

A Scientometric Analysis and Visualization of Global LEED Research

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Abstract: With the promotion of the concept of sustainable development and green buildings, green building rating systems are beginning to emerge and gradually attract more attention. Leadership in Energy and Environmental Design (LEED) is a widely used and influential rating system worldwide, and research on it has shown an increasing trend year by year. To establish a comprehensive understanding of the LEED research field, this article visualizes and analyzes the LEED research literature by CiteSpace to obtain journal, author, institution, and country collaboration networks, reference co-citations and clusters, keyword co-occurrence networks and citation bursts. The study found the relationships among journals, authors, institutions, countries, research frontiers, research hotspots, and research processes in the field of LEED research. A framework of the knowledge system of LEED research was constructed based on these findings to present the current status and future trends and provide a reference for future research.

Keywords: LEED; green building rating systems/tools; CiteSpace; visual analysis; green buildings; sustainability; occupant satisfaction; indoor environmental quality (IEQ); building energy consumption



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1. Introduction

Since the 19th century, with the rapid development of the global economy, industrialization, and urbanization, material civilization has ushered in unprecedented prosperity. [1] However, the energy crisis has become a serious problem in the world's social and economic development. Energy is an essential material condition for human life and the basis for social and economic development. Without energy supply, there would be nothing. At the same time, environmental pollution has become the second most important problem encountered by human beings in the process of energy utilization. As a basic space for human beings to work, study, and live, buildings not only consume extremely large amounts of resources and energy during the entire process of design, construction, use, and demolition but also cause serious environmental pollution.

For their survival and development, human beings have gradually begun to reflect deeply on the traditional development model and have actively sought a development model of harmony between humanity and nature. The concept of sustainable development was first articulated in the report "Our Common Future" [2] submitted to the UN General Assembly by the World Commission on Environment and Development in 1987: "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In June 1992, with the signing of the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity, sustainable development was officially adopted as a strategy for the common development of human society. The construction industry, which consumes enormous amounts of energy, has also started to implement building sustainability, and the concept of green buildings has been born [3].

The U.S. Green Building Council (USGBC) has long been committed to developing an evaluation system that can accurately define green buildings. After studying the existing

rating system, an evaluation system was drafted in 1994, and after four years of further refinement and validation, Leadership in Energy and Environmental Design (LEED) 1.0 was launched as a pilot version at the USGBC Summit in 1998 [4,5]. Following the pilot program's success, LEED for New Construction saw a public launch in March 2000.

With the expansion of the global influence of LEED, which is an important green building rating system (GBRS), academic research on LEED is increasing year by year. For example, the comparative study of GBRSs [6–8], the occupant satisfaction in LEED buildings [9–11], the rent premium of LEED-certified buildings [12–14], and so on.

Using scientometric software to analyze the LEED research field can help interested researchers quickly grasp the research focus and the present situation and initially form comprehensive and systematic knowledge.

This article quantitatively summarizes the present situation and development trends in the LEED research field, and the research includes the following:

- (1) Organizing the publication trends and the current status of research partnerships in the LEED research field;
- (2) Identifying LEED research frontiers and research hotspots through literature co-citation and keyword co-occurrence analysis;
- (3) Presenting the history and development of the LEED research field based on citation burst analysis;
- (4) Based on the above research, constructing the knowledge system of the LEED research field.

The purpose of this study was to quantitatively and more comprehensively present the research situation in the LEED research field by using scientometric software to further promote research on LEED, promote the development of LEED practices, and meet the challenges of energy consumption and environmental pollution in the construction industry.

2. Research Methodology

Many visualization tools have emerged in recent years, such as VOSviewer, Co-PalRed, Bibexcel, and CiteSpace. All of these tools support literature co-citation analysis and keyword co-occurrence analysis, which can help us perform quantitative analysis of related fields. Quantitative analysis based on visual tools can intuitively reflect the research status, focus on the key research topics, greatly enrich the analyzable content, and present a comprehensive, systematic, and objective description of related research fields [15]. Qualitative analysis based on manual review shows a certain degree of subjectivity and limitations compared to quantitative analysis [16]. Although qualitative analysis is also valuable, it is difficult to achieve a more extensive and comprehensive literature review using only qualitative analysis. If the quantitative analysis is supplemented with appropriate qualitative analysis, it will present the study more clearly. Due to the clear objectives of this study, a systematic quantitative analysis of the literature in the field of LEED research was first conducted using CiteSpace software to create a scientific knowledge map. Based on the quantitative analysis, combined with the qualitative analysis of induction and summary, the current trends of research were sorted out, and the future development trends were also discussed.

CiteSpace is an information visualization software developed in the Java language. It was developed by Chaomei Chen of Drexel University. The version used in this paper is 5.8.R1. It is mainly based on co-citation analysis theory and pathfinder network scaling (PF-NET). CiteSpace measures the literature (collection) in a specific field to determine the key path and knowledge turning point of disciplinary evolution, and through a series of visualization maps, it analyzes the potential dynamic mechanism of disciplinary evolution and detects the frontier of disciplinary development. CiteSpace can help readers effectively understand the target research field. It can not only show the overall situation of the research field but also highlight some specific, important documents in the development of the field [17]. For example, Li et al. conducted literature co-citation analysis and cluster analysis on related literatures from 2004 to 2015 through CiteSpace, and quantitatively put forward the knowledge map of building information modeling (BIM) [18]. Based on the

Web of Science (WOS) database, Jiang et al. [19] derived the research focus and development trend of urban planning in response to climate change from 1990 to 2016 through the cluster analysis and knowledge evolution analysis of CiteSpace. Zhao et al. [20] used CiteSpace to analyze the characteristics and trends of the reliability of new energy vehicles based on the literature from 1998 to 2017. Chen et al. [21] used CiteSpace to analyze 3875 articles related to regenerative medicine from 2000 to 2011 and found emerging trends in the field.

2.1. Data Collection

The data collection for this study was based on the core collection in the Web of Science (WOS) database. WOS was used because it is one of the most extensive databases covering mainstream journals in the multidisciplinary fields of green building, sustainable development, etc. [22]. Since LEED is an abbreviation for not only “Leadership in Energy and Environmental Design” but also “low-energy electron diffraction”, to ensure the relevance of the searched documents, the search formula is LEED (Topic) not “low-energy electron diffraction” (Topic). The literature data contain the basic information of a paper, including its author, title, abstract, keywords, and references.

