Bibliometric Visualization Analysis of Sustainable Design Research - Based on a Review of Three Decades

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Abstract. This investigation explores the fundamental research, prominent hotspots, and prevailing trends of sustainable design through the analysis of 3,317 papers from the Web of Science (WoS) Core Collection database spanning from 1994 to 2023. The following conclusions are reached: (1) The annual publication volume has manifested a general upward trajectory; nevertheless, the growth rate has exhibited considerable variance. Significantly, there was a substantial escalation in publications from 2010 to 2023, suggesting that the sustainable design domain is likely to sustain a high research momentum in the future. (2) Concerning the development of the academic community, the scholar collaboration network is relatively decentralized. Among the institutional collaboration networks, Egyptian Knowledge Bank, Northwestern University, and Delft University of Technology have the highest publication output. The top three countries in the national collaboration network in terms of publication volume are the United States, China, and the United Kingdom. (3) The knowledge foundation of sustainable design research encompasses two main components. One focuses on sustainable design or life cycle optimization within biofuel supply chains, while the other pertains to the integration of sustainable design principles into product design, ecological design, and environmental planning. (4) The current research hotspots in the sustainable design field comprise sustainable development, green architecture, multi-objective optimization, and life cycle optimization. The current research trend has shifted from the early phases of life cycle assessment, energy efficiency, sustainable development, buildings, climate change, thermal comfort, and design education to contemporary concerns such as circular economy, sustainability, global optimization, environmental impact, waste, recovery, water, machine learning, and products.

Keywords: Sustainable Design, Bibliometric, Visualization Analysis.

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1 Introduction

In the 21st century, human society faces unprecedented environmental and social challenges. With the growth of the global population and shifts in consumption patterns, issues such as excessive resource depletion, environmental pollution, ecosystem disruption, and social inequality have become increasingly pronounced. These challenges pose a significant threat to humanity's sustainable development, necessitating a re-examination and adjustment of existing production and consumption models. In this context, sustainable design has emerged as a vital strategy for addressing these multifaceted challenges.

The concept of sustainable design emerged in the 1970s, coinciding with the rise of the environmental protection movement and the widespread adoption of sustainable development principles. This prompted a critical reflection within the design field regarding traditional practices that overlooked environmental and social impacts. In 1987, the United Nations World Commission on Environment and Development introduced the concept of sustainable development in its report "*Our Common Future*", thereby establishing a theoretical foundation for sustainable design's evolution. Following this, designers, scholars, and policymakers began to investigate methods for integrating environmental and social considerations into the design process to promote efficient resource utilization, minimize waste and pollution, and enhance product life cycle value [1, 2]. As global consensus around sustainable development goals has increasingly solidified, sustainable design has emerged as a significant research focus within the design discipline, with its theories and practices continually deepening and expanding [3].

Over the past few decades, research in sustainable design has made significant advancements. Transitioning from initial Ecodesign to contemporary sustainable design, this field has evolved from a singular environmental focus to an integrated consideration of social, economic, and environmental dimensions. Researchers have developed various tools and methodologies to assist designers in incorporating sustainability requirements into product development processes. Ceschin and Gaziulusoy (2016) proposed a framework for the evolution of sustainable design based on four levels of innovation (product, product-service systems, social-spatial systems, and social-technological systems), which synthesizes the progression within the realm of sustainable design and illustrates how different approaches facilitate specific aspects of sustainability [4]. Ryan (2013), through the Visions and Pathways 2040 project, demonstrated how design can guide future visions by creating a series of "glimpses of the future" aimed at fostering low-carbon and resilient urban environments. These visions were generated through participatory methods and utilized to promote strategic dialogues among stakeholders, resulting in diverse future scenarios and pathways for policy innovation [5]. Furthermore, the roles of social innovation and system innovation within sustainable design are increasingly acknowledged. Social innovation emphasizes facilitating societal change through design practices while system innovation focuses on transforming socio-technical systems via design interventions. These studies underscore the potential role of design in advancing both social equity and environmental sustainability while simultaneously highlighting challenges that must be addressed in practice—such as altering user behavior, accounting for cultural differences, and navigating the process of innovation diffusion [6, 7].

