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Systematic Review

Smart Sustainable Buildings: A Bibliometric and Systematic Review of Research Trends, Themes, and Future Directions

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Abstract

This study presents a bibliometric and systematic review of 480 articles meeting the following inclusion criteria: English-language articles, reviews, or proceeding papers focusing on building topics with full text available, retrieved from the Web of Science Core Collection on 9 Jannary 2026 to map the intellectual landscape of smart-sustainable building (SSB) research. Employing the PRISMA framework combined with scientometric mapping (VOSviewer), thematic classification, and qualitative synthesis (no risk of bias assessment was performed as this was a bibliometric review), the analysis reveals exponential publication growth since 2022, identifying three dominant thematic clusters: digital enabling technologies (41.0%), energy systems (30.8%), and advanced building envelopes and materials (28.3%). Keyword analysis identifies "smart buildings," "green buildings," and "energy efficiency" as central conceptual anchors, while temporal trends indicate increasing attention to artificial intelligence, digital twins, and blockchain. Notably, 51.4% of articles address two or more themes simultaneously, confirming the field's interdisciplinary character. Critical analysis reveals persistent fragmentation: sustainable building rating tools (e.g., BREEAM, LEED) and smart building evaluation methods (e.g., Smart Readiness Indicator). Seven challenges, including assessment fragmentation, high costs, and cybersecurity vulnerabilities, are identified as barriers to SSB adoption. Limitations include reliance on a single database (Web of Science) and subjective thematic classification. This review provides a roadmap for future research emphasizing integrated assessment frameworks and interdisciplinary collaboration. Registration: Not pre-registered. Funding: National Key R&D Program of China (2025YFF0521003).

Keywords: bibliometric analysis; smart buildings; sustainable buildings; artificial intelligence; smart sustainable buildings; systematic review

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1. Introduction

Improving human quality of life, which encompasses enhancements in social, economic, and environmental dimensions, is fundamentally linked to the concept of sustainability. Within this framework, the building sector exerts its primary environmental pressures on natural resources, ecosystems, and the general public [1,2]. Consequently, the adoption of sustainable buildings plays a crucial role in facilitating the shift toward

an environmentally sustainable future [3,4]. A sustainable or green building is formally characterized as "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building lifecycle from siting to design, construction, operation, maintenance, renovation, and demolition" [5].

Within the context of dual-carbon policy, zero carbon/energy buildings have attracted increasing attention due to their innovative technologies, which can lower energy demand and carbon emissions while providing low-cost, clean energy sources [6,7]. In addition, the escalating public emphasis on life quality and domestic convenience has accelerated the development of smart building concepts and their associated technological implementations. A range of intelligent and smart solutions, such as the Internet of Things (IoT) [8–10], data analytics [11,12], digital twins [13–15], building information modeling (BIM) [16–18], Building Management Energy Systems (BEMS) [19–21], artificial intelligence (AI) [22–24], and 5G [25,26], are increasingly being adopted to support energy and carbon management at the household level. So far, there have been three core definition paradigms for smart buildings (SBs), i.e., system-based definition, performance-based definition, and service-based definition, depicting intelligence of SBs from different perspectives (user experience, technical composition, and ultimate goals) [27,28]. A typical definition of SBs was given by Hernández et al. [29]: "A smart building is one that incorporates automation, interactivity, and interoperability technologies to enhance energy efficiency, reduce operational cost, and improve user interaction". Modern sustainable building design and operation are intrinsically linked to intelligent technologies, just as contemporary SBs rely fundamentally on sustainability principles and performance criteria. A smart-sustainable building (SSB) is an intelligent built environment that systematically integrates digital technologies (e.g., IoT, BMS, digital twins, AI) with sustainable design and operational principles to enhance energy efficiency, reduce operational cost and environmental burdens, and improve user interaction. Hence, smart-sustainable buildings (SSBs) focus on improving occupant quality of life by forecasting and catering to user needs in urban activities and services and offering efficient measures to lower energy consumption, reduce environmental burdens, and increase the share of renewable energy [30].

Modern high-performance buildings integrate smart and sustainable technologies to optimize energy efficiency, occupant comfort, and environmental performance. As depicted in Figure 1, SB technologies center on building automation systems (BAS) [31,32], IoT sensor networks [33,34], and data-driven platforms [30,35,36]. BAS coordinates HVAC, lighting, access control, and fire safety, while IoT sensors (e.g., occupancy, temperature, CO2, humidity) provide real-time data for automated adjustments. Connectivity protocols such as BACnet, Modbus, Zigbee, and 5G enable seamless device communication. Advanced tools like digital twins and machine learning algorithms enable predictive control, fault detection, and energy forecasting. Edge computing and cybersecurity gateways ensure reliable, secure data processing. Sustainable building technologies focus on energy efficiency, renewable energy integration, water conservation, and indoor environmental quality [37–40]. High-performance envelopes (insulation, triple glazing) [41,42], heat pumps [43,44], and energy recovery ventilators [45,46] reduce operational energy. On-site renewable energy technologies—building-integrated photovoltaics (BIPV) [47,48], solar thermal systems [49,50], and geothermal systems [51,52]—can supply clean energy for buildings. Low-carbon materials (e.g., recycled steel, mass timber) [53,54] and lifecycle assessment (LCA) tools (e.g., SimaPro, One Click LCA) [55–57] support resource management. The intersection of smart and sustainable technologies is where the greatest synergies occur. BMS-based energy analytics enable demand-controlled HVAC and lighting, directly reducing energy waste. Digital twins simulate lifecycle performance, optimizing both real-time operations and long-term carbon footprints. AI-driven predictive control fine-tunes

setpoints to minimize energy while maintaining comfort. Fault detection and diagnostics (FDD) prevent inefficient equipment operation. Thus, truly high-performance buildings are neither purely smart nor purely sustainable; they are smart and sustainable, leveraging intelligent technologies to achieve environmental goals while maintaining operational excellence. As shown in Figure 2, the core technologies are mapped across the key phases of the building lifecycle, including design and engineering, construction, operation and maintenance, and end-of-life.

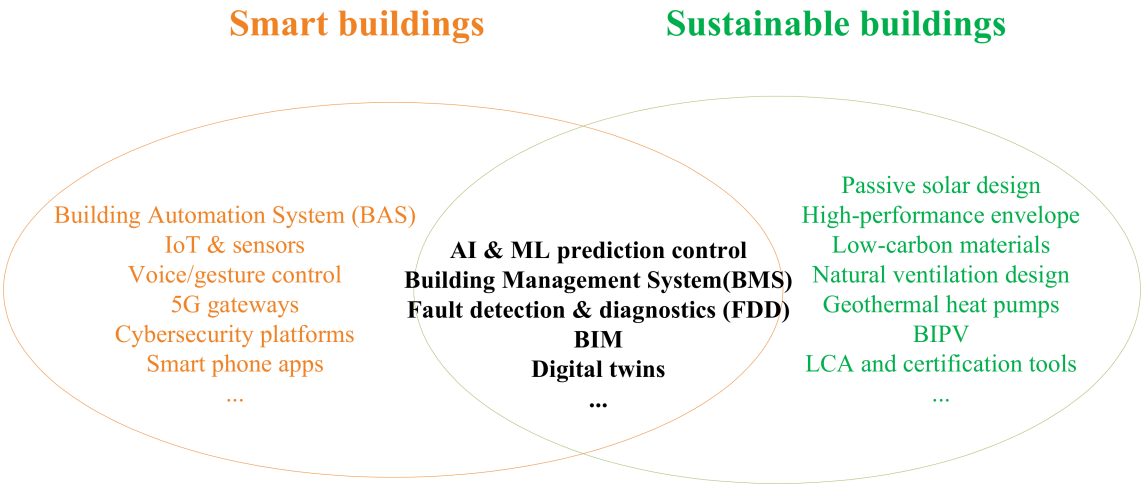


Figure 1. Core technologies for smart buildings and sustainable buildings.

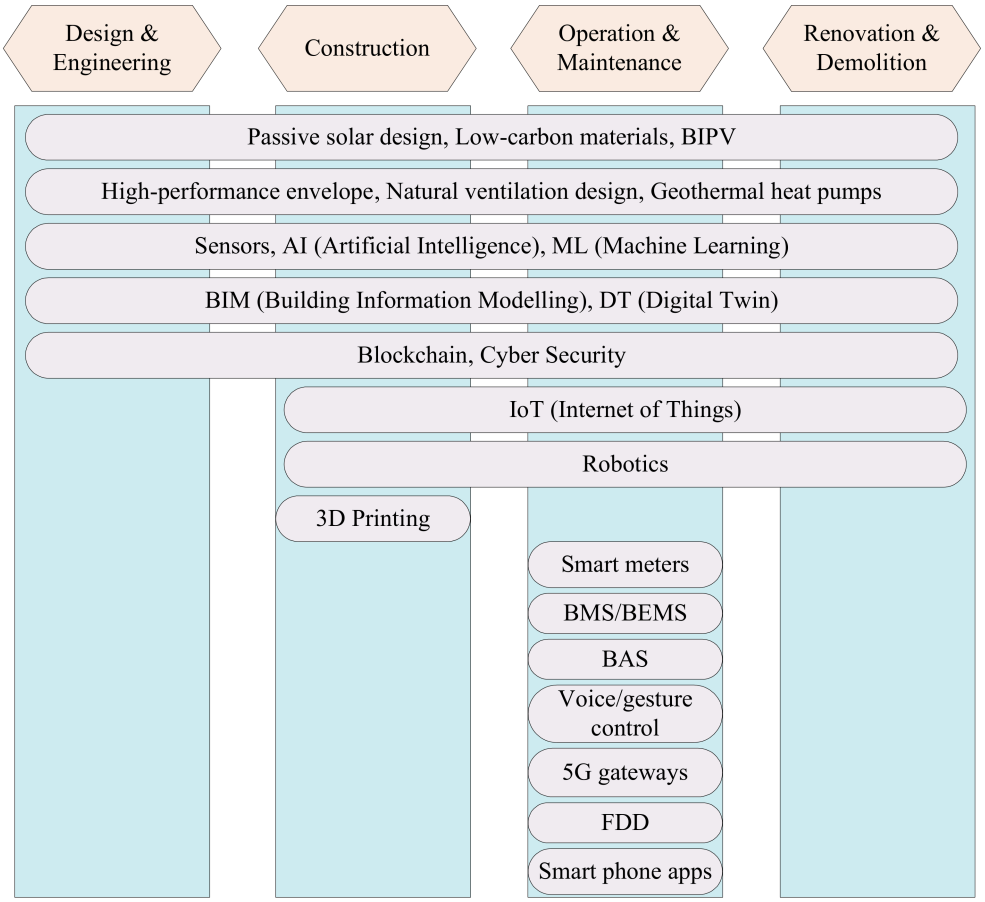


Figure 2. Application domains of core technologies across a building's lifecycle.