Since LEED was officially proposed in March 2000, the search time range is from 1 March 2000, to 24 November 2021. The type of literature was articles, and the language was English. A total of 2358 documents were retrieved. The search string is as follows:

- LEED (Topic) not low-energy electron diffraction (Topic) and Article (Document Types)
- Timespan: 1 March 2000 to 24 November 2021 (Publication Date)
- Collections = BIOSIS, CCC, CSCD, DIIDW, KJD, MEDLINE, SCIELO, WOS

After the document titles were manually screened and duplicates were removed by CiteSpace, 1046 valid documents related to LEED were finally obtained.

2.2. Data Analysis

CiteSpace was used to build partnership networks including journals, authors, institutions, and countries as well as literature co-citations, cluster views, keyword co-occurrence networks, and citation burst views to analyze the research frontiers, research hotspots, and research process in the LEED research field and to organize the LEED research knowledge system.

3. Results and Discussion

3.1. Descriptive Analysis

3.1.1. Trend of Publications

Figure 1 shows that the literature in the LEED research field shows an increasing trend year by year from 2000 to 2021. Specifically, before 2006, the number of related papers increased slowly because LEED was in the early stages of development. The number of papers started to show a significant increase in 2006 and has maintained stable growth every year. (The literature retrieval time of this study was November 24, 2021; thus, literature appearing in WOS thereafter was not included in the statistics.) This finding indicates that research on LEED has entered a stage of steady growth, and researchers’ attention to the field of LEED has also shown a sustained and stable state.

3.1.2. Journal Analysis

Table 1 shows the top 10 journals with the most published papers in the field of LEED. Combined with Figure 2, Table 1 shows that the top 3 journals in terms of the literature citation frequency are Building and Environment, Energy and Buildings, and Building Research and Information. These highly cited journals are considered more authoritative and influential in the LEED research field. Analyzing the scientific cooperation network in the LEED research field is helpful for understanding the current situation of research cooperation at different levels in this field.

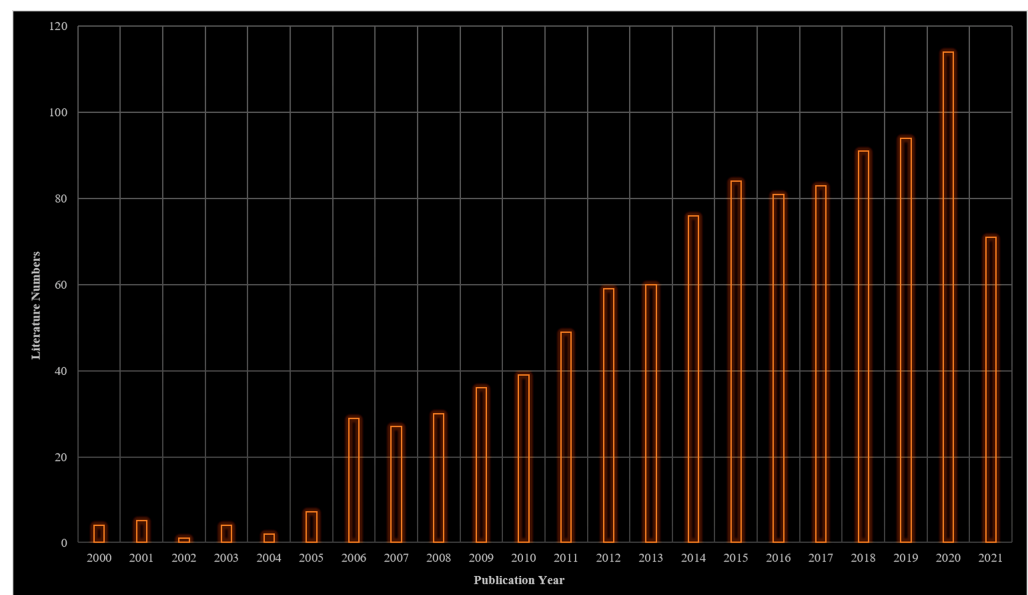


Figure 1. The numbers of the LEED papers from 2000 to 2021.

CiteSpace, v. 5.8.R1 (64-bit)
 November 25, 2021 3:24:43 PM GMT+08:00
 WoS: D:\citespace\LEED1124\data
 Timespan: 2000-2021 (Slice Length=1)
 Selection Criteria: q index (k=25), LRF=3.0, L/N=10, LBV=5, a=1.0
 Network: N=762, E=4464 (Density=0.0154)
 Largest CC: 705 (92%)
 Nodes Labeled: 1.0%
 Pruning: None



Figure 2. Journal co-citation network in the field of LEED.

Table 1. Top 10 publication titles of LEED.

Publication Titles	Literature Numbers
Journal of Green Building	125
Building and Environment	71
Sustainability	61
Energy and Buildings	40
Journal of Cleaner Production	31
Sustainable Cities and Society	25

Table 1. Cont.

Publication Titles	Literature Numbers
Building Research and Information	16
Journal of Architectural Engineering	15
ASHRAE Journal	13
Energies	13

3.1.3. Co-Authorship Analysis

This article used CiteSpace's cooperative relationship analysis function to intuitively analyze the cooperative relationships among authors, institutions, and countries in the LEED research field from the macrolevel to the microlevel.

Authors

In CiteSpace, we selected 2000 to 2021 as the time span, 1 year as the time slice, and “Author” as the label type for visual analysis. Finally, Figure 3 was obtained.



Figure 3. Collaboration network of authors in the field of LEED.

From Figure 3, the more prominent researchers in the field of LEED are Svetlana Pushkar, Walaa S.E. Ismaeel, Zhonghua Guo, Annie. R. Pearce, Stefano Schiavon, Oleg Verbitsky, Asli Pelin Gurgun, and Julie Cidell. The research fields involve the observational study of LEED-certified projects [23], the operating mechanisms of GBRs [24], and occupant satisfaction in LEED and non-LEED-certified buildings [11].

Although there are some prominent researchers, the author collaboration network shows a trend of a small amount of concentration, mostly dispersion. This finding indicates that there is a lack of cooperative relationships and strong academic ties among researchers.

Institutions

In CiteSpace, we selected 2000 to 2021 as the time span, 1 year as the time slice, and “Institution” as the label type for visual analysis. Finally, Figure 4 was obtained.