Despite the growing volume of research outcomes in sustainable design, a review of the existing literature reveals that the distribution of literature, knowledge base, research directions, and development trends within this field remain unclear. Consequently, this paper employs bibliometric methods alongside visualization tools to investigate the domain of sustainable design over a thirty-year period, with the aim of providing meaningful insights for both theoretical advancement and practical approaches in sustainable design.

2 Materials and Methods

2.1 Data Sources

The research data was sourced from the Web of Science (WoS) database provided by Thomson Reuters, which encompasses the fields of natural sciences, social sciences, engineering technology, and arts and humanities, characterized by its comprehensiveness, integration, and authority [8]. On October 2, 2023, a search was conducted through the electronic library within the Web of Science™ Core Collection. The temporal scope of the retrieved data extended from January 1, 1994 to September 30, 2023; the search parameter utilized was TS: ("sustainable design"). A total of 3,317 documents were identified. Following data cleaning procedures, the number of documents remained unchanged.

2.2 Data Sources

Utilizing CiteSpace 6.2.R4 (64bit) Advanced, the data was meticulously analyzed and examined. The configurations in the functional parameter area are as follows: In the Time Slicing functional area, the selected time frame spans from 1994 to 2023, and the extracted value of "#Years Per Slice" is 1; The parameters in the Pruning functional area and the Visualization functional area are set as default; In the Links functional area, the Cosine algorithm is chosen to calculate the association strength of network nodes, as in (1)

$$\text{Cosine}(c_{ij}, s_i, s_j) = \frac{c_{ij}}{\sqrt{s_i s_j}} \tag{1}$$

where is the co-occurrence count of i and j, is the frequency of i, and is the frequency of j [9].

Furthermore, in the Selection Criteria functional area, the g-index is selected to extract knowledge units, as in (2)

$$g^2 \leq k \sum_{i \leq g} c_i, k \in Z^+ \tag{2}$$

where k is the scale factor and the threshold is set to 20.

Finally, calculations and sorting of measurement indicators were conducted using Excel 2019 while data visualization and graphing were executed through Origin Pro 2019.

3 Results and Discussion

3.1 Analysis of Annual Publication Volume

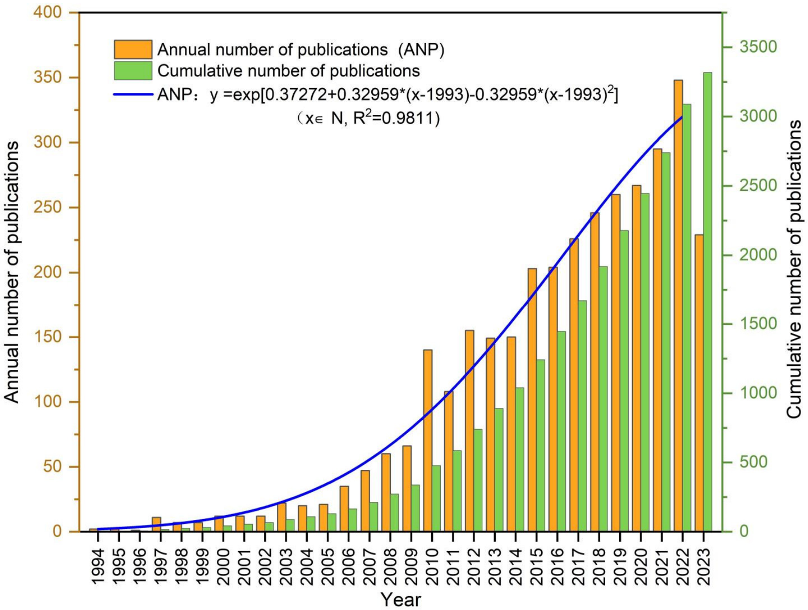

Fig. 1. The inter-annual variation of article quantity and the cumulative article quantity from 1994 to 2023.

The inter-annual variations in the number of published articles were systematically analyzed for the 3317 publications in the WoS database. As illustrated in Fig. 1, the volume of literature on "sustainable design" has exhibited a consistent upward trend from 1994 to 2023. In 1996, there was only one publication, marking the lowest point over these years; conversely, in 2022, the number surged to 348, reaching its peak and constituting 10.49% of the total output. The distribution of literature within the field of "sustainable design" can be categorized into three distinct phases. From 1994 to 2002, annual publications did not exceed twelve, reflecting an exceedingly slow growth rate. Between 2003 and 2009, there was a noticeable acceleration in annual publications; however, none surpassed seventy during this period. From 2010 to 2023, there was an explosive increase in annual publications—accounting for an impressive 89.84% of total outputs over these fourteen years—with an average annual publication rate soaring to approximately 212.9 articles per year. Utilizing existing statistical data on literature production trends, a cumulative index growth model for annual publications was developed based on observed growth patterns: $y=\exp[0.37272 + 0.32959^{*}(x - 1993) - 0.32959^{*}(x - 1993)^2]$ ($x \in N$, $R^2 = 0.9811$). This model indicates that research within the domain of "sustainable design" is likely to sustain high levels of interest and topic relevance for a significant duration into the future.