Sustainable and green building rating tools (SBRT/GBRT) are fundamental mechanisms for evaluating building sustainability performance. They have prompted nations worldwide to develop context-specific assessment frameworks tailored to their regional priorities, regulatory environments, and climatic conditions. Prominent examples include the UK's Building Research Establishment Environmental Assessment Method (BREEAM), the United States' Leadership in Energy and Environmental Design (LEED), Japan's Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), and Australia's GREEN STAR [58,59]. These established systems have gained international recognition as authoritative benchmarks for quantifying and mitigating the environmental footprint of built infrastructure. The proliferation of diverse assessment methodologies has generated substantial scholarly interest in comparative evaluation of their respective strengths, limitations, and applicability contexts [60–62]. Researchers have conducted systematic comparisons between specific rating tools, examining methodological divergences between LEED and Italy's ITACA protocol [63], Hong Kong's BEAM and LEED [64], and LEED versus BREEAM [65]. Within this comparative literature, LEED and BREEAM have attracted disproportionate academic attention, reflecting their dominant positions in global green building certification markets and their influence on subsequent framework developments worldwide.

As a key instrument for evaluating building intelligence, the Smart Readiness Indicator (SRI) was introduced through the Energy Performance of Buildings Directive (EPBD) in 2018 [66]. Its primary purpose is to assess a building's effectiveness in leveraging Information and Communication Technologies (ICT) and electronic systems to adapt its operations to occupant needs and grid conditions, ultimately enhancing energy efficiency and overall performance. The Smart Readiness Indicator (SRI) operates through a multi-criteria assessment framework. For non-residential buildings, Method B (Expert SRI Assessment) is typically applied, examining 54 smart services distributed across nine technical domains, including heating, cooling, domestic hot water, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control. These services are evaluated against seven impact criteria: energy efficiency, maintenance and fault prediction, comfort, convenience, health, well-being and accessibility, information to occupants, energy flexibility, and storage [67,68]. The SRI test phases across European member states reveal significant heterogeneity in implementation approaches, reflecting diverse national priorities, infrastructural conditions, and regulatory contexts. Italy's test phase demonstrated that office and educational buildings achieve approximately 50% SRI scores for building and user functionalities, while grid interaction capabilities consistently underperform due to immature enabling technologies. Buildings constructed after 2010 show markedly higher scores, attributed to mandatory Class B BACS requirements introduced in 2015 [69]. France adopted a selective approach, designating cooling, domestic hot water, and electric vehicle charging as non-mandatory domains. This reflects national priorities favoring passive cooling strategies and alternative transport modes over energy-intensive systems and EV infrastructure [70]. Germany proposed a dual methodology distinguishing between a basic standardized SRI and an individualized version incorporating facility management and IT infrastructure domains tailored to national specificities [71]. Finland's implementation revealed that the current SRI framework inadequately addresses cold-climate contexts, particularly for buildings reliant on district heating systems [72]. Poland's test phase confirmed progressive score improvements correlated with construction periods, with post-2010 buildings achieving scores above 40% compared to approximately 15% for mid-twentieth-century structures [73]. In summary, the heterogeneity in assessment criteria, domain weighting, and calculation procedures undermines cross-country comparability and hinders identification of transferable best practices [69,74–76].

While numerous reviews have examined the features of SBs and sustainable buildings, the existing literature is characterized by fragmentation across multiple disciplines, lacking a systematic categorization and thematic scope analysis of research topics related to SSBs. For example, Kim et al. [27] reviewed smart building technologies but did not examine sustainability assessment frameworks. Asif et al. [4] discussed digitalization applications but did not quantify the proportional representation of different research streams (e.g., digital enabling technologies vs. human dimensions vs. policy implementation). In addition, most of these reviews fail to examine the relationship between sustainability and intelligence and offer only limited integration of quantitative scientific mapping with qualitative critical synthesis. For example, Gugliandolo et al. [69] examined the SRI, but they did not analyze its relationship with established sustainability certifications. Conversely, Mao et al. [58] analyzed green building rating systems without considering smart readiness indicators like the SRI. This separation means that the 'smart-sustainable nexus' remains conceptually underexplored. This study contributes to the field in the following respects:

- Integrated quantitative and qualitative synthesis of the SSB intellectual landscape. While prior reviews have examined specific aspects of SSBs, this study combines scientometric mapping with qualitative synthesis to provide a more integrated perspective on publication trends, thematic evolution, and research frontiers.
- A structured thematic classification and roadmap for future research. Through a three-stage analytical framework, this review identifies eight core research themes (e.g., digital enabling technologies, energy systems, human dimensions) and their interdisciplinary integration patterns. Furthermore, it delineates seven key challenges (e.g., assessment fragmentation, cybersecurity vulnerabilities, skill shortages) and provides a comprehensive research roadmap, offering actionable priorities to accelerate the transition toward genuinely smart and sustainable built environments.
- An analysis of the relationship between sustainability and intelligence assessment paradigms, contributing to the conceptualization of the 'smart-sustainable' nexus. While the existing literature largely examines smart and sustainable building dimensions separately, this review critically analyzes the relationship between sustainability and intelligence, revealing persistent fragmentation between sustainable building rating tools (e.g., BREEAM, LEED) and smart building evaluation methods (e.g., Smart Readiness Indicator). It explicitly conceptualizes the "smart-sustainable" nexus and exposes the need for integrated assessment frameworks.

The remainder of this paper is structured as follows. Section 2 describes the three-stage analytical framework combining bibliometric, scientometric, and qualitative synthesis methods employed to review 480 articles from the Web of Science core collection. Section 3 presents the results and discussion, including publication trends, journal and regional analyses, keyword evolution, document citation patterns, thematic classification, and a critical examination of the smart-sustainable nexus in building assessment. Section 4 identifies seven key challenges impeding SSB adoption and outlines corresponding future research directions. Section 5 concludes the study by summarizing its principal findings and highlighting the implications for integrated assessment frameworks and interdisciplinary collaboration. By systematically mapping the intellectual landscape of smart-sustainable buildings and exposing the critical fragmentation between sustainability and intelligence paradigms, this review provides researchers, practitioners, and policymakers with a comprehensive evidence base to guide the transition toward built environments that are simultaneously intelligent, sustainable, and resilient.

2. Methodology

In this study, a systematic review was conducted following the PRISMA framework for investigating the field of SSBs. The review was not pre-registered in any public registry (e.g., PROSPERO or OSF) and no review protocol was prepared. As illustrated in Figure 3, a four-stage PRISMA workflow was implemented: identification, screening, eligibility assessment, and inclusion [77]. Given its established reputation as a highly authoritative and selective source for bibliometric data, the Web of Science (WoS) core collection provides the standardized citation metrics required for VOSviewer-based analyses. Moreover, prior bibliometric studies in related disciplines have commonly relied on WoS as a singular data source to ensure consistency in citation indicators. Accordingly, the literature search was conducted on 9 January 2026 using the WoS Core Collection. The literature retrieval process employed a search strategy combining article titles and author keywords, using the following query: {("intelligent building" OR "smart building" OR "intelligent house" OR "smart house" OR "intelligent home" OR "smart home") AND ("sustainable building" OR "green building" OR "zero energy building" OR "zero carbon building" OR "energy efficient building")} OR ("smart green building" OR "smart sustainable building" OR "intelligent green building" OR "intelligent sustainable building"). This combined search strategy is considered more precise and targeted than approaches relying on a single search field, and boolean operator was applied for the search strategy. A total of 663 records were initially retrieved from the WoS Core Collection database. Articles were then excluded if they: (1) were not written in English (items = 3); (2) were not review articles or proceeding paper or articles (items = 13); (3) were not focused on building topics (items = 155); or (4) had unavailable full text (items = 12). Finally, 480 articles remained for an in-depth analysis in the next stage.

A scientometric approach was subsequently adopted to examine publication trends, major research fronts, and the scholarly influence and impact of papers, authors, journals, and regions. This method can offer a macro-level, empirically grounded perspective on large-scale academic datasets, thereby establishing a foundation for more detailed investigations into the subfields of SSB. Among the widely used tools for scientometric analysis, VOSviewer and CiteSpace are two prominent examples. This study employed VOSviewer version 1.6.20.0, owing to its intuitive usability and robust functionality, including the generation of high-quality visualizations. The software manual, which is freely accessible for download, provides additional details regarding the data analysis and the procedures for science mapping [78,79]. A further analysis was conducted aiming at deeply exploring the thematic evolution and the evaluation and assessment frameworks, as well as the potential challenges and barriers to SSB development. The integration of quantitative and qualitative insights facilitates a comprehensive understanding of the field's developmental trajectory, thereby supporting evidence-informed decision-making for future research directions.