Figure 4. Collaboration network of institutions in the field of LEED.

From Figure 4, the more prominent institutions in the field of LEED are Hong Kong Polytechnic University, Arizona State University, the Georgia Institute of Technology, the University of California, Berkeley, and Ariel University. Hong Kong Polytechnic University has the most research achievements and the closest cooperation with other universities, followed by the Arizona State University and the Georgia Institute of Technology.

Countries

In CiteSpace, we selected 2000 to 2021 as the time span, 1 year as the time slice, and “Country” as the label type for visual analysis. Finally, Figure 5 was obtained.



Figure 5. Collaboration network of countries in the field of LEED.

From Figure 5, the country with the most active and influential LEED research is the United States; the number of publications of the United States is four times that of China, which ranks second. This finding is related to the fact that LEED was developed and promoted by the United States. In addition, countries such as Canada, the UK, Turkey, Australia, and Egypt have shown some interest in research on LEED.

3.2. Thematic Analysis

3.2.1. High Co-Citation Literature of LEED

In CiteSpace, we selected 2000 to 2021 as the time span, 1 year as the time slice, and “Reference” as the label type for visual analysis. Finally, Figure 6 was obtained. The reference co-citation network of the LEED literature contained 800 nodes and 2876 links. Nodes represent cited papers. The larger the node is, the more frequently the paper is cited and the more important it is within the LEED research field. The connecting lines between nodes indicate the co-citation relationship between different nodes.

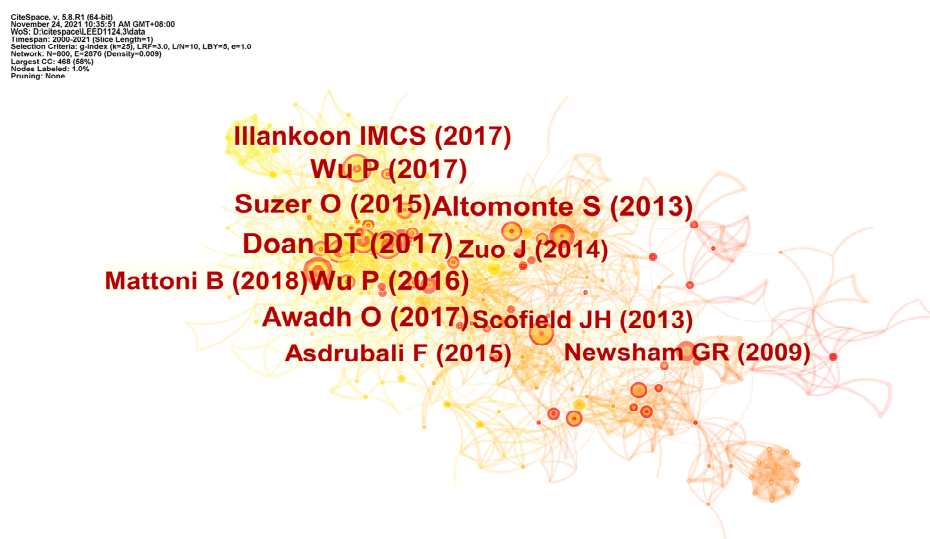


Figure 6. Reference co-citation network of the LEED literature.

The top 10 most frequently co-cited papers in LEED research are shown in Table 2.

Table 2. The top 10 most frequently co-cited papers in LEED research.

Author	Title	Year	Freq.	Source
Doan, D.T.; Ghaffarianhoseini, A.; Naismith, N. [25]	A Critical Comparison of Green Building Rating Systems	2017	39	Building and Environment
Altomonte, S.; Schiavon, S. [10]	Occupant Satisfaction in LEED and Non-LEED Certified Buildings	2013	37	Building and Environment
Wu, P.; Mao, C.; Wang, J. [26]	A Decade Review of The Credits Obtained By LEED v2.2 Certified Green Building Projects	2016	36	Building and Environment
Suzer, O. [27]	A Comparative Review of Environmental Concern Prioritization: LEED Vs Other Major Certification Systems	2015	34	Journal of Environmental Management
Wu, P.; Song, Y.; Shou, W. [28]	A Comprehensive Analysis of The Credits Obtained By LEED 2009 Certified Green Buildings	2017	33	Renewable and Sustainable Energy Reviews
Awadh, O. [29]	Sustainability and Green Building Rating Systems: LEED, BREEAM, GSAS and Estidama Critical Analysis	2017	32	Journal of Building Engineering
Illankoon, I. M. C. S.; Tam, V. W. Y.; Le, K. N. [30]	Key credit criteria among international green building rating tools	2017	28	Journal of Cleaner Production
Mattoni, B.; Guattari, C.; Evangelisti, L. [31]	Critical review and methodological approach to evaluate the differences among international green building rating tools	2018	25	Renewable and Sustainable Energy Reviews

Table 2. Cont.

Author	Title	Year	Freq.	Source
Asdrubali, F.; Baldinelli, G.; Bianchi, F. [32]	A comparison between environmental sustainability rating systems LEED and ITACA for residential buildings	2015	25	Building and Environment
Newsham, G. R.; Mancini, S.; Birt, B. J. [33]	Do LEED-certified buildings save energy? Yes, but . . .	2009	24	Energy and Buildings