3.2 The Development of the Academic Community

The academic community is defined as a collective of individuals who share identical or similar values, convene around common conceptual frameworks or interest objectives, and adhere to established behavioral norms. In practical contexts, this collaboration is manifested through scientific research partnerships, encompassing author collaboration, institutional cooperation, and national alliances [10].

Upon analysis, the author collaboration network within the domain of sustainable design research appears relatively fragmented. Among these scholars, 13 have published at least five articles. They are listed in descending order based on publication frequency: Fengqi You (frequency = 66), Victor Yepes (frequency = 18), Jian Gong (frequency = 18), Rafiqul Gani (frequency = 15), Jiyao Gao (frequency = 11), Bin He (frequency = 10), Dajun Yue (frequency = 10), Hyo Seon Park (frequency = 6), Daniel J. Garcia (frequency = 6), Ignacio J. Navarro (frequency = 6), Erin F. MacDonald (frequency = 6), Gaurav Ameta (frequency = 5), and Leanne M. Gilbertson (frequency = 5).

Fig. 2 illustrates the largest institutional collaboration subnetwork within the field of sustainable design research. The size of the nodes reflects each institution's publication output, with red nodes indicating burst values (which signify a sudden increase in attention or popularity for the institution over a specified period) and purple nodes representing centrality values (which denote the institution's significant role within the network as a key hub connecting distinct institutions). Among the top ten research institutions ranked by publication volume are: Egyptian Knowledge Bank (frequency = 53), Northwestern University (frequency = 43), Delft University of Technology (frequency = 34), Cornell University (frequency = 29), Technical University of Denmark (frequency = 27), Loughborough University (frequency = 25), Universitat Politecnica de Valencia (frequency = 25), Pennsylvania Commonwealth System of Higher Education (frequency = 23), Indian Institute of Technology System (frequency = 23), and Hong Kong Polytechnic University (frequency = 23). The institutions occupying critical hub positions include Egyptian Knowledge Bank and State University System of Florida. Over the past five years, there has been a notable increase in attention to published papers from several institutions, specifically: Egyptian Knowledge Bank (burst = 6.29), Islamic Azad University (burst = 4.97), University of Sheffield (burst = 4.96), Southeast University (burst = 4.18), and University of New South Wales Sydney (burst=3.69). Furthermore, Texas A&M University System's publications have maintained high popularity for an extended duration with a burst value of four, while those from Technical University of Berlin have sustained similar interest at a burst value of three point eight—both lasting six years.