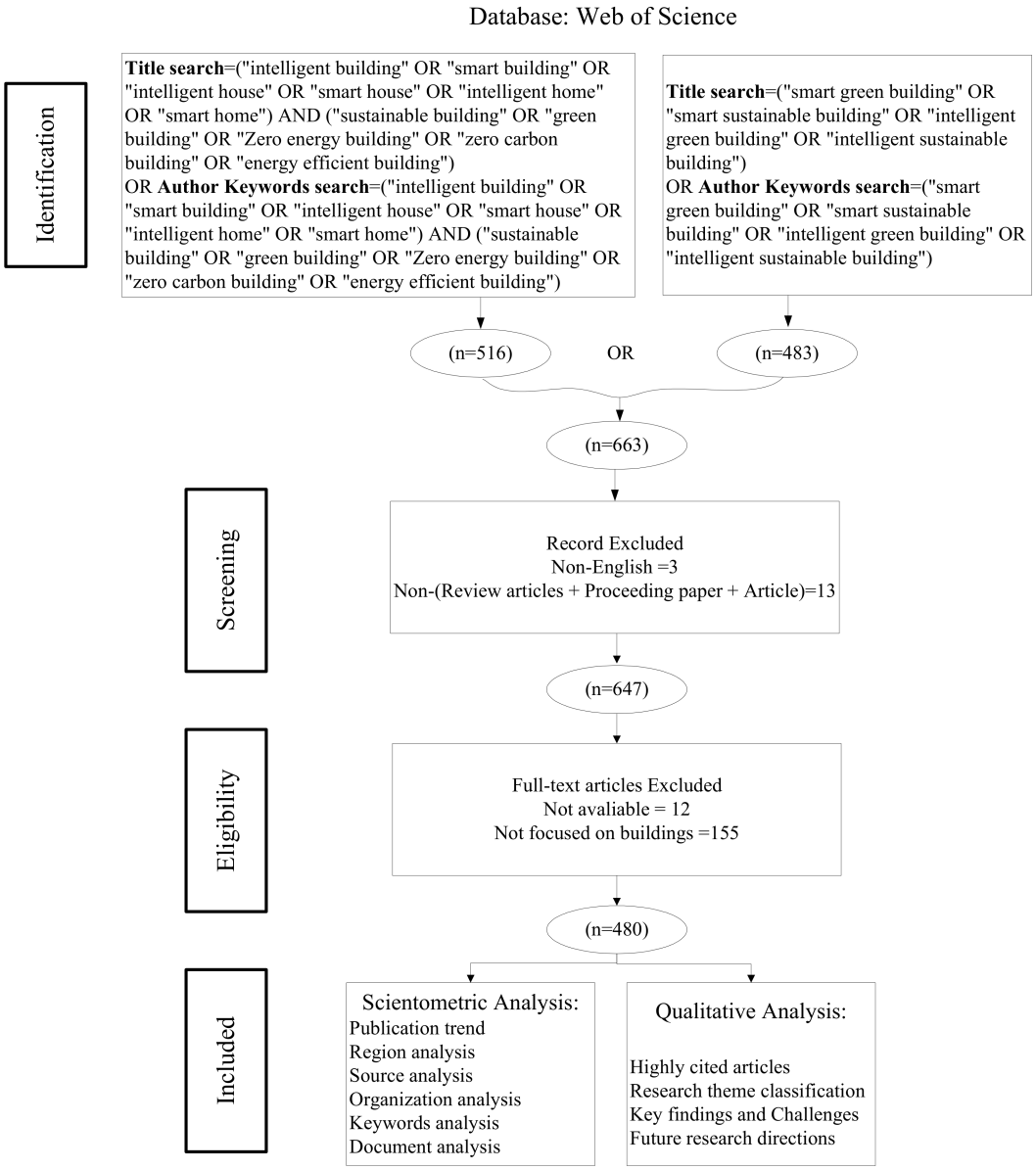


Figure 3. An overview of PRISMA framework for this review study.

3. Results and Discussion

3.1. Overview of Publication Trends

Figure 4 reveals the publication trajectory of SSB research over time. The earliest article in the database dates back to 2009, indicating that this field is relatively young and still in an emerging phase. Between 2009 and 2015, the annual number of publications remained consistently low, reflecting a prolonged period of limited academic activity. A gradual increase in publication output began to emerge around 2015, suggesting a turning point in scholarly attention. This upward trend may be attributed to factors such as technological advancements, increased data availability, or a growing recognition of the field's academic significance. From 2022 onward, the growth rate accelerated markedly, entering a phase characterized by exponential increases in publication volume. The peak was reached in 2025, with 86 articles published in a single year, accounting for approximately 18% of the total literature. This recent surge confirms that SSB research has evolved into a prominent and rapidly developing area of inquiry. Overall, the publication pattern follows a trajectory of gradual emergence followed by accelerated growth, indicating that the field has progressed beyond the exploratory stage and is now undergoing a period of rapid

expansion. This trend reflects both the maturation of the field and its strong potential for continued scholarly contributions in the future.

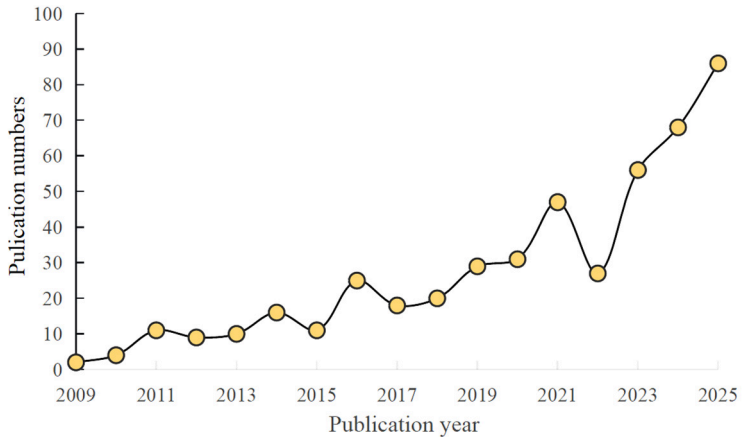


Figure 4. Distribution of 480 article studies.

Figure 5 presents the distribution of cited references across the 480 articles, offering insight into the breadth of literature synthesis within this research field. The analysis reveals a highly concentrated pattern, with the majority of articles (approximately 58%) citing less than 50 references. This concentration suggests a prevailing consensus among researchers regarding an adequate reference volume to support empirical or conceptual contributions. A considerable portion of articles (about 26%) cite between 50 and 100 references, reflecting a more extensive engagement with the prior literature, often associated with studies that provide comprehensive theoretical grounding or address complex, interdisciplinary themes. Notably, only a small fraction of articles cite between 100 and 150 references (around 9%) or more than 200 references (approximately 7%). The overall distribution indicates that while most studies operate within a conventional reference range, a subset adopts a more integrative approach, signaling varying depths of scholarly synthesis across the dataset.

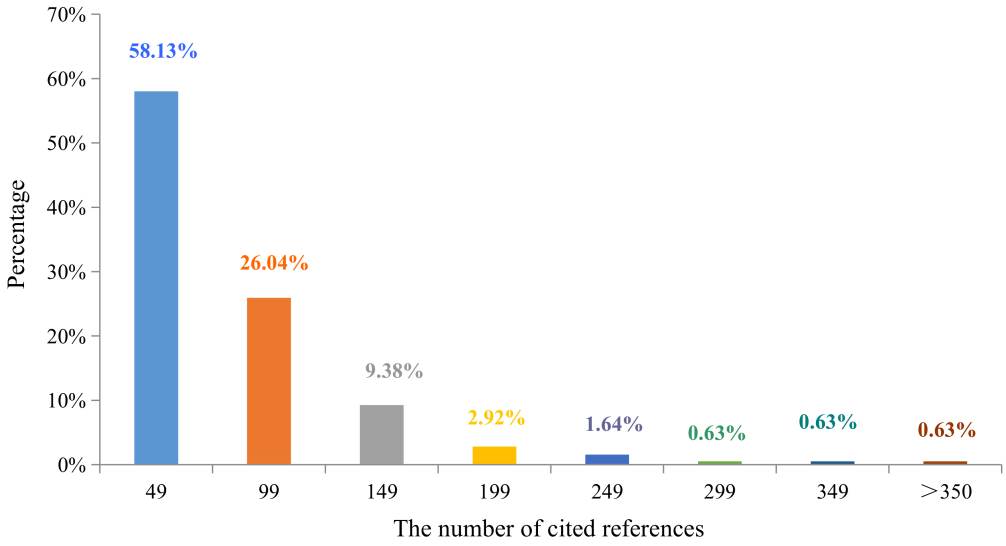


Figure 5. Number distribution of cited references in 480 article studies.

Figure 6 illustrates the citation frequency distribution of the 480 articles, revealing a markedly skewed pattern that underscores disparities in academic influence. The fact that 75% of the articles have been cited fewer than 30 times suggests that the majority of studies in this field achieve relatively limited academic impact. This can be attributed

to several factors inherent to SSB research. First, the field's inherently interdisciplinary nature spanning architecture, engineering, and computer science has led to considerable fragmentation, with many articles addressing highly specialized niches that naturally attract narrower readership. Second, a substantial portion of the literature consists of incremental studies that refine existing knowledge rather than introducing paradigm-shifting concepts. Additionally, given the field's recent exponential growth phase, many articles may not have accumulated sufficient citation windows. A modest proportion (approximately 13%) of articles range from 30 to 60 citations, typically representing well-executed empirical studies or comprehensive subdomain reviews that serve as valuable references for specific research communities. Conversely, a small minority (7%) achieve high impact, garnering over 90 citations. These highly cited works are predominantly foundational contributions–seminal papers establishing theoretical frameworks, pioneering interdisciplinary integrations, or agenda-setting reviews that define research frontiers. Such articles benefit from early-mover advantage and broad applicability across the field's diverse subdomains, confirming that exceptional influence remains concentrated among landmark publications that shape the trajectory of smart-sustainable buildings research.

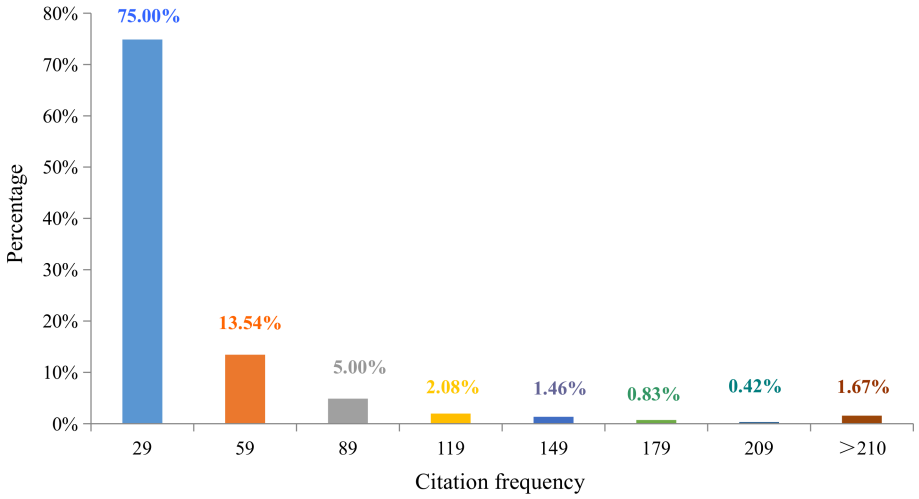


Figure 6. Citation frequency distribution of 480 article studies (based on all databases).

3.2. *Analysis of Article Sources*

Figure 7 presents the leading and most relevant journals in the field of SSB, as identified through a VOSviewer-based analysis of the bibliographic data. From the 480 articles under review, a total of 217 distinct journal sources were identified. By applying a minimum threshold of two articles per source, a network comprising 42 interconnected journals was constructed, and the detailed information was displayed for the first 30 journals, as shown in Table 1. In the visualization, the size of each node and its corresponding label reflect the journal's publication volume, with larger nodes indicating greater scholarly output. Notably, *Energy and Buildings* emerged as the most prolific journal, contributing 32 articles with 1143 citations, followed by *Buildings* (21 articles; 572 citations) and the *Journal of Building Engineering* (16 articles; 241 citations). The connections between nodes represent bibliographic coupling strength, where thicker lines indicate more frequent citation relationships and closer proximity denotes stronger thematic association. With a total link strength of 36, *Buildings* ranked as the most interconnected journal, surpassing *Energy and Buildings*, which recorded a total link strength of 30. Although journals such as *Advanced Functional Materials*, *Advanced Materials*, *Renewable & Sustainable Energy Reviews*, *Solar Energy Materials and Solar Cells*, and *Solar Energy* each contributed no more than five articles, they demonstrated exceptionally high scholarly impact based on average

normalized citation scores. Notably, *Advanced Functional Materials* exhibited the highest average normalized citations among all journals, underscoring its significant influence in the SSB domain despite its relatively modest publication output. Node color corresponds to the average publication year of articles within each journal, offering insight into the temporal evolution of research engagement. The data indicate that *Advanced Materials*, *Journal of Energy Storage* and *Chemical Engineering Journal* began publishing SSB-related research most recently, with average publication years of 2025. In contrast, *IEEE Transactions on Smart Grid*, *Solar Energy*, and *Indoor and Built Environment* were among the earliest contributors to the field, reflecting the foundational role of smart grid and information systems research in shaping the early development of SSB scholarship.