Among these 10 papers, 5 are comparative studies of GBRs. Based on reviewing the development process of GBRs, Doan and other authors compared the similarities and differences as well as the advantages and disadvantages of LEED, the Building Research Establishment Environmental Assessment Method (BREEAM), the Comprehensive Assessment System for Built Environment Efficiency (CASBEE), and Green Star NZ. The study concluded that although the four rating systems were initiated in different contexts and with different criteria, indoor environmental quality (IEQ), energy, and materials were the core common categories of all the rating systems. Environmental issues are the focus of the New Construction Manual, while social issues are the focus of the Neighborhood Development Manual. BREEAM is considered the only tool that can assess all four sustainability factors [25]. Suzer focused on the weighting of environmental issues in the LEED certification system. In this article, the assessment methods of the LEED 3rd and 4th editions, cases from different countries and regions, and the comparison of environmental assessment methods such as BREEAM, SBTool, CASBEE, Green Star NZ, and LEED were studied in detail. The results show that the latest version of LEED still pays insufficient and inconsistent attention to environmental issues, and the study proposes the similarities and differences in the environmental assessment tools and methods as well as the factors that should be considered in the future version of LEED [27]. Awadh analyzed two internationally accepted GBRs, LEED and BREEAM, as well as two systems developed specifically for the Gulf region, Estidama and the Global Sustainability Assessment System (GSAS). The research shows that BREEAM, Estidama, and GSAS attach the highest importance to the energy category, while LEED gives priority to the indoor environment category. It is easiest to have a high score in water reduction in Estidama, and Estidama and LEED have stricter minimum indoor water reduction requirements than BREEAM. In terms of addressing the environmental, economic, and social pillars of sustainability, all four rating systems focus on the environmental pillar, with the least emphasis on the social pillar [29]. Mattoni conducted an analysis and comparative study of CASBEE, Green Star NZ, BREEAM, LEED, and Istituto per l'innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale (ITACA) using a macrocategorical domain definition. The “energy” area is always the heaviest, and “water” has the least impact. In addition, CASBEE pays the most attention to the “comfort and safety” area. The study concluded that CASBEE considered the most sustainability issues. However, none of the five GBRs takes into account additional and useful indicators of sustainable development [31]. Asdrubali analyzed two GBRs, LEED and ITACA, by defining five new categories: the site, water, energy, materials, and IEQ. The results show that LEED is more concerned with the site and materials, ITACA is more concerned with energy and water, and the IEQ results are important in both systems [32].

There are two articles on LEED-certified buildings. Altomonte studied IEQ satisfaction in LEED-certified office buildings versus noncertified office buildings. The results show that LEED certification does not have a significant impact on occupant satisfaction with IEQ [10]. Newsham reanalyzed the energy usage data of 100 LEED-certified American commercial and institutional buildings and conducted a comparative study with the ordinary commercial buildings in the U.S. The results show that, on average, LEED buildings use 18–39% less energy per floor area than conventional buildings. However, 28–35% of LEED buildings use more energy than conventional buildings. At the same time, the measured energy performance of LEED buildings has little correlation with a building’s certification level or the number of energy credits that the building received at the time of design [33].

The two articles studied LEED credits. Wu analyzed the database of LEED v2.2-certified projects and studied the distribution model of credits. The results show that innovation-related credits are the easiest to earn and that energy- and material-related credits are the hardest to earn [26]. Wu also analyzed the distribution of credits for the LEED 2009 certification program and showed that the issue of chasing innovation-related credits has been mitigated compared to the previous version of LEED, i.e., LEED v2.2. However, energy- and material-related credits remain the most difficult to earn [28].

Illankoon studied the key credit criteria for evaluating green buildings. Through literature research, the key credit standards were determined as follows: the site, energy, water, IEQ, materials, waste and pollution, and management. The study then evaluated eight GBRs. The results show that the “energy” standard has the highest degree of consideration, followed by the “water” and “IEQ” standards. In addition, existing GBRs generally lack economic and social credit standards [30].

3.2.2. Main Research Areas of LEED

Through the analysis of the literature co-citation network and highly cited papers, the research emphasis of the LEED research field was preliminarily obtained. On this basis, cluster analysis was carried out, and the results reflect the research frontier of the LEED field and the corresponding literature. The cluster labels were extracted from noun phrases, including the titles, keywords, and abstracts of the papers, reflecting more in-depth and comprehensive information.

CiteSpace provides three cluster label extraction algorithms, and the log-likelihood ratio (LLR) algorithm was adopted in this article. After the cluster operation is performed, modularity (Q value) and contour (S value) appear, representing the cluster effect. The cluster structure is generally considered significant at $Q > 0.3$, reasonable at $S > 0.5$, and convincing at $S > 0.7$.

Figure 7 shows the co-citation cluster view of the LEED literature. The results show that $Q = 0.7897$ and $S = 0.8906$, indicating that the results of this cluster are meaningful. The five largest clusters are presented in Figure 7. The smaller the cluster number is, the greater the number of papers contained in the cluster.

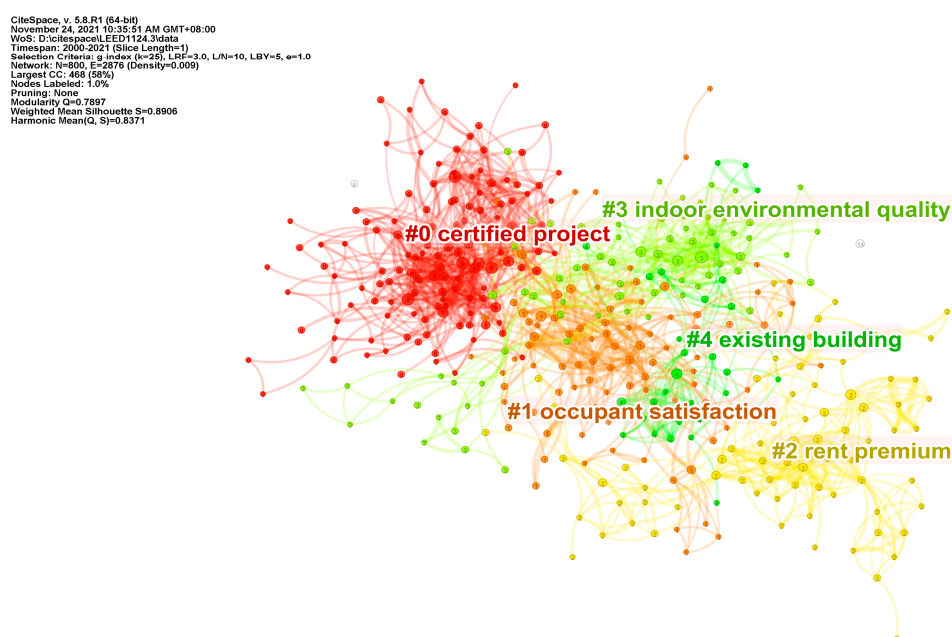


Figure 7. The co-citation cluster view of the LEED literature.

Detailed information on the clusters is shown in Table 3.

Table 3. Top-ranked clusters and the terms within the clusters.

