection methods to capture the most up-to-date trends and advancements.

4 Conclusion

Green roofs have become an important nature-based solution for enhancing urban sustainability and resilience. However, research gaps remain in quantifying their full carbon impacts and optimizing their design for the developing world context. Recent studies show that urban vegetation can provide notable carbon sequestration benefits. However, accurately measuring the net carbon footprint of green roofs and walls has remained challenging due to the diverse emission sources, pathways, and quantities associated with varied materials, installation, and maintenance. Computational tools using LCA and process-based biogeochemical modeling show promise for holistically assessing carbon fluxes. However, improved sensor data collection and model parameterization are needed.

Some evidence suggests green roofs may confer cooling benefits in some developing world cities. More research is required to improve the design and selection of plant species assemblages, including more native members, composition and properties of growing mediums, and irrigation practices for cost-effectiveness, climate suitability, and local relevance to natural and socioeconomic conditions in different regions. As cities grapple with converging sustainability crises, nature-based solutions like green roofs and walls are increasingly prioritized in climate adaptation and ecosystem service strategies. However, design tradeoffs related to biodiversity, energy use, and microclimate regulation are complex. Continued research can develop multi-criteria sustainability frameworks and scenario modeling to evaluate ecosystem service bundles and improve decision support.

Additionally, connecting green infrastructure into conjoined landscape-scale green networks demonstrates the potential to enhance and synergize associated ecological benefits. In summary, key research directions are proposed to advance green roofs and walls as innovative and enlightened urban sustainability solutions. They include improving biogeochemical models and sensor networks to strengthen carbon accounting; optimizing designs for the developing world context through climate-smart plant selection and optimized resource-use efficiency; leveraging emerging computational tools to

evaluate ecosystem service tradeoffs; and integrating green roofs and walls into interconnected urban green networks to maximize biodiversity and resilience functions. Addressing these research gaps through interdisciplinary approaches and international collaboration can provide a stronger foundation to harness the full potential of urban green infrastructure.

Author contributions

CX: Data curation, Formal Analysis, Investigation, Methodology, Software, Writing – original draft. DL: Data curation, Formal Analysis, Investigation, Software, Writing – review & editing. CJ: Formal Analysis, Validation, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research was funded by the National Natural Science Foundation of China (grant number: 32360417), the Natural Science Foundation of Hainan Province (grant number: 423MS061, 623RC519), and the Education Department of Hainan Province (grant number: Hnky2023ZD-17).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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