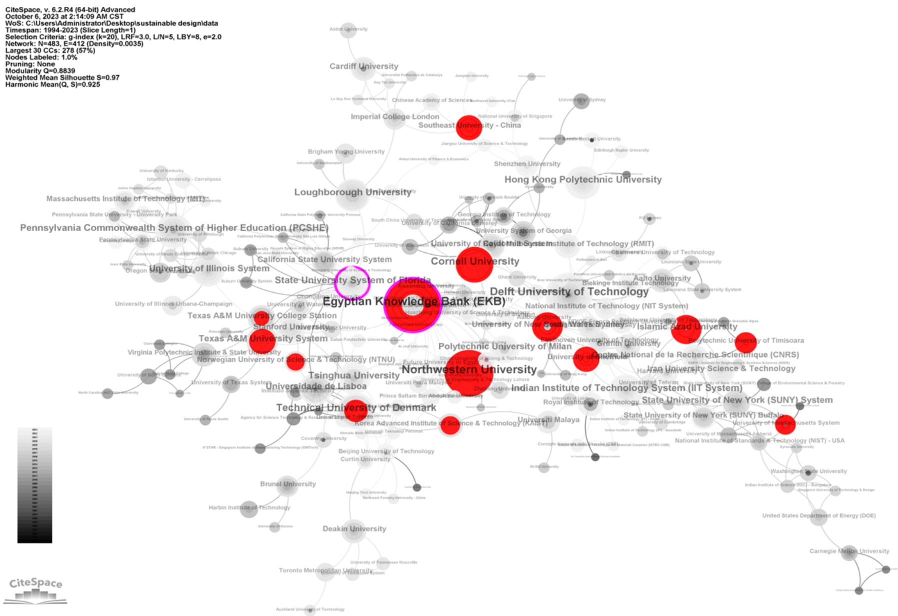

Fig. 2. The largest sub-networks of co-institution.

Table 1 clearly indicates that, within the national collaboration network, there are eight countries with a publication volume exceeding 100. Among these, the United States ranks first in terms of publication output, followed by China and the United Kingdom. The United States commenced its research in this field earlier (year = 1997), whereas Spain (year = 2004), Malaysia (year = 2005), and South Korea (year = 2007) initiated their efforts at a later date. Furthermore, among the top ten countries based on publication volume, the United States (burst = 9.7), the United Kingdom (burst = 4.5), Australia (burst = 3.75), and Canada (burst = 5.12) exhibit significant burst values. Additionally, Iran (burst = 9.91), Saudi Arabia (burst = 6.14), and Pakistan (burst = 4.7) also demonstrate notable burst values. It is noteworthy that in the realm of sustainable design research, Canada's contributions have garnered sustained attention for an extended duration of eleven years; Iran possesses the highest burst value (burst=9.91); while Pakistan's research has recently gained prominence from2021 to present day . Moreover, a cluster analysis conducted on the national collaboration network revealed ten clusters—six of which form distinct networks—where Italy, Canada, Germany, Spain, and Turkey are classified under #0 (sustainability assessment). In contrast, China, Malaysia, Iran, Egypt, and Saudi Arabia fall into #1(ecological design). Countries such as South Korea, India, Poland, Portugal, and Romania belong to #2(sustainable process design); England, the United Arab Emirates, Norway, Wales, and Czech Republic are categorized under #3(natural ventilation). Lastly, the United States, Jordon, Qatar, Lebanon, and Uganda comprise cluster #4(life cycle optimization); while Australia,Singapore, New Zealand, South Africa, and Nigeria constitute cluster #5(sustainable design).

In conclusion, it is clear that the academic community within the field of sustainable design exhibits distinct developmental characteristics across various network scales. The author collaboration network is fragmented and relatively small in scale; however, Chinese scholars demonstrate a greater willingness and intensity for research collaboration compared to their international counterparts. While the largest subnetwork of the institutional collaboration network is substantial, the representation of Chinese research institutions within this subnetwork remains limited, indicating a need to strengthen scientific cooperation between domestic and foreign entities. In terms of national collaboration networks, although China ranks second in publication volume, it lags behind the United States— which leads in total publications— regarding both attention received and sudden surges in popularity for its research outputs. Furthermore, there are notable disparities when compared to countries such as Iran, Saudi Arabia, and Canada.

Table 1. The top ranked item by article quantity in co-country

Frequency	Country	Burst	Year	Frequency	Country	Burst	Year
803	America	9.7	1997	90	India	–	2008
511	China	–	2001	89	Turkey	–	2003
275	England	4.5	2000	83	Iran	9.91	2010
178	Italy	–	2001	80	Netherlands	–	2001
159	Australia	3.75	2001	73	Poland	–	2007
145	Canada	5.12	1999	62	Denmark	–	2009
119	Germany	–	2001	58	Egypt	–	2010
109	Spain	–	2004	55	Portugal	–	2008
98	Malaysia	–	2005	54	Sweden	–	1999
92	South Korea	–	2007	52	France	–	2008

3.3 Knowledge Evolution and Research Trends

Knowledge Foundation and Evolutionary Process.
The knowledge base is comprised of a collection of co-cited literature, and the dynamic temporal variations in the citing literature set that references these knowledge bases delineate the evolution process of the research field. Fig. 3 illustrates the co-citation network for sustainable design literature. The size of the nodes is positively correlated with the citation frequency of each paper. The connections between nodes represent the co-citation relationships among corresponding literatures, while the color of these connections indicates when two papers were first co-cited. By analyzing both the structure and color changes within this comprehensive co-citation network, one can gain insights into both the knowledge base and evolutionary trajectory of this research domain.