Cluster ID	Size	Silhouette	Mean (Year)	Label (LLR)
0	129	0.888	2017	certified project; green building rating tool; green building rating system; sustainable building assessment method; brazilian context
1	95	0.853	2012	occupant satisfaction; gis modeling; city scale; leed-nd sustainability assessment; lisbon case study
2	76	0.863	2010	rent premium; sustainable real estate; sustainable building construction; high performance; office market
3	74	0.871	2014	indoor environmental quality; occupant satisfaction; indoor environment quality; green office building; indoor environmental quality tradeoff
4	31	0.932	2011	existing building; ghg emission analysis; existing public building; green building certification process; residential high-rise building

Cluster number 0 is related to certified projects and the GBRS. It contains 129 articles. In the context of global environmental deterioration, the practice of green buildings is increasing day by day. With the rapid development of green building practices, a large number of GBRSs have emerged, and green building certification has also begun to be promoted worldwide. LEED is one of the most popular GBRSs in the world, and it is also the most widely used GBRS [6]. The comparative study of LEED and other GBRSs, such as BREEAM, CASBEE, Green Star NZ, SBTool, and ITACA, has been a key focus direction. By comparing different systems, we find the similarities and differences among them, which holds great significance for promoting the development of GBRSs, including LEED. These comparative studies can be broadly categorized into three types. (1) The first is general comparison: these studies mainly compare general information about the GBRS, including the developer, history, and available options. (2) The second type is comparison of indicator systems: the main purpose is to identify the similarities and differences between different systems, to advance developers' understanding, and to, thus, identify directions for improvement. (3) The third type is the comparison of quantitative evaluation systems (QESs) [7]. Research has concluded that LEED lacks a more flexible framework, which imposes some restrictions on its universal use [8]. LEED-certified projects also include buildings that do not perform well in terms of sustainability. How to ensure a higher relevance of sustainability and certification is an issue that should not be ignored and that should be considered in the future LEED improvement and refinement process.

Cluster number 1 is related to occupant satisfaction and Leadership in Energy and Environmental Design for Neighborhood Development (LEED-ND) sustainability assessment. It contains 95 articles. Regarding the satisfaction of occupants, the literature usually concludes that the occupants of LEED-certified green buildings have a high evaluation of all aspects of environmental satisfaction. Notably, due to the different levels of importance of various aspects of occupant satisfaction, in some cases, the actual difference in occupant satisfaction between non-green buildings and green buildings is very small [9]. Some of the literature has studied this issue [10,11]. With the application of the concept of sustainable development in urban planning and urban renewal, the scale of sustainable assessment is further expanded, leading to the development of a GBRS. For example, the LEED-ND sustainability assessment tool has emerged. It is often combined with geographic information system (GIS) modeling to provide a new approach to urban sustainability assessment, greatly advancing the application and development of sustainability assessment at the city scale [34].

Cluster number 2 is related to rent premium. It contains 76 articles. Studies on rental premiums usually focus on commercial buildings, especially office buildings, such as the article of Prashant [12]. LEED-certified buildings usually have higher occupancy rates and receive additional rent premiums or sales price premiums. A study of residential single-family properties also found a green building premium after examining the transaction prices of single-family properties [13]. In addition, research on green multifamily property shows that in addition to the rent premium related to such property, LEED certification entails an additional premium [14].

Cluster number 3 is related to indoor environmental quality (IEQ). It contains 74 articles. These papers are closely related to the keyword “occupant satisfaction” contained in cluster number 1. The reason is that IEQ directly affects the experience of occupants. An increasing number of studies of IEQ in green buildings are appearing now that green buildings are being put into service. The purpose of such studies is to understand the difference between the actual performance and expected performance of green buildings to meet the demand to improve IEQ with the least energy consumption. There are two kinds of research results at present. Some studies have concluded that green buildings such as LEED-certified buildings have higher IEQ satisfaction, while others have concluded that green buildings have little relationship to IEQ satisfaction. In addition, some scholars have studied the relationship between energy-use intensity (EUI) and IEQ, which are two key characteristics in evaluating green building operational performance. High-EUI buildings show a good thermal environment, but there is no significant difference in air quality and the visual environment between low-EUI buildings and high-EUI buildings. The difference is that occupants are less satisfied with the quality of the indoor environment in high-EUI buildings compared to low-EUI buildings, except for the visual environment. The potential reasons may be related to the different levels of environmental control [35].

Cluster number 4 is related to existing buildings. It contains 31 articles. It is very important for sustainable development and environmental protection to upgrade existing buildings and to improve their sustainability to stabilize and reduce their greenhouse gas emissions. One study proposed a multiobjective optimization model to maximize the sustainability of existing buildings in three aspects: minimizing the negative environmental impact of buildings, minimizing the cost of building upgrading, and maximizing the leading edge of the scoring system of energy and environmental upgrading of existing buildings [36]. In addition, one LEED project, LEED for Existing Buildings: Operations and Maintenance (LEED-EBOM), is also working on retrofitting existing buildings from the perspective of “an upgrade at an existing building to improve energy and environmental performance, reduce water use, improve comfort and quality of space in terms of natural lighting, air quality and noise” [37,38].

Among the above research areas, researchers have conducted their studies through different methods. The main methodologies involved are comparative research [7], data survey and statistical analysis [8–10,12], development of optimization models [36,39], development of conceptual frameworks and case validation [40], and literature review with scientometric methods [19]. Although CiteSpace’s visual network cannot directly reflect the research methodologies involved in papers, the addition of research methodologies can help present a more comprehensive view of the LEED research area. By combing through the important literature in clustering, the main research methodologies involved are summarized. Clustering is a visual representation of important research areas, and the important literature contained in the clusters is also the core of the study in the area. Based on this, the research methodologies summarized are also representative to some extent.

3.2.3. LEED Research Hotspots

In CiteSpace, we selected 2000 to 2021 as the time span, 1 year as the time slice, and “keywords” as the label type for visual analysis. Finally, Figure 8 was obtained. The keyword co-citation network of the LEED literature contained 623 nodes and 3094 links. Nodes represent keywords. The larger the font of the node or keyword is, the higher the

frequency of co-occurrence of that keyword. By analyzing the keyword co-occurrence network, we can identify the research hotspots in the field of LEED.



Figure 8. Keywords co-occurrence network of the LEED literature.

The top 30 keywords of the LEED literature are shown in Table 4.

Table 4. Top 30 keywords of the LEED literature.