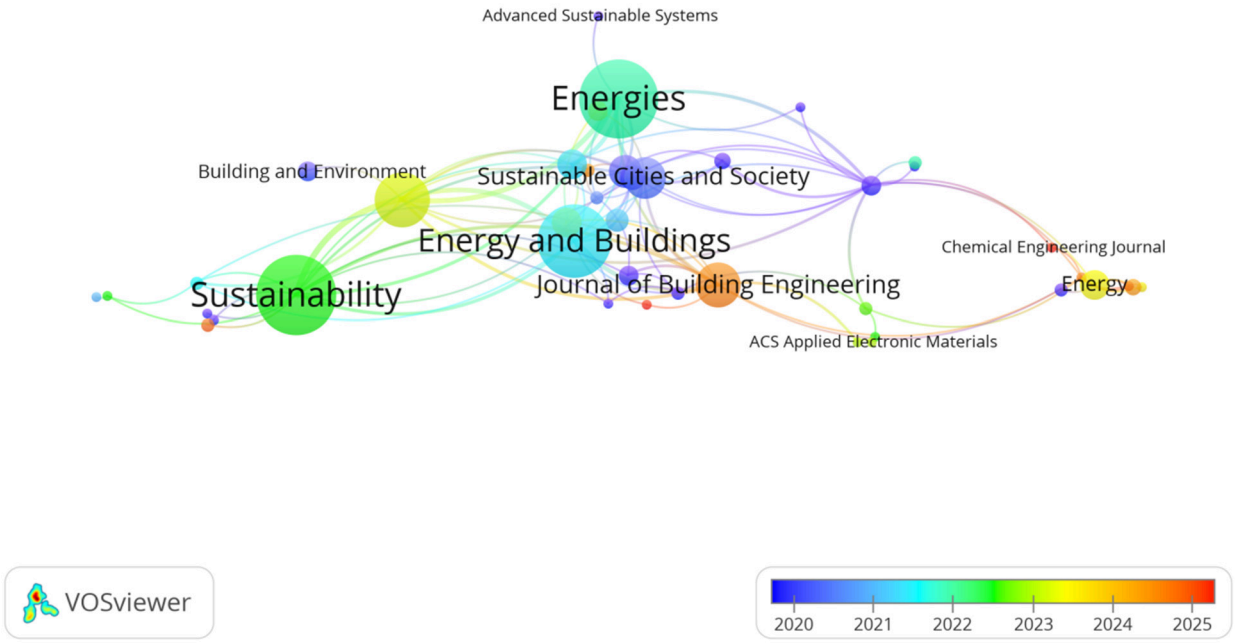


Figure 7. Visualization of article sources.

Table 1. Journal sources of articles related to SSBs.

Journal	Total Link Strength	Article Number	Citation Number	Norm. Citations [1]	Avg. Citations	Avg. Norm. Citations [2]	Avg. Pub. Year [3]
Advanced Functional Materials	4	4	260	39.3	65.00	9.8	2024
Advanced Materials	6	2	64	11.1	32.00	5.5	2025
Renewable & Sustainable Energy Reviews	21	5	1046	22.0	209.20	4.4	2020
Solar Energy Materials and Solar Cells	3	2	127	6.5	63.50	3.3	2023
Solar Energy	5	3	361	9.7	120.33	3.2	2017
Energy Conversion and Management	6	7	568	18.8	81.14	2.7	2019
Journal of Energy Storage	2	2	21	5.3	10.50	2.6	2025
Engineering Construction and Architectural Management	3	2	55	4.6	27.50	2.3	2022
Sensors	8	3	142	6.7	47.33	2.2	2020

Table 1. *Cont.*

Journal	Total Link Strength	Article Number	Citation Number	Norm. Citations [1]	Avg. Citations	Avg. Norm. Citations [2]	Avg. Pub. Year [3]
Nano Energy	9	2	37	4.1	18.50	2.1	2024
IEEE Transactions on Smart Grid	5	4	293	7.3	73.25	1.8	2015
Sustainable Cities and Society	17	14	637	23.2	45.50	1.7	2020
Energy and Buildings	30	32	1143	45.9	35.72	1.4	2021
Construction and Building Materials	5	3	86	4.1	28.67	1.4	2022
Building and Environment	1	5	301	6.3	60.20	1.3	2020
Applied Sciences-basel	12	9	300	11.2	33.33	1.2	2021
Ceramics International	2	2	53	2.5	26.50	1.2	2022
Journal of Building Engineering	25	16	241	18.0	15.06	1.1	2024
Chemical Engineering Journal	2	2	8	2.0	4.00	1.0	2025
IEEE Sensors Journal	5	5	250	4.9	50.00	1.0	2018
Applied Energy	4	6	245	5.9	40.83	1.0	2021
IEEE Access	11	10	249	9.4	24.90	0.9	2020
Buildings	36	21	572	19.3	27.24	0.9	2023
ACS Applied Materials & Interfaces	3	2	33	1.8	16.50	0.9	2023
Journal of Cleaner Production	6	3	91	2.5	30.33	0.8	2021
Indoor and Built Environment	1	2	24	1.7	12.00	0.8	2016
Automation in Construction	3	2	71	1.6	35.50	0.8	2019
Sustainable Energy Technologies and Assessments	5	9	135	7.1	15.00	0.8	2023
Energy	4	9	147	6.9	16.33	0.8	2023
Advanced Sustainable Systems	1	2	38	1.5	19.00	0.8	2018

[1] Norm. citation symbolizes the results of citation standardization by VOSviewer's algorithm. It is obtained by dividing the total number of citations by the average citations published per year. [2] Avg. norm. citation symbolizes the normalized citation per article. It is obtained by dividing norm citations by the number of articles. [3] Avg. pub. year symbolizes the average publication year of articles published in the journal [80].

3.3. Analysis of Article Regions

An analysis of national contributions to SSB research is visualized in Figure 8. The analysis was conducted using VOSviewer with a minimum threshold of five documents per country, yielding a final set of 40 nations. Subsequently, the first 30 nations were selected and displayed in Table 2. China is represented by the largest node, leading in both publication output (132 articles) and total citations (2579), underscoring its dominant position in the field. The United States (42 articles; 1081 citations) and England (38 articles;

1449 citations) follow, reflecting their substantial scholarly influence. China's prominent contribution can be attributed to national policy frameworks that prioritize SSBs as a strategic imperative aligned with energy independence (e.g., the Dual Carbon goals mandate peak carbon emissions by 2030 and carbon neutrality by 2060, and the 14th Five-Year Plan (2021–2025) for Building Energy Efficiency (MOHURD, 2021) sets targets for zero-energy building demonstrations across 30 cities). In contrast, the United States employs a multifaceted approach combining federal financial incentives (e.g., tax credits and deductions), state and local regulatory mandates (e.g., California's Title 24 building code, New York City's Local Law 97), and research funding from agencies such as the Department of Energy (DOE) and the National Institute of Standards and Technology (NIST), collectively fostering market-driven innovation in SSBs. England's contributions are driven by the UK Net Zero Strategy (2021), requiring a 78% emissions reduction by 2035; the Future Homes Standard (2024) mandates no new homes with fossil fuel heating from 2025. Additionally, UK Research and Innovation (UKRI) provides substantial funding for academic research in smart grids, digital construction, and building energy management, further accelerating SSB advancements. Node colors in Figure 8 represent average publication years, with data spanning from 2016 to 2022. Temporal analysis reveals that the Netherlands and Taiwan (China) were among the early contributors to SSB research, whereas countries such as China, Australia, and Iran have engaged more recently. A critical finding is that despite relatively low publication volumes (fewer than 10 articles each), countries including Scotland, Wales, Switzerland, and Pakistan exhibit the highest normalized citation impacts, indicating that their contributions, though limited in quantity, exert considerable scholarly influence within the field. Why are developing countries underrepresented? We identify four contributing factors:

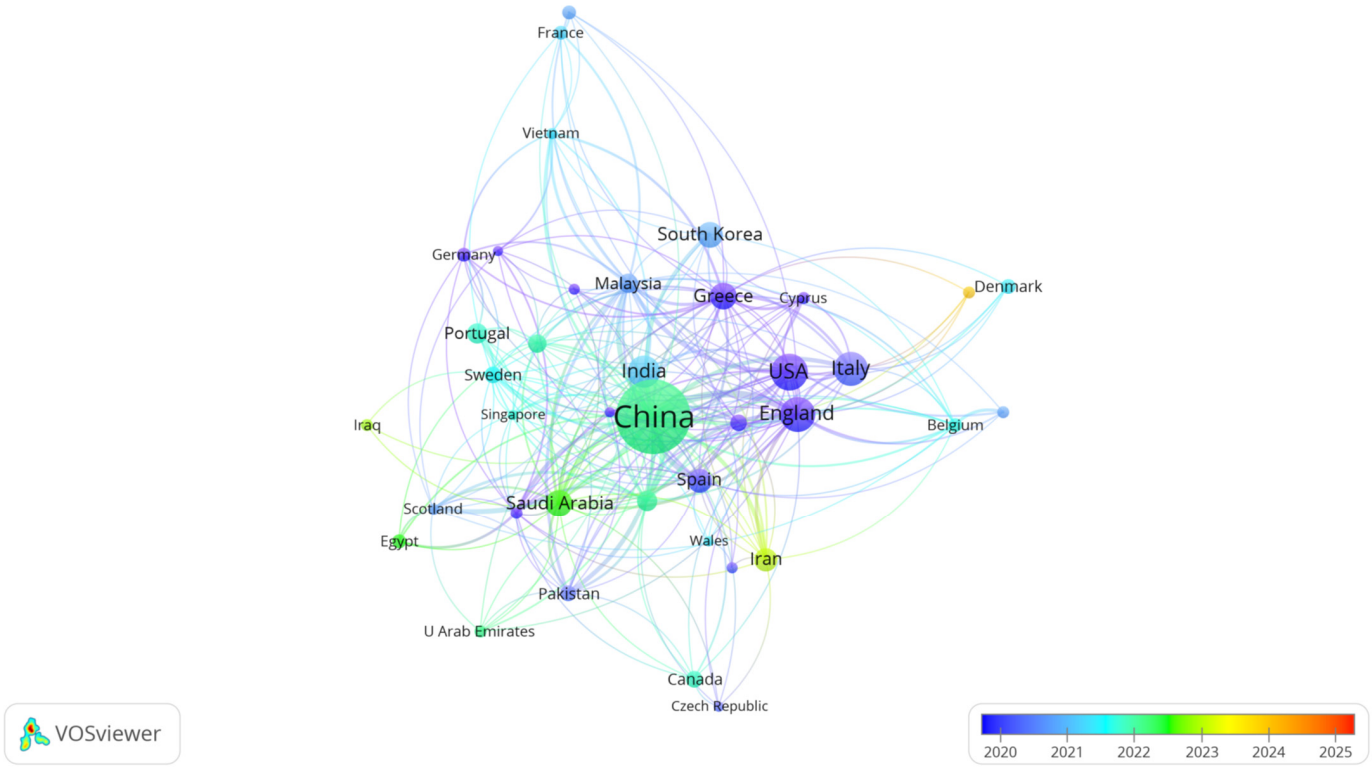


Figure 8. Visualization of article regions.