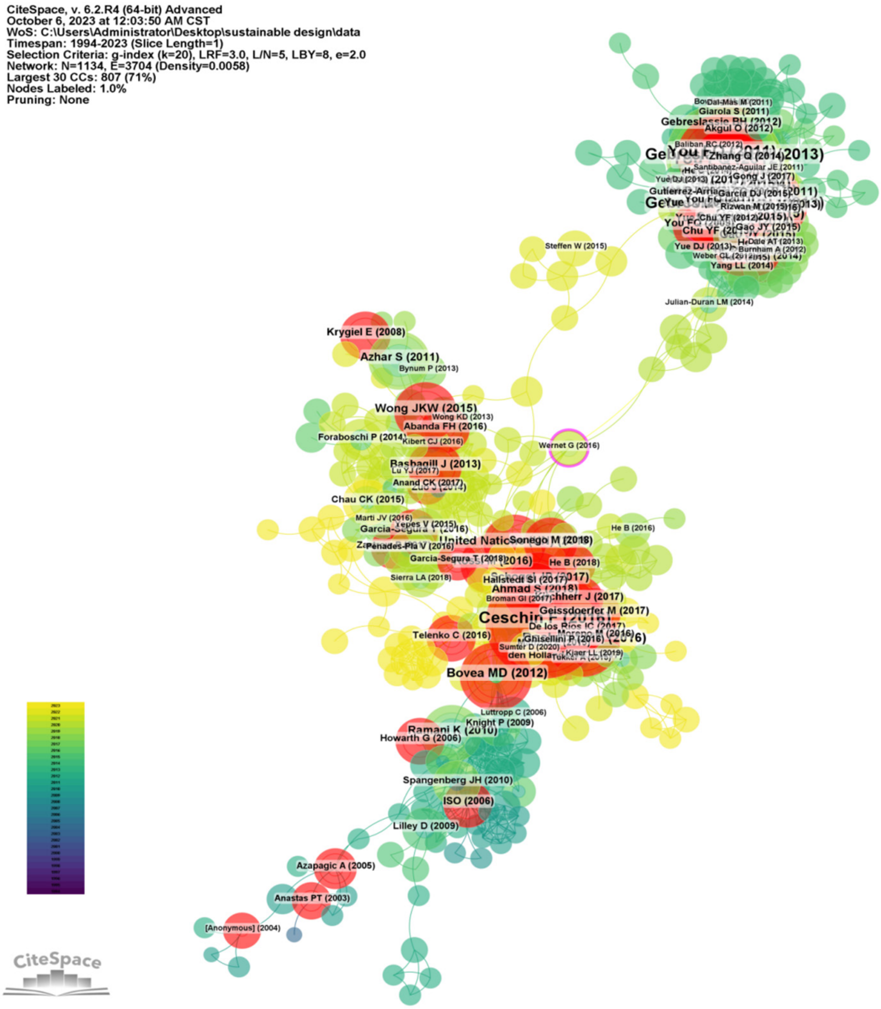

Fig. 3. Network of cite-reference in the research field of sustainable design.

Analyzing the overall structure of the literature co-citation network reveals that the knowledge base of the sustainable design research field comprises two primary components. The first component predominantly addresses sustainability design and life cycle optimization within biofuel supply chains. For example, the most frequently cited paper, "*Global optimization for sustainable design and synthesis of algae processing network for CO_2 mitigation and biofuel production using life cycle optimization*" by Gong and You (2014), explores comprehensive global optimization issues related to large-scale algae processing networks based on economic and environmental criteria. Furthermore, in their study titled "*Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input-output analysis*", Fengqi You et al. (2012) developed a multiobjective mixed-integer linear programming (mo-MILP) model to predict and elucidate trade-offs among the economic, environmental, and social dimensions of sustainable biofuel supply chains [11, 12]. The bi-criteria nonlinear programming (NLP) model proposed by Gebreslassie et al. in their published work effectively captures the trade-off relationship between economic viability and environmental sustainability in hydrocarbon biorefineries [13]. Additionally, as indicated by centrality metrics, paper titled "*Sustainable design and synthesis of hydrocarbon biorefinery via gasification pathway: Integrated life cycle assessment and technoeconomic analysis with multiobjective superstructure optimization*" plays a pivotal role within this segment of the network (centrality = 0.12) [14]. The second component pertains to early interventions involving sustainable design concepts across product design, ecological design, environmental planning, among other areas. A core perspective posits that designers face significant challenges in integrating sustainability into their processes; thus these designs must increasingly account for all stakeholders' demands more than ever before [15, 16]. After nearly two decades of intellectual evolution, sustainable design has progressively transitioned from a technology-centric or product-centric focus towards large-scale systemic transformations while shifting its research orientation toward enhancing human settlement quality alongside innovations in product design [17].