No.	Freq.	Keywords	No.	Freq.	Keywords
01	352	leed	16	38	office building
02	206	green building	17	37	model
03	170	sustainability	18	34	health
04	123	performance	19	31	quality
05	80	energy	20	30	rating system
06	74	design	21	29	comfort
07	69	system	22	28	energy consumption
08	69	impact	23	27	indoor environmental quality
09	57	construction	24	27	green
10	51	energy efficiency	25	26	simulation
11	49	building	26	24	optimization
12	45	sustainable development	27	23	management
13	42	occupant satisfaction	28	22	life cycle assessment
14	42	BREEAM	29	22	tool
15	40	certification	30	22	efficiency

High-frequency keywords such as LEED, green building, sustainability, performance, energy, energy efficiency, sustainable development, energy consumption, green, and efficiency revolve around LEED-certified building performance and energy consumption research. This research focuses on the sustainability of LEED-certified buildings, including the measured energy performance analysis of LEED-certified buildings [41], the energy-saving analysis of LEED-certified buildings [33], and other analysis and research related to sustainability.

High-frequency keywords such as occupant satisfaction, office building, health, quality, comfort, and indoor environmental quality revolve around LEED-certified building post-occupancy assessment research. The focus is on occupant satisfaction and IEQ. Related research mainly focuses on a comparative study of LEED-certified office building data and uncertified office building data [10].

High-frequency keywords such as model, simulation, optimization, management, and life cycle assessment revolve around the simulation and optimization of the LEED assessment system. Related research involves the study of the application of building information modeling (BIM) in the LEED certification process [40].

High-frequency keywords such as BREEAM, certification, rating system, and tool revolve around GBRs and tools. These articles focus on comparative studies of GBRs around the world, to further improve LEED through comparison.

3.2.4. The Research Process of LEED

The view of references with the strongest citation bursts was obtained after further processing with CiteSpace (Figure 9). The literature presenting citation bursts is shown in chronological order, reflecting, to some extent, the evolution of research hotspots in the LEED field.

Top 25 References with the Strongest Citation Bursts

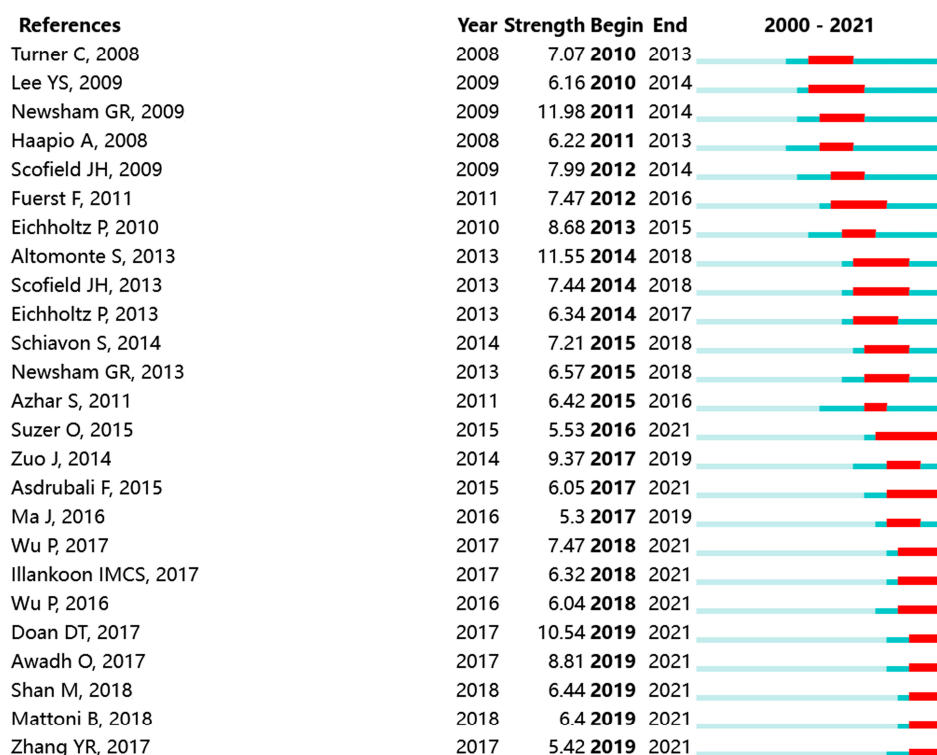


Figure 9. Top 25 references with the strongest citation bursts.

From Figure 9, it is clear that the burst of citations began in 2010. This outbreak is related to a report in 2008: *Energy Performance of LEED for New Construction Buildings*. This report was prepared by the New Buildings Institute (NBI) and funded by the USGBC with support from the U.S. Environmental Protection Agency. The report analyzed the measured energy performance of 121 new LEED buildings. Three different indicators were used in the report: EUI, which was used to compare LEED and the national building stock; the energy star ratings of LEED buildings; and measured results, which were compared to the initial design and baseline modeling. The report concluded the following: (1) On average, LEED buildings are delivering anticipated savings. (2) Within each of the metrics,

measured performance displays a large degree of scattering, suggesting opportunities for improved programs and procedures. (3) More feedback is needed from actual building performance results to design-phase energy modeling. (4) Project types with high process loads are problematic. (5) The energy performance baseline used by LEED to define a reference benchmark is not as aggressive as anticipated. (6) Continued improvements to the LEED program are suggested. [41] Another article relates to IEQ and occupant satisfaction in LEED-certified buildings. The study concluded that in 15 LEED-certified buildings in the United States, the quality of office furniture had a significant impact on occupant satisfaction and job performance, while IEQ affected only occupant job performance [42].

The 2011 citation burst is associated with Guy R. Newsham's study [33]. This study reanalyzed the data presented in Cathy Turner's report. It is considered that the study of green buildings can save much energy, but further work is needed to improve the green building rating scheme to ensure more consistent success at the single building level. The other paper is an analytical study of green building rating tools, covering 16 assessment tools including LEED. The study clarified the basic status of green building assessment tools by analyzing and classifying existing tools [43].

The 2012 citation burst is associated with John H. Scofield's study [44]. He provided a critique of Guy R. Newsham's research [33]. Scofield's research shows that, in general, the energy consumption (especially the source energy) of LEED-certified office buildings is not lower than that of non-LEED-certified office buildings because large buildings dominate the energy consumption. Another paper investigated the price impact of environmental certification on commercial real estate assets. The results show that there is a premium for both the lease and sale prices of certified buildings [45].