Table 2. Active region analysis of SSB-related articles.

Country	Total Link Strength	Article Number	Citation Number	Norm. Citations	Avg. Citations	Avg. Norm. Citations	Avg. Pub. Year
Scotland	35	6	414	15.9	69.0	2.65	2020
Wales	6	5	242	9.6	48.4	1.91	2021
Malaysia	87	15	1083	28.5	72.2	1.90	2020
Switzerland	33	7	347	12.4	49.6	1.77	2019
Pakistan	39	10	365	16.8	36.5	1.68	2020
Vietnam	24	6	187	9.9	31.2	1.65	2021
U Arab Emirates	9	7	218	11.3	31.1	1.62	2022
Netherlands	12	5	268	8.0	53.6	1.60	2016
Sweden	27	11	1081	16.4	98.3	1.49	2021
England	88	38	1449	55.2	38.1	1.45	2020
Norway	13	5	132	7.2	26.4	1.44	2019
Czech Republic	6	5	121	7.1	24.2	1.42	2020
Saudi Arabia	60	24	707	33.8	29.5	1.41	2022
Australia	67	16	620	21.7	38.8	1.36	2022
Luxembourg	13	7	271	9.1	38.7	1.30	2020
France	10	8	290	10.1	36.3	1.26	2021
India	38	34	1042	41.1	30.6	1.21	2021
China	226	132	2579	158.1	19.5	1.20	2022
Egypt	10	8	168	9.5	21.0	1.18	2022
USA	50	42	1081	47.3	25.7	1.13	2018
Greece	59	25	810	27.6	32.4	1.10	2019
Iran	32	19	375	19.0	19.7	1.00	2023
Cyprus	18	7	319	6.8	45.6	0.97	2019
Morocco	8	8	173	6.9	21.6	0.86	2020
Denmark	6	9	159	7.7	17.7	0.85	2021
Taiwan	15	11	187	9.3	17.0	0.85	2017
Iraq	3	7	77	5.9	11.0	0.84	2022
Portugal	15	16	271	12.2	16.9	0.76	2021
Finland	4	6	102	4.6	17.0	0.76	2020
Canada	9	11	163	8.3	14.8	0.75	2021

(1) Research infrastructure and funding disparities: SSB research requires investment in sensor networks, building automation systems, and data analytics platforms. Institutions in low- and middle-income countries may lack this infrastructure. The National Key R&D Program of China (which funded this study) represents a scale of research investment not available in many developing economies. (2) Publication bias toward English-language journals: While our search explicitly included all English-language articles, researchers from non-English-speaking developing countries face additional barriers to publication in Web of Science-indexed journals, potentially biasing the literature toward countries with English as a primary or strong secondary language. (3) Building stock characteristics: SSB research often focuses on modern, high-performance buildings. However, many developing countries have predominantly older building stocks or rapid informal urbanization, where retrofitting smart technologies pose different challenges not well-represented in the current literature. (4) Policy and market maturity: The adoption of smart building technologies often follows regulatory mandates (e.g., EU's EPBD requiring SRI assessment) or market incentives (e.g., US tax credits). In countries without such policies, the research base remains underdeveloped.

3.4. Analysis of Keywords

Figure 9 presents the core keywords derived from the analyzed articles, generated using the "Author keyword" field in VOSviewer. A minimum occurrence threshold of five

was applied to ensure analytical relevance, and synonymous terms (e.g., "smart building" versus "smart buildings" versus "smart home(s)" versus "intelligent building(s)"; "building information modelling" versus "BIM" versus "building information modeling"; "green intelligent building" versus "intelligent green building" versus "smart green building") were consolidated to minimize redundancy and enhance interpretability, as shown in Table 3. From an initial set of 1777 keywords, 46 met the inclusion threshold and were retained for visualized analysis, and the first 30 keywords were displayed in detail in Table 4. Within the visualization, both node dimensions and font sizes reflect keyword frequency. The term "smart buildings" emerged as the most prevalent, appearing 142 times, followed by "green buildings" (68 occurrences), "energy efficiency" (61 occurrences), and "smart cities" (43 occurrences). The thickness of links connecting nodes represents co-occurrence strength, indicating the frequency with which keyword pairs appear together across the literature. Aggregate link strength, calculated as the sum of connection weights for each keyword, further illuminates thematic centrality. Notably, "smart buildings" and "energy efficiency" demonstrated elevated total link strength, confirming their function as integrative themes bridging smart development, smart technologies, and energy conservation discourses. Temporal evolution is conveyed through node coloration. Earlier scholarship predominantly emphasized energy-related concepts such as "smart green building" (avg. 2017) and "intelligent control" (avg. 2017). Conversely, more recent contributions have increasingly concentrated on specialized advanced technologies, including "digital twin" (avg. 2023), "artificial intelligence" (avg. 2022), and "deep learning" (avg. 2022). The continued prominence of 'energy efficiency' (61 occurrences) alongside emerging AI keywords indicates that technological novelty is being evaluated against enduring performance metrics.

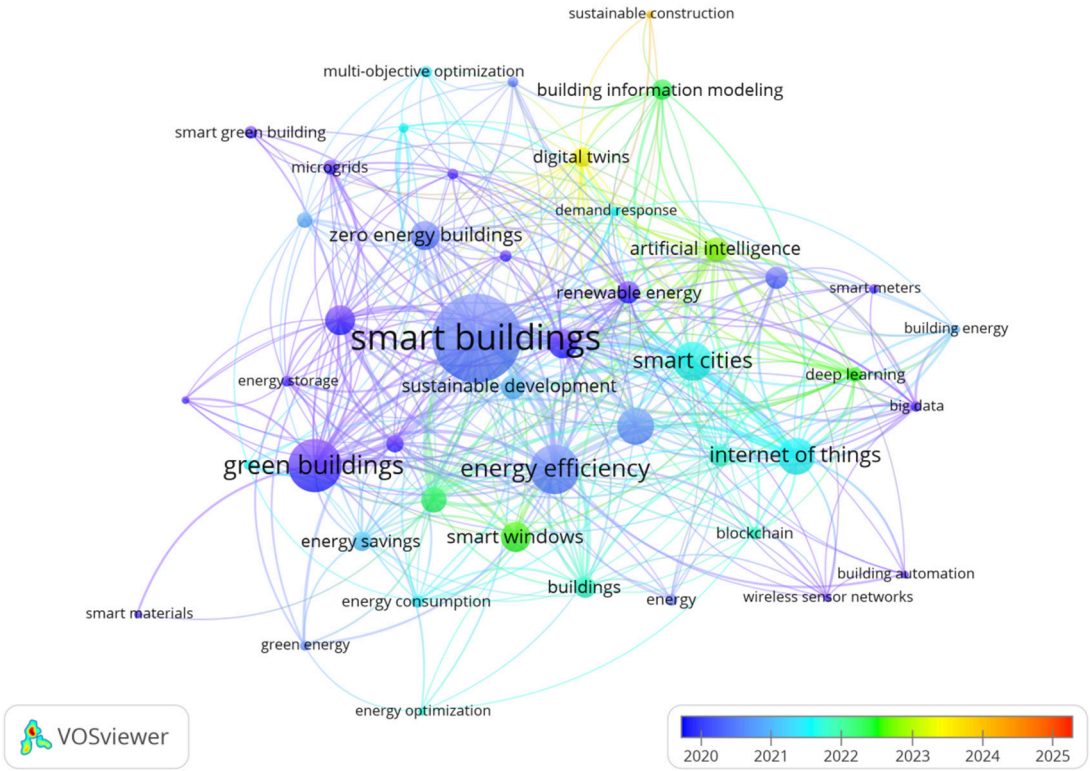


Figure 9. Visualization of core keywords in SSB research.

Table 3. Key keyword consolidation mapping.

Original Terms	Consolidated Term	Explanation
smart building, smart buildings, smart home, smart homes, intelligent building, intelligent buildings	smart buildings	Grammatical variants; conceptually identical in SSB literature
Zero energy building, zero energy building (zeb), zero-energy building, nearly zero energy buildings, net zero energy building, zero energy buildings	zero energy buildings	Hierarchical
building energy management, energy management system, building management systems, home energy management system, energy management	energy management system	Grammatical variants; conceptually identical in SSB literature
AI, artificial intelligence	artificial intelligence	Abbreviation expansion
digital twin, digital twins	digital twins	Grammatical plural
internet of things, IoT, internet of things (IoT)	internet of things	Abbreviation expansion
building information modelling, bim, building information modelling (bim), building information modeling (bim), building information modeling	building information modeling	Abbreviation; British/American spelling
energy-efficient building, energy-efficient buildings, building energy efficiency, energy efficient buildings	energy efficient buildings	Grammatical variants
green intelligent building, intelligent green building, smart green building	smart green building	Functional equivalence
energy saving, energy conservation, energy savings	energy savings	Functional equivalence

Table 4. Keyword co-occurrence analysis of SSB-related articles.