Research Focuses and Trends.

The keyword co-occurrence network in scientometric research effectively illustrates the research hotspots and trends within a specific scientific domain. The frequency of co-occurrence in the indicators indicates the degree of association with the research theme of sustainable design. Furthermore, the magnitude of the mutation value is positively correlated with the prominence of the keyword within the network [18].

Based on the findings from keyword co-occurrence analysis, seven primary clusters have been identified in the research field of sustainable design (see Fig. 4). The largest cluster is circular economy (#0), encompassing such high-frequency keywords as "framework (frequency = 106), "circular economy (frequency = 69, burst = 5.73)", "product design (frequency = 67)", "sustainability (frequency = 62)", "system (frequency = 57)", "technology (frequency = 48, burst = 5.01)", "selection (frequency = 43)", "challenges (frequency = 42)", "innovation (frequency = 41)", and "environmental impact (frequency = 41)". The cluster of thermal performance (#1) comprises high-frequency keywords like "sustainable development (frequency = 80, burst = 5.94)", "impact (frequency = 78)", "energy efficiency (frequency = 77, burst = 4.95)", "buildings (frequency = 57, burst = 3.44)", "consumption (frequency = 48)", "simulation (frequency = 46)", "climate change (frequency = 37)", and "thermal comfort (frequency = 36, burst = 3.47)". The cluster of ionic liquid (#2) has the top three high-frequency keywords of "sustainable design (frequency = 1042, burst = 20.79)", "design (frequency = 182)", and "green design (frequency = 14, burst = 5.07)". The cluster of algae processing network (#3) includes high-frequency keywords such as "energy (Freq = 114)", "multiobjective optimization (frequency = 57, burst = 5.19)", "global optimization (frequency = 42, burst = 13.11)", "hydrocarbon biorefinery (frequency = 38, burst = 11.76)", and "life cycle optimization (frequency = 37, burst = 10.78)". The cluster of concrete column (#4) features high-frequency keywords like "model (frequency =

148)", "optimization (frequency = 118)", "construction (frequency = 80)", "behavior (frequency = 67)", "cost (frequency = 32)", and "life cycle (frequency = 30, burst = 3.99)". The cluster of environmental benefit (#5) has the top three high-frequency keywords of "life cycle assessment (frequency = 206)", "management (frequency = 126)", and "systems (frequency = 74)". The cluster of occupant productivity (#6) has only two high-frequency keywords, namely "performance (frequency = 173)" and "health (frequency= 28)".

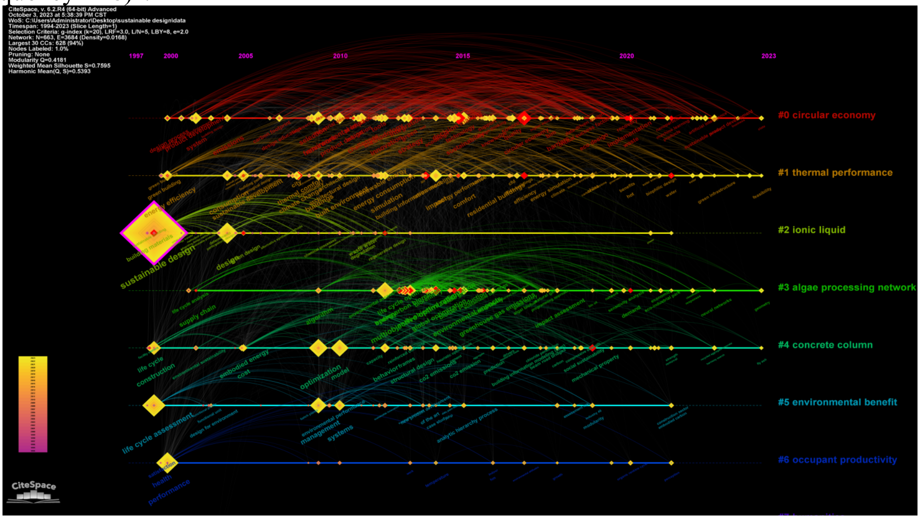

Fig. 4. The time-line view of co-keywords in the field of sustainable design.