The 2013 citation burst is related to an analysis of the impact of green buildings on market economies in commercial real estate, investigating the relationship among energy efficiency investments, rents, effective rents, and sales prices in design and construction. The results show that green buildings have higher rents, effective rents, and selling prices [46].

The 2014 citation burst is associated with occupant satisfaction, energy consumption in LEED-certified buildings, and the economics of green buildings. Sergio Altomonte's study [10] concluded that LEED certification has no significant effect on occupant satisfaction with IEQ. John H. Scofield built on the original study of LEED-certified buildings in terms of energy consumption and greenhouse gas emissions. The results show that compared with non-LEED-certified buildings, LEED-certified buildings are generally not economical [47]. Based on original research, Piet Eichholtz continued to analyze a large number of office buildings and linked the economic premium of green buildings with energy efficiency. The results show that thermal efficiency and sustainable properties contribute to the premium in rent and asset value [48].

Two of the 2015 citation bursts are related to occupant satisfaction. Stefano Schiavon and Sergio Altomonte [11] further found that LEED-certified buildings may provide higher resident satisfaction in open spaces and small buildings, which may decline over time. Guy R. Newsham conducted separate post-use evaluations of green office buildings versus traditional office buildings. The results show that green buildings exhibit superior performance and occupant satisfaction [49]. Another article is related to the application of BIM in the sustainable design and LEED certification process. The results of this study indicate that documentation supporting LEED credits may be directly or indirectly prepared using the results of BIM-based sustainability analysis software [40].

The 2016 citation burst is associated with a comparative study of GBRs [27]. The study compared and analyzed GBRs, including LEED, and discussed the weighting of LEED environmental issues

The 2017 citation burst is also associated with a comparative study of GBRs. F. Asdrubali [12] analyzed and compared the systems, LEED and ITACA. Zuo Jian [50] conducted some research on green building rating tools in a review of green building research. The other article is related to LEED credits. This study analyzed the credit

achievements of the LEED program using data-driven techniques, and also analyzed the relationship between credits using association rule mining [51].

The 2018 citation burst is associated with a LEED credit study. Wu Peng [26] conducted a ten-year review of LEED v2.2 certified building projects in 2016, examining the LEED point allocation model. The results show that innovation-related credits are the easiest to obtain, while energy- and material-related credits are the most difficult to obtain. He conducted another study on LEED 2009 credits in 2017. This study found that innovation-related credit chasing issues were mitigated compared to LEED v2.2, but energy- and material-related credits were still more difficult to obtain [28]. The study by I.M. Chethana S. Illankoon [30] evaluated key credit criteria in several green building rating tools.

The 2019 citation burst is associated with a comparative study of GBRs. Dat Tien Doan [25] examined four rating tools, LEED, BREEAM, CASBEE, and Green Star NZ. Omair Awadh examined four rating tools: LEED, BREEAM, GSAS, and Estidama [29]. B. Mattoni examined five rating tools: CASBEE, Green Star NZ, BREEAM, LEED, and ITACA [31]. Ming Shan conducted a literature review of practical and research work on GBRs [52]. Zhang YuRong [53] conducted a comparative study of green building evaluation standards in China, the UK, and the US: the Green Building Rating Standard, the Code for Sustainable Homes (CSH), and LEED.

3.3. Knowledge Graph for LEED

The results of the literature co-citation and cluster analysis constitute the knowledge domain of LEED research. The keyword co-occurrence analysis constitutes the knowledge base. In CiteSpace, the clustering labels that constitute the knowledge domain were selected from noun phrases. The noun phrases were extracted from the titles, keywords, and abstracts of the literature. Thus, the clustering labels are a collection of core contents of different research topics. The keywords that constitute the knowledge base, as the core of the literature, are a more comprehensive presentation of the focus of the research area under the hierarchy of clustering. It is one of the foundations that constitute the knowledge domain. The knowledge base and the knowledge domain are contrasted with each other to reflect the comprehensive and detailed research content at different levels. Meanwhile, citation burst analysis constitutes the knowledge evolution. These three parts were integrated to construct a framework diagram of the knowledge system of LEED research. The knowledge graph can help us better understand the current status of LEED-related research and future trends. As shown in Figure 10, the LEED research field can be divided into three major directions: GBRs/tools, sustainability, and the economy. GBRs/tools focus on a comparative study of LEED and other tools. Sustainability focuses on studies such as IEQ and occupant satisfaction. The economy focuses on studies such as the rental premium of certified buildings. The research process shows that LEED has shifted from research on GBRs/tools to research on building energy consumption and occupant satisfaction. After a period of time, in recent years, the research hotspot has continued to shift back to the study of GBRs/tools.

Since the selection date of the literature ends on 24 November 2021, it is necessary to add LEED studies from December 2021 to the present to ensure the comprehensiveness of the study. The study found that there is still a high proportion of comparative research on rating systems, involving comparative research and optimization of GBRs [54–58]. Occupant satisfaction and IEQ-related research still occupy a certain proportion, mainly around aspects such as post-occupancy assessment research of LEED-certified buildings [59–62]. The second is research related to the simulation and optimization of LEED assessment systems [63,64], part of which involves the application of BIM in the LEED certification process [65–67]. There is also research related to LEED credits [68], research on the impact of LEED certification on rental premiums [69,70], research on the energy sustainability of LEED-certified buildings [71,72], and research related to the safety of building projects [73,74].