Keyword	Total Link Strength	Occurrences	Avg. Citations	Avg. Norm. Citations	Avg. Pub. Year
smart buildings	233	142	19.2	0.81	2020
green buildings	107	68	18.3	0.85	2019
energy efficiency	128	61	13.9	0.68	2020
smart cities	104	43	29.2	1.07	2021
internet of things	111	41	28.3	1.11	2021
energy efficient buildings	54	40	24.6	1.73	2020
energy management system	71	31	16.5	0.85	2019
smart windows	28	30	58.4	2.77	2022
smart grids	62	29	26.7	0.83	2018
zero energy buildings	43	29	20.9	0.83	2020
sustainability	68	24	17.3	0.78	2022
artificial intelligence	76	22	21.0	1.03	2022
sustainable development	62	22	18.3	0.85	2021
renewable energy	44	20	23.1	0.96	2019
sustainable buildings	28	20	23.8	0.81	2020
machine learning	55	19	22.3	1.04	2021
buildings	46	19	47.1	0.98	2021
building information modeling	26	18	23.1	1.02	2022
digital twins	39	16	42.8	1.56	2023
energy savings	34	16	27.5	1.11	2021
optimization	37	14	80.0	1.71	2019

Table 4. *Cont.*

Keyword	Total Link Strength	Occurrences	Avg. Citations	Avg. Norm. Citations	Avg. Pub. Year
thermal comfort	22	12	21.8	0.85	2020
microgrids	23	11	51.0	1.87	2019
deep learning	47	11	38.8	1.34	2022
blockchain	22	9	59.3	1.84	2021
smart green building	8	9	22.7	0.98	2017
energy consumption	25	9	20.1	0.67	2021
energy	12	8	114.9	1.78	2020
intelligent control	16	8	31.8	1.28	2017
multi-objective optimization	9	8	11.3	0.78	2021

3.5. Analysis of Document Citations

The network map of citation patterns for core documents is presented in Figure 10, derived from VOSviewer. The minimum citation threshold was set as 30 and a connected network of 40 items were identified from 480 articles. Finally, the top 20 highly cited articles were selected and presented in Table 5. The citation number and normal citation were provided as they are widely accepted for assessing a publication's academic impact and value. Three articles, i.e., "A review on optimized control systems for building energy and comfort management of smart sustainable buildings" published in 2014 in *Renewable & Sustainable Energy Reviews* with 635 citations, "A roadmap towards intelligent net zero- and positive-energy buildings" published in 2011 in *Solar Energy* with 289 citations, and "Efficient energy consumption and operation management in a smart building with microgrid" published in 2013 in *Energy Conversion and Management* with 257 citations, are particularly notable for their exceptional citation performance. These foundational works have shaped subsequent research trajectories in optimized control systems, net-zero energy buildings, and microgrid-integrated smart building management, respectively. In terms of normal citation, Marinakis et al. (2018) [81] in *Sensors* with 6.19 normal citation and Sepasgozar et al. (2021) [82] in *Buildings* with 6.05 normal citation were deemed as another two influential articles. Temporal analysis reveals that the majority of highly cited articles were published after 2020, indicating both the field's recent expansion and the increasing citation velocity characteristic of emerging research domains. In addition, *Buildings* appears most frequently with four articles, underscoring its centrality in disseminating influential SSB research. The *Journal of Building Engineering* and *Energy Conversion and Management* contribute two articles, respectively. This concentration confirms that high-impact SSB scholarship is predominantly published in journals specializing in building science, energy systems, and sustainability transitions.

Table 5. List of 20 highly cited papers.

Article	Title	Source	Citation Numbers	Norm. Citations
Kolokotsa (2011) [83]	A roadmap towards intelligent net zero- and positive-energy buildings	*Solar Energy*	289	7.14
Zhang (2013) [84]	Efficient energy consumption and operation management in a smart building with microgrid	*Energy Conversion and Management*	257	7.02
Marinakis (2018) [81]	An advanced iot-based system for intelligent energy management in buildings	*sensors*	129	6.19

Table 5. *Cont.*

Article	Title	Source	Citation Numbers	Norm. Citations
Sepasgozar (2021) [82]	Differentiating digital twin from digital shadow: elucidating a paradigm shift to expedite a smart, sustainable built environment	*Buildings*	242	6.05
Shaikh (2014) [85]	A review on optimized control systems for building energy and comfort management of smart sustainable buildings	*Renewable & Sustainable Energy Reviews*	635	5.65
Wang (2012) [86]	Intelligent multiagent control system for energy and comfort management in smart and sustainable buildings	*IEEE Transactions on Smart Grid*	170	4.64
Shaikh (2016) [87]	Intelligent multi-objective control and management for smart energy efficient buildings	*International Journal of Electrical Power & Energy Systems*	67	4.61
Liu (2023) [88]	Advanced controls on energy reliability, flexibility and occupant-centric control for smart and energy-efficient buildings	*Energy and Buildings*	76	3.92
Dagdougui (2012) [89]	Modeling and optimization of a hybrid system for the energy supply of a “green” building	*Energy Conversion and Management*	143	3.90
Jiang (2018) [90]	Combining bim and ontology to facilitate intelligent green building evaluation	*Journal of Computing in Civil Engineering*	70	3.36
Aslam (2017) [91]	Towards efficient energy management of smart buildings exploiting heuristic optimization with real time and critical peak pricing schemes	*Energies*	104	3.21
Kylili (2015) [92]	European smart cities: the role of zero energy buildings	*Sustainable Cities and Society*	218	3.14
Liu (2019) [93]	Building information management (bim) and blockchain (bc) for sustainable building design information management framework	*Electronics*	86	3.13
Gupta (2021) [94]	Energy-efficient heating control for smart buildings with deep reinforcement learning	*Journal of Building Engineering*	124	3.10
Um-e-Habiba (2024) [95]	A review on enhancing energy efficiency and adaptability through system integration for smart buildings	*Journal of Building Engineering*	36	2.63
Froufe (2020) [96]	Smart buildings: systems and drivers	*Buildings*	64	2.61
Comodi (2015) [97]	Multi-apartment residential microgrid with electrical and thermal storage devices: experimental analysis and simulation of energy management strategies	*Applied Energy*	180	2.59
Kampelis (2017) [98]	Evaluation of the performance gap in industrial, residential & tertiary near-zero energy buildings	*Energy and Buildings*	83	2.56
Yang (2022) [99]	Digital twins for intelligent green buildings	*Buildings*	89	2.48
Chen (2023) [100]	Exploring building information modeling (bim) and internet of things (iot) integration for sustainable building	*Buildings*	47	2.42

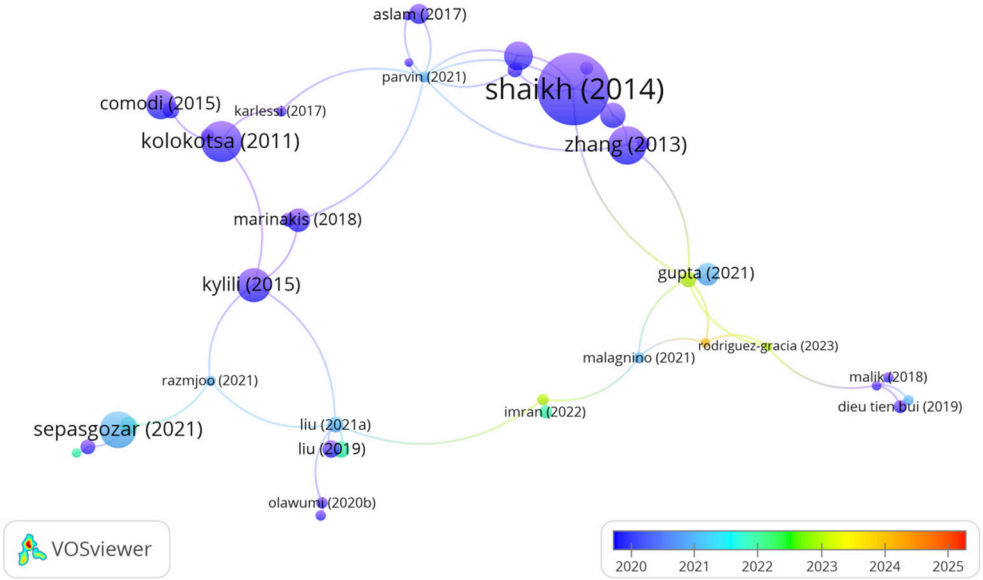


Figure 10. Mapping of document citation patterns.

3.6. Analysis of Research Themes

The 480 articles were further classified into eight core research themes based on information from the titles and abstracts, as shown in Figure 11. As this review did not perform a meta-analysis, the results of the thematic syntheses are presented as descriptive statistics (counts, percentages, and distributions) rather than pooled effect estimates. This classification enables a comprehensive understanding of the intellectual structure and research priorities characterizing the SSB field. Digital enabling technologies (T2) emerge as the dominant research stream, comprising 41.0% of the publications (197 articles), reflecting the transformative potential of digital solutions (e.g., artificial intelligence, IoT, and automation systems) in enabling real-time monitoring, predictive control, and optimized building performance. Energy systems (T3) constitute the second most prevalent theme, with 148 articles (30.8%), followed closely by advanced envelopes and materials (T4), represented in 136 articles (28.3%). The substantial proportion of T2, T3, and T4 underscores the field's fundamental orientation toward technological innovation as the primary driver of smart and sustainable building development. Human dimensions, encompassing occupants, comfort, and behavior (T5), account for 108 articles (22.5%). The prominence of this theme signals a paradigm shift from purely technological optimization toward human-centric design approaches. Foundations and concepts (T1) (91 articles, 19.0%) and implementation and policy (T8) (97 articles, 20.2%) demonstrate comparable representation, indicating sustained scholarly attention to theoretical frameworks, conceptual development, and the practical deployment of SSB innovations within regulatory and market contexts. These themes bridge academic research with real-world application, addressing questions of scalability, feasibility, and policy alignment. Conversely, evaluation and assessment (T6) (70 articles, 14.6%) and emerging paradigms (T7) (58 articles, 12.1%) receive relatively modest attention, and the limited coverage of the two themes indicates potential research frontiers warranting further investigation. Note that many studies address more than one theme; therefore, articles are counted in each applicable category, and the sum of percentages exceeds 100%.

The thematic coverage analysis of 480 SSB research articles was further investigated as shown in Figure 12. Remarkably, over half of the articles (51.4%, 247 articles) address two themes simultaneously, indicating that interdisciplinary integration is the prevailing mode of inquiry in SSB research. Articles covering three themes account for 30.8% (148 articles),

while those focused on a single theme represent only 13.9% (67 articles). Four-theme integration, though least common at 4.0% (19 articles), demonstrates the field's capacity for comprehensive synthesis.

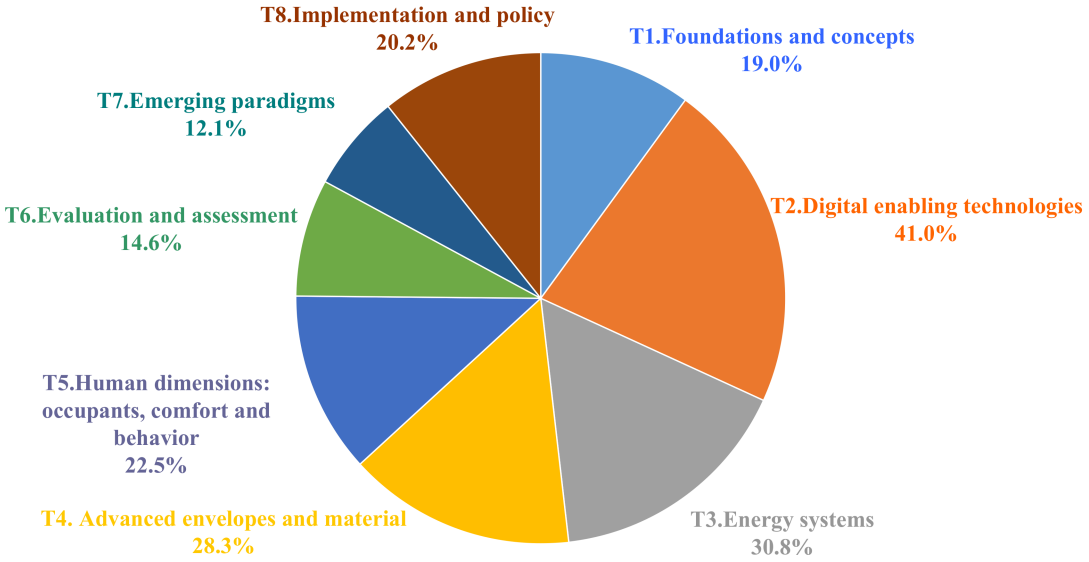


Figure 11. Thematic focus and trends in SSBs research.