Analyzing the distribution of published articles across three distinct stages, the research directions during the period of 1994 - 2002 included "life cycle assessment (frequency = 206, year = 1999)", "performance (frequency = 173, year = 2000)", "construction (frequency = 80, year = 1999)", "energy efficiency (frequency = 77, year = 2000)", "system (frequency = 57, year = 2002)", and "life cycle (frequency = 30, year = 1999)". During the period of 2003 - 2009, the main research directions were "design (frequency = 182, year = 2004)", "management (frequency = 126, year = 2009)", "optimization (frequency = 118, year = 2009)", "framework (frequency = 106, year = 2009)", "sustainable development (frequency = 80, year = 2005)", "buildings (frequency = 57, year = 2009)", "consumption (frequency = 48, year = 2004)", "selection (frequency = 43, year = 2009)", "emissions (frequency = 40, year = 2004)", "climate change (frequency = 37, year = 2008)", "thermal comfort (frequency = 36, year = 2008)", "design education (frequency = 33, year = 2007)", "cost (frequency = 32, year = 2005)", and "city (frequency = 30, year = 2008)". Since 2010, the main research directions have been identified as "model (frequency = 148, year = 2010)", "energy (frequency = 114, year = 2012)", "impact (frequency = 78, year = 2014)", "systems (frequency = 74, year = 2010)", "circular economy (frequency = 69, year = 2017)", "product design (frequency = 67, year = 2010)", "behavior (frequency = 67, year = 2012)", "sustainability (frequency = 62, year = 2015)", "multiobjective optimization (frequency = 57, year = 2013)", "technology (frequency = 48, year = 2015)", "simulation (frequency = 46, year

= 2012)", "challenges (frequency = 42, year = 2011)", "global optimization (frequency = 42, year = 2014)", "environmental impact (frequency = 41, year = 2010)", and "innovation (frequency = 41, year = 2012)". It is notable that in recent years, "waste (year = 2020, burst = 5.57)", "implementation (year = 2020, burst = 4.56)", "recovery (year = 2020, burst = 4.3)", "demand (year = 2020, burst = 4.14)", "water (year = 2021, burst = 4.37)", "machine learning (year = 2021, burst = 3.54)", and "products (year = 2021, burst = 3.54)" have emerged as research hotspots [19].

4 Conclusions

To explore the research foundation, hotspots, and trends of sustainable design, a bibliometric visualization analysis was conducted on the related literature in the Web of Science (WoS) database from 1994 to 2023. The conclusions are as follows: (1) The annual publication volume of 3,317 papers has generally trended upward, but the growth rate varies. From 1994 to 2002, the growth was slow; from 2003 to 2009, it accelerated; and from 2010 to 2023, it entered an explosive stage. Based on the cumulative index growth model, sustainable design is expected to maintain high research enthusiasm and topic persistence in the future. (2) Regarding the academic community, the scholar collaboration network is decentralized, with 13 scholars publishing at least 5 papers. Among institutional collaborations, the top three in publication volume are Egyptian Knowledge Bank, Northwestern University, and Delft University of Technology. In the national network, 8 countries have over 100 publications, with the United States leading, followed by China and England. (3) In terms of the knowledge base and evolution, the sustainable design field consists of two parts. One focuses on sustainable design or life cycle optimization of biofuel supply chains, and the other involves the intervention of sustainable design concepts in product, ecological, and environmental design. Currently, it has shifted from a focus on technology and products to large-scale system-level changes and towards improving the quality of the human living environment and product design innovation. (4) Regarding research hotspots and trends, the keyword co-occurrence network mainly clusters into 7 groups, including sustainable development, energy efficiency, buildings, thermal comfort, green design, multiobjective optimization, life cycle optimization, life cycle assessment, management, and systems. The research focus has shifted from earlier aspects like life cycle, energy efficiency, sustainable development, buildings, climate change, thermal comfort, and design education to circular economy, sustainability, multiobjective optimization, global optimization, environmental impact, waste, recovery, water, machine learning, and products.

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