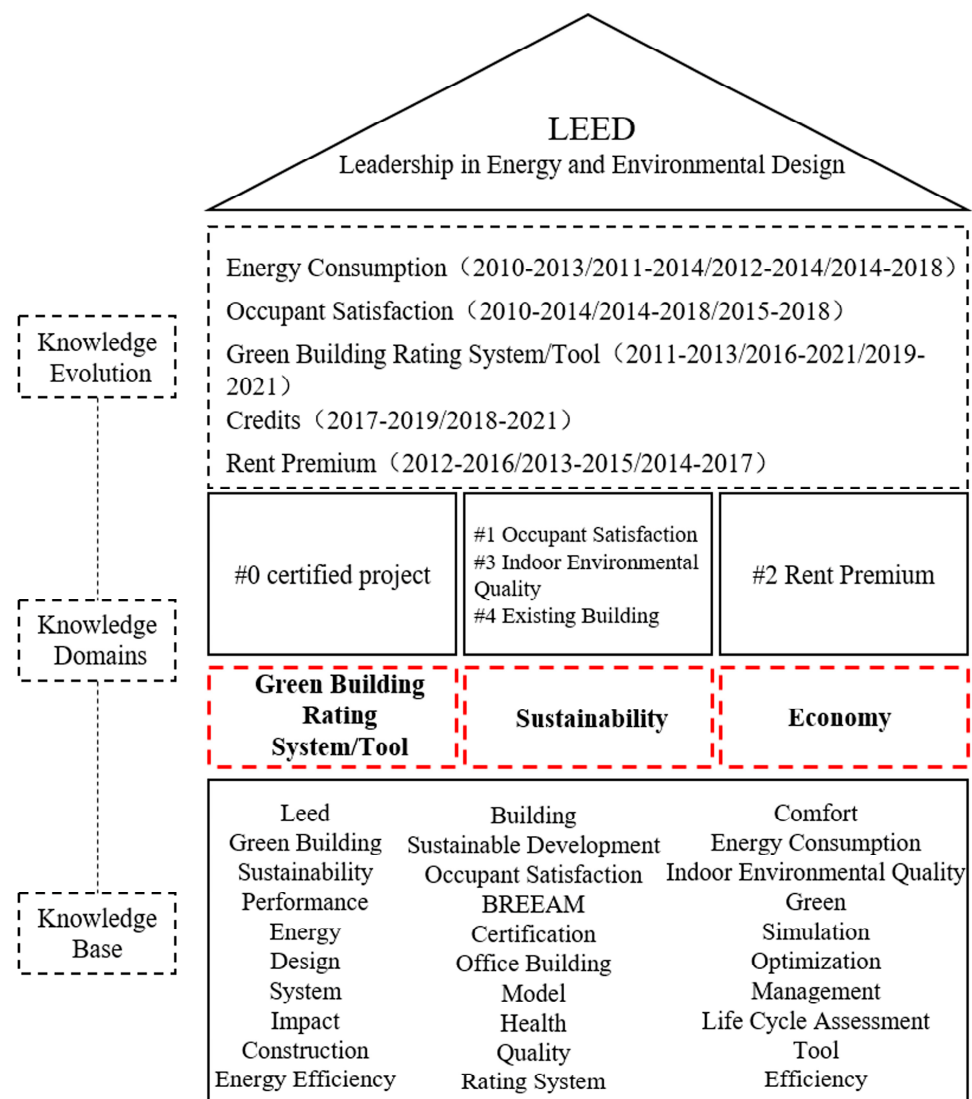


Figure 10. Knowledge graph of LEED.

4. Conclusions and Future Trends

Using CiteSpace software, visual analysis was performed on 1046 documents in the core collection of the WOS database, and the following results were obtained:

- (1) The literature in the LEED research field has been increasing year by year. It has increased substantially since 2006 and has been steadily increasing every year since then;
- (2) The most highly cited journals in the LEED research field are Building and Environment, Energy and Buildings, and Building Research and Information;
- (3) In the field of LEED research, there are some prominent researchers such as Svetlana Pushkar, Walaa S.E. Ismaeel, Zhonghua Guo, etc. However, the overall status of the author collaboration network shows that a small number of researchers have close and concentrated collaborative relationships. The majority of researchers are still scattered, lacking close collaborative relationships and strong academic ties with other researchers;
- (4) The most prominent research institutions in the LEED research field are Hong Kong Polytechnic University and Arizona State University, and the most prominent countries are the United States, followed by China, Canada, and the United Kingdom;
- (5) As shown in Figure 7, the main areas of research frontiers in LEED are research on GBRs/tools, occupant satisfaction, rental premiums, IEQ, and existing buildings;

- (6) As shown in Figure 8, the research hotspots of LEED mainly cover research on the sustainability of certified buildings, post-use evaluation, simulation and optimization, and the comparative study of GBRSs;
- (7) The process of research in the field of LEED is derived through citation burst analysis, which reveals the evolutionary trend of research on LEED over time.

Using the quantitative analysis function of CiteSpace, this article constructs a knowledge system framework of the LEED research field based on the analysis of literature co-citations and clusters, keyword co-occurrence analysis, and citation bursts, and presents an overview of the LEED research field from different perspectives.

Based on the summary of the current status of the LEED research field, the following suggestions are made for future research trends and possible applications.

GBRSs tools are mentioned in the main areas of research frontiers and research hotspots. Moreover, the main purpose of these studies is to find out the shortcomings of LEED through the comparison between different tools to provide possible ideas for optimization. [7,8,29] Therefore, the research around the optimization and improvement of future versions of LEED can be considered one of the future trends. In response to the problems presented in the current study, the optimization of LEED can consider the degree of focus on the environmental pillar and the social pillar. The existing GBRS tools generally have a low focus on the social pillar and need to be further optimized and improved. Research on the support and application of BIM in the LEED certification process has also started to receive more attention. Additionally, occupant satisfaction related post-use assessments, existing buildings, and larger scale sustainability studies are recurring in the research frontiers and hotspots. The future trends analyzed are about the main contents of the relevant literature: [9–11,34,37] study on the relationship between LEED certification and IEQ and occupant satisfaction, based on real post-occupancy feedback data to explore more influencing factors; LEED certification for larger-scale sustainability assessment studies at the city scale to advance the application of sustainability in urban planning and renewal; in addition to using LEED for green building rating, attempts to improve the sustainability of existing buildings are also worthy of attention, such as the study of LEED-EBOM.

However, this study still has limitations. We only analyzed English journal papers in the WOS database, which is not yet comprehensive coverage. In addition, the analysis of monographs, conference reports, and other language papers can provide a broader perspective for the study of the LEED field. Moreover, CiteSpace has some limitations in the data processing. CiteSpace is mainly used to analyze and visualize co-citation networks, providing a burst word detection algorithm [75]. Compared with analysis tools that can output data for the whole time period, like SCI2, it extracts networks based on time slices. CiteSpace focuses more on revealing the research patterns and research directions of the discipline and is not as capable of demonstrating the relationships between research topics and the dynamics of the research. In addition, in terms of the construction of visual networks, CiteSpace's layout algorithm is more single and less structured. In contrast, software like SCI2 provides various algorithms in network construction and presents a variety of structural views, which is helpful to develop analysis from different perspectives [76,77]. Therefore, these limitations should be taken into account when considering the results of this research. Subsequent research can be further improved by expanding the sources of literature and adding different visualization software.

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