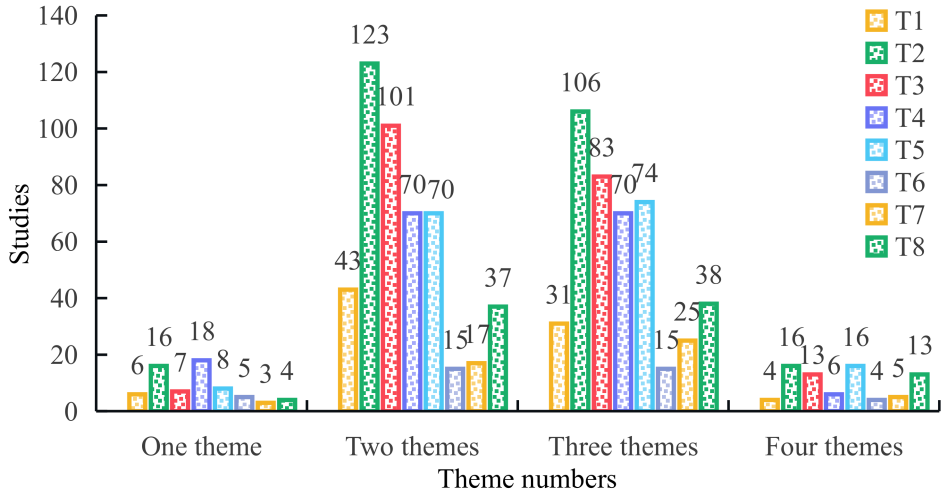


Figure 12. Themes covered in the 480 research articles.

Digital enabling technologies (T2) dominate the field with the highest degree of thematic integration, featuring 123 two-theme and 106 three-theme articles, confirming their role as cross-cutting enablers that connect diverse research domains. Energy systems (T3) and advanced envelopes and materials (T4) exhibit substantial multi-theme presence, reflecting the inherently interconnected nature of building performance research. Notably, human dimensions (T5) demonstrate remarkable integration despite moderate total articles, with 70 two-theme and 74 three-theme publications, indicating growing recognition that occupant factors must be considered within broader technological contexts. Conversely, evaluation and assessment (T6) and emerging paradigms (T7) show limited multi-theme integration, suggesting specialized or nascent research areas yet to achieve full cross-disciplinary synthesis. Four-theme integration remains rare across all categories, with T2 and T5 leading at only 16 articles each, highlighting the challenge of comprehensive interdisciplinary synthesis. Overall, SSB research exhibits substantial cross-thematic engagement, particularly among digital technologies, energy systems, advanced materi-

als, and human dimensions, confirming its inherently integrative nature while revealing opportunities for deeper synthesis across underrepresented thematic combinations.

To better understand the nature of two-theme integration, the specific thematic combinations were analyzed in Figure 13. The most dominant pairing is Technology–Technology (31.6%), reflecting extensive integration among digital enabling technologies, energy systems, and advanced materials, which collectively form the technical backbone of SSB research. This is followed by Technology–Human combinations (23.5%), confirming that occupant-centric considerations are increasingly embedded within technological developments. Foundation–Implementation pairings account for 15.0%, indicating sustained attention to bridging conceptual frameworks with practical deployment. Technology–Implementation combinations represent 10.9%, while Technology–Emerging paradigms (5.3%) and Technology–Evaluation (4.0%) are less frequent, suggesting that assessment methodologies and emerging concepts remain weakly integrated with core technologies. Human–Implementation combinations are notably scarce (2.8%), revealing a gap between occupant research and practical application.

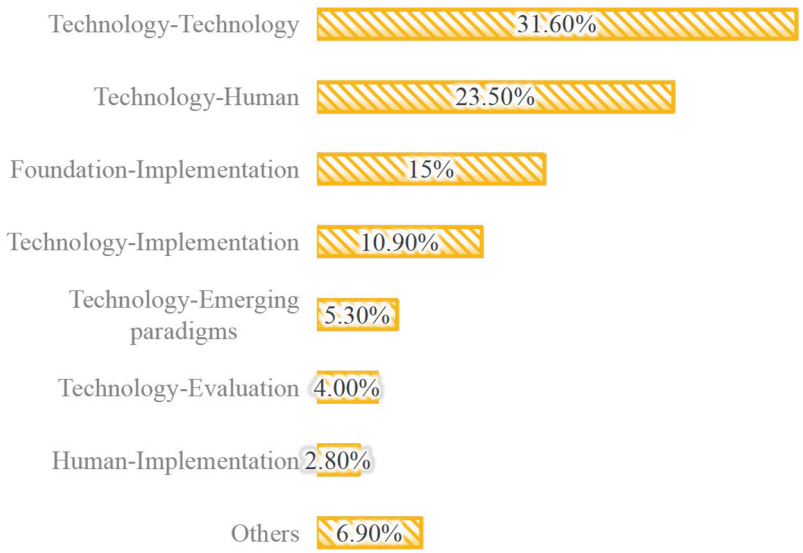


Figure 13. Classification of studies covering two research themes.

3.7. The "Smart-Sustainable" Nexus in SSB Evaluation

The finding that only 14.6% of articles address evaluation and assessment themes (T6) indicates a gap in the SSB literature. To explore this gap further, this section undertakes a critical synthesis of the selected literature on building assessment frameworks, complementing the bibliometric findings with qualitative analysis of how sustainability and intelligence paradigms intersect.

3.7.1. Assessment Fragmentation of the "Smart-Sustainable" Nexus

A critical examination of the existing assessment landscape reveals that sustainable building rating tools and smart building evaluation frameworks have largely developed along parallel, albeit interconnected, trajectories. This historical separation has created a fragmented understanding of building performance, where the synergistic potential between digital intelligence and sustainability outcomes remains underexplored. The "smart-sustainable" nexus represents the critical intersection where these two dimensions converge, demanding integrated assessment paradigms that move beyond siloed evaluation.

The foundational work of Alwaer and Clements-Croome [101] presciently identified this challenge, arguing that a truly sustainable intelligent building is not merely one equipped with advanced technologies but rather a complex system integrating environmen-

tal, social, economic, and technological factors. Their development of the SuBETool demonstrated that effective assessment requires balancing stakeholder priorities across these four dimensions. However, their empirical work revealed a persistent issue that continues to resonate: subjectivity in weighting and priority setting among different stakeholders can substantially skew assessment outcomes, with priority level differences sometimes having a greater impact on final scores than measured performance data.

More recent methodological advances have sought to operationalize an integrated perspective. Stylianides et al. [102] proposed a holistic assessment framework that explicitly encompasses four impact categories: energy efficiency, resource utilization, occupants' comfort, and smart/digital readiness level. Their weighted average scoring methodology enables a unified assessment that captures both passive sustainable features and active smart functionalities. Meanwhile, Gugliandolo et al. [69] critically examined the SRI within European decarbonization governance, revealing that even advanced frameworks remain predominantly focused on technological readiness rather than integrated sustainability outcomes. Their review of national test phases demonstrates a fundamental disconnect: deep energy efficiency renovations may substantially improve traditional energy performance certificates while generating only marginal improvements in SRI scores, and conversely, high SRI scores do not necessarily correlate with proportionally lower operational carbon emissions.

3.7.2. Beyond Synthesis: Toward a Causal and Operational Nexus Framework

The assessment fragmentation is not merely technical but epistemological. Existing frameworks treat "smartness" and "sustainability" as additive properties rather than transformative relationships. The SRI asks "how automated is this building?" while LEED asks "how energy-efficient is this building?" Neither asks the essential question: "How does this building's smartness enable measurable sustainability outcomes, and how do sustainability constraints shape the value of its smartness?" Without this bidirectional causal logic, any integration remains superficial.

In addition, current frameworks lack temporal and adaptive logic. Sustainability is a dynamic target as decarbonization pathways, grid conditions, and occupant expectations will evolve over a building's lifecycle. Yet existing assessments are predominantly static and conducted at a single point in time. A genuine nexus framework must accommodate adaptive reassessment, learning from operational data, and continuous recalibration of the relationship between smart functionalities and sustainability performance.

Finally, stakeholder subjectivity should be reframed as a design feature rather than a bug. Different stakeholders legitimately value different dimensions of the smart-sustainable nexus. Rather than attempting to eliminate subjectivity through fixed weightings (which inevitably embed arbitrary expert judgments), a robust framework should make stakeholder preferences transparent, negotiable, and traceable, enabling context-sensitive yet comparable assessments.

3.7.3. Toward an Integrated Evaluation System for the Smart-Sustainable Nexus: A Conceptual Blueprint

Building on the above analysis, this review proposes a conceptual blueprint for a next-generation evaluation system specifically designed to capture the smart-sustainable nexus. The proposed system rests on four design principles and the following principles are proposed as a conceptual starting point requiring empirical validation. They are presented as design heuristics rather than a validated assessment tool.

Principle 1: Bidirectional Causal Mapping. The evaluation system must explicitly map how each smart functionality (e.g., predictive HVAC control, demand-response participation, real-time occupancy sensing) contributes to specific sustainability outcomes (e.g., kWh

energy reduction, CO_2 emissions avoided, peak load shaving, occupant productivity gains). Conversely, it must assess how sustainability constraints (e.g., passive design limitations, material embodied carbon, renewable energy intermittency) condition the effectiveness of smart technologies. This bidirectional logic transforms the nexus from a conceptual slogan into an operational framework.

Principle 2: Dynamic and Data-Informed Scoring. Moving beyond static point-in-time checklists, the proposed system should incorporate three temporal layers: (a) design-stage predictive scoring based on specifications and simulation; (b) operational scoring based on continuous monitoring data from BMS, IoT sensors, and smart meters; and (c) adaptive updating where scores evolve as buildings learn and optimize over time. This dynamic approach aligns with emerging concepts such as the Digital Building Logbook and operational digital twins discussed by Gugliandolo et al. [69].

Principle 3: Modular and Context-Adaptable Weighting. Recognizing that the optimal balance between smart and sustainable dimensions varies by building type, climate zone, grid carbon intensity, and regulatory context, the framework should adopt a modular architecture. Core indicators are fixed to ensure cross-jurisdictional comparability, while regional or project-specific modules allow adjustment of weightings based on local priorities. However, unlike purely subjective approaches, these weightings must be justified through transparent, evidence-based criteria.

Principle 4: Stakeholder-Configurable Reporting Dashboards. Building on diverse stakeholder perspectives, the evaluation system should produce not a single aggregated score but a multidimensional dashboard. Different stakeholders, i.e., policymakers, building owners, facilities managers, and occupants, can configure the display to emphasize dimensions relevant to their decision context (e.g., carbon abatement cost for policymakers, operational savings for owners, comfort metrics for occupants). This transparency preserves comparability while respecting legitimate differences in valuation.

The proposed conceptual blueprint requires empirical validation through: (1) retrospective application to existing dual-certified buildings (LEED + SRI) to test scoring consistency; (2) pilot implementation in 5–10 buildings across different climate zones and building types; (3) stakeholder workshops to calibrate modular weightings; and (4) longitudinal tracking (minimum 24 months) to validate dynamic scoring. This validation work is beyond this review's scope but constitutes an immediate research priority.

4. Challenges and Future Research Directions

The adoption of smart technologies in sustainable buildings, while promising, faces several significant challenges that must be addressed to realize their full potential, as shown in Table 6.

Fragmentation of Assessment Paradigms: The thematic analysis (Section 3.6) reveals that evaluation and assessment themes (T6) account for only 14.6% of articles (70/480), ranking among the least represented themes. Furthermore, two-theme integration analysis (Figure 13) shows that Technology–Evaluation combinations represent only 4.0% of paired studies, indicating weak integration between assessment research and core technological developments. Future research should develop integrated assessment frameworks that explicitly capture the smart-sustainable nexus, moving beyond additive scoring toward causal methodologies that quantify how smart functionalities generate measurable sustainability outcomes. Priority should be given to bridging the Technology–Evaluation gap identified in Figure 13.

High Initial Costs: While cost-related keywords (e.g., "energy savings," "optimization") appear in the keyword analysis (Table 4), economic barriers are rarely the primary focus of SSB research. Only 20.2% of articles address implementation and policy themes

(T8) and within this category, cost-related discussions typically appear as secondary considerations rather than primary research questions. The regional analysis (Section 3.3, Table 2) shows that countries with emerging economies (e.g., China, India, Iran) have joined the field more recently (average publication years 2022–2023), suggesting that cost barriers may be particularly salient in these contexts but remain underexplored. Implementing smart technologies in buildings requires substantial upfront investment. For instance, building automation systems for a typical 100,000 square foot (approx. 9290 m^2) building can cost around $230,000, while software licensing for BIM and digital twin applications presents financial barriers for many practitioners [103,104]. Future research should focus on developing cost-effective solutions tailored to diverse economic contexts, such as the Building Data Lite system demonstrated by Anik et al. [105], which achieved indoor environment sensing at just $70 per node. Comprehensive cost–benefit analysis frameworks are needed to help building owners evaluate viable options.

Table 6. Bibliometric evidence under each challenge.

Challenge	Bibliometric Evidence Source	Quantitative Indicator
Assessment fragmentation	Thematic distribution (Figure 11); two-theme integration (Figure 13)	T6 = 14.6% of articles; Technology–Evaluation = 4.0% of pairs
High costs	Keyword analysis (Table 4); regional analysis (Table 2)	'Energy savings' = 16 occurrences; China avg. pub. year 2022 (emerging economy)
Compatibility issues	Keyword analysis; thematic integration	'Standardization' is absent from top 30 keywords; Technology–Implementation = 10.9%
Cybersecurity	Keyword analysis; highly cited articles (Table 5)	No cybersecurity terms in top 30 keywords; zero of 20 highly cited articles focus on security
Skilled workforce	Thematic distribution; regional citation analysis	T5 (human dimensions) = 22.5%; high-impact countries have low volume
User adoption	Two-theme integration (Figure 13)	Human–Implementation = 2.8% (lowest combination)
Regulatory gaps	Thematic distribution; geographic concentration	T8 = 20.2%; China, US, UK = 44% of articles

Compatibility Issues: The keyword co-occurrence analysis shows that "building information modeling" (18 occurrences), "internet of things" (41 occurrences), and "digital twins" (16 occurrences) appear with moderate frequency, but terms related to interoperability (e.g., "standardization," "protocols," "integration frameworks") are notably absent from the top 30 keywords. The thematic integration analysis (Section 3.6, Figure 12) reveals that while 51.4% of articles address two or more themes, Technology–Technology pairings (31.6%) dominate, whereas Technology–Implementation combinations represent only 10.9%, suggesting that research on translating technological interoperability into practice remains limited. Future research should explore standardization protocols, interoperability frameworks, and modular system designs that facilitate seamless integration across diverse technology generations and manufacturers.

Cybersecurity Vulnerabilities: The keyword analysis reveals that cybersecurity-related terms do not appear among the top 30 keywords. "Smart meters" (six occurrences), "wireless sensor networks" (five occurrences), and "big data" (seven occurrences) appear with low frequency, and none of the highly cited articles in Table 5 focus primarily on cybersecurity. This absence suggests a critical research gap, as digitalization increases connectivity without corresponding attention to security implications. With increasing

connectivity through smart meters, BIM, BMS, and IoT, buildings become susceptible to cyber threats. Industry reports suggest four out of ten connected buildings may be at risk of cyber-attacks. Data privacy concerns arise from large datasets containing sensitive occupant information [4,106–108]. Research priorities include developing robust cybersecurity frameworks specifically tailored for building systems, establishing incident response mechanisms, and creating security assessment methodologies that evolve with emerging threats.

Skilled Workforce Shortage: The thematic analysis (Section 3.6) shows that human dimensions (T5) account for 22.5% of articles (108/480), indicating moderate attention to occupant comfort and behavior. However, workforce development and skills training are not explicitly represented as sub-themes within T5. The regional analysis (Table 2) shows that countries with the highest normalized citation impacts (Scotland, Wales, Switzerland, Pakistan) have relatively low publication volumes (fewer than 10 articles each), suggesting that research capacity is concentrated in a few regions while workforce development needs are global. Smart technologies require new knowledge and skills for optimal operation and maintenance. The lack of digital competencies in the workforce represents a significant adoption barrier, compounded by routine-biased technological change, shifts in job market demand, and competency pressure [109–111]. Future research should investigate effective training methodologies, competency frameworks, and educational programs that bridge the digital skills gap in the construction sector.

User Comprehension and Adoption: The keyword analysis shows that "thermal comfort" (12 occurrences) appears, but terms such as "user acceptance," "technology adoption," or "human factors" are absent from the top 30 keywords. The two-theme integration analysis (Figure 13) reveals that Technology–Human combinations account for 23.5% of pairings, indicating growing attention to occupant-centric considerations. However, Human–Implementation combinations are notably scarce (2.8%), revealing a gap between occupant research and practical application. The success of smart technologies depends critically on user adoption, yet many occupants struggle to understand technology functions and operational strategies. Research should explore user-centered design approaches, intuitive interface development, and behavioral studies that enhance technology acceptance. Priority should be given to bridging the Human–Implementation gap through field studies and longitudinal adoption research.

Regulatory and Policy Gaps: Implementation and policy themes (T8) account for 20.2% of articles (97/480), indicating moderate attention. However, the thematic integration analysis (Figure 13) shows that Foundation–Implementation pairings account for 15.0% of two-theme studies, while Technology–Implementation combinations represent only 10.9%. The regional analysis reveals substantial geographic concentration, with China (132 articles), the United States (42 articles), and England (38 articles) dominating publication output, while many regions with significant building stocks (e.g., Southeast Asia, South America, Africa) are underrepresented. Many regions lack robust legal and regulatory frameworks addressing data privacy, security, and emerging technology guidelines. Given digitalization's global scope, international cooperation is needed to develop consistent, harmonized regulations. Research should examine policy mechanisms that foster innovation while protecting stakeholder interests. Comparative policy analysis across different regulatory regimes, studies of technology transfer to underrepresented regions, and investigation of incentive structures for SSB adoption are urgently needed. International cooperation to develop harmonized standards should be prioritized.

5. Conclusions

This systematic and bibliometric review of 480 articles has comprehensively mapped the intellectual landscape of smart-sustainable building research, revealing a field experiencing exponential growth and increasing scholarly attention. This study makes three principal contributions to the SSB literature.

First, the analysis confirms that SSB research has matured from fragmented, technology-focused inquiries into an interdisciplinary domain characterized by substantial cross-thematic integration. Digital enabling technologies, energy systems, and advanced materials constitute the technical backbone, while human dimensions and implementation frameworks are emerging as complementary priorities. The finding that 51.4% of articles address multiple themes simultaneously substantiates the field's integrative character, though four-theme integration remains rare (4.0%), indicating opportunities for deeper synthesis.

Second, the bibliometric evidence reveals a critical gap: evaluation and assessment themes (T6) account for only 14.6% of articles, and Technology–Evaluation pairings represent just 4.0% of the two-theme studies. This underrepresentation, combined with keyword analysis showing absence of interoperability and cybersecurity terms from high-frequency keywords, exposes systemic fragmentation between sustainability rating tools and smart readiness evaluation. The smart-sustainable nexus, the bidirectional relationship where digital capabilities enable sustainability outcomes, remains conceptually underexplored and methodologically unoperationalized.

Third, the geographic and citation analyses demonstrate concentrated research capacity, with China, the United States, and England contributing 44% of articles, while nations with smaller publication volumes (Scotland, Wales, Switzerland, Pakistan) exhibit disproportionately high normalized citation impacts. This pattern suggests that scholarly influence is not solely a function of publication volume and that diverse research traditions contribute meaningfully to the field.

For research policy and practice, these findings imply that future investments should prioritize: (i) development of integrated assessment frameworks that move beyond additive scoring toward causal methodologies; (ii) standardization of interoperability protocols and cybersecurity baselines; (iii) workforce development programs targeting the digital skills gap; and (iv) comparative policy research across underrepresented geographic contexts. Addressing these priorities will require coordinated interdisciplinary collaboration among building scientists, computer scientists, social scientists, and policymakers.

This review has several limitations. The sole reliance on the Web of Science core collection may have excluded relevant publications from other databases (e.g., Scopus, Google Scholar, or discipline-specific databases) and the underrepresentation of certain regions may reflect database bias rather than actual research activity. The search query, while systematically constructed, may not have captured all the SSB literature. The thematic classification involved subjective judgments without formal inter-rater reliability testing. The qualitative synthesis of assessment frameworks (Section 3.7) is purposive rather than systematic. Citation-based analyses favor older publications and may underrepresent recent contributions that have not yet accumulated citations. Finally, much of the existing literature assumes institutional and infrastructural contexts characteristic of high-income countries, limiting its applicability elsewhere. These limitations should be considered when interpreting the findings and should inform the design of future reviews.

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