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Review

The Role of Straw Materials in Energy-Efficient Buildings: Current Perspectives and Future Trends

Qing Yin [1,2], Muhan Yu [1,2], Xueliang Ma [1], Ying Liu [1,2,*] and Xunzhi Yin [1,2,*]

[1] School of Architecture, Harbin Institute of Technology, Harbin 150001, China; hityin@126.com (Q.Y.); 21s134162@stu.hit.edu.cn (M.Y.); 21s134169@stu.hit.edu.cn (X.M.)
[2] Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, Harbin 150001, China
* Correspondence: liuying8361@163.com (Y.L.); x.yin@hit.edu.cn (X.Y.); Tel.: +86-451-139-3664-8002 (Y.L.); +86-451-185-0363-4273 (X.Y.)

Abstract: The need to effectively control and reduce energy consumption in buildings has become a global concern, prompting an increasing number of studies on the energy efficiency of straw buildings. However, previous review articles on straw research have primarily focused on fragmented material properties such as thermal insulation and mechanical strength and have lacked a comprehensive review of straw materials in building energy efficiency, as well as a thorough analysis of the development lineage of straw building materials. To fill this research gap, this study conducted a bibliometric analysis of 338 papers on the energy efficiency of straw materials published in the WOS core database between 1992 and 2022. The study constructed and visualized multifaceted co-occurrence networks representing the research literature on the energy efficiency of straw building materials, providing a comprehensive understanding of current research efforts, development trends, hot research directions, and the development lineage of this field since 1992. The study's conclusions suggest that the next research hotspots in this area will be the whole life-cycle of straw materials and their compounding, performance, and application to construction. By tracing the development lineage and clarifying the relationship between the macroscopic building environment and microscopic straw materials, this study offers better predictions of the future development prospects of straw buildings. These findings provide researchers with valuable insights into current research efforts and future research directions in this field, while also serving as a reference for governments seeking to formulate relevant policies for the energy-efficient design of buildings made of straw materials.

Keywords: straw building materials; energy saving; literature measurement research; visualization; future trends

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1. Introduction

The construction industry is responsible for a significant share of energy consumption and CO_2 emissions among all sectors. The Paris Agreement, signed in 2016, specifies that the global building and construction sector must be almost entirely decarbonized by 2050. According to statistics, the energy consumption of buildings has increased over the past decade, from 115 EJ in 2010 to almost 135 EJ in 2021, accounting for 30% of global final energy consumption [1]. If we include final energy use associated with the production of cement, steel, and aluminum, this share increases to 34%, as shown in Figure 1a. According to the "Global Status Report for Buildings and Construction 2021" released by the Global Alliance for Buildings and Construction led by the United Nations Environment Programme, the construction industry accounted for 37% of energy-related CO_2 emissions in 2020. In 2019, CO_2 emissions from building operations amounted to approximately 10 billion tons, accounting for 28% of the total energy-related CO_2 emissions worldwide. When combined with emissions from the construction industry, this proportion rises to 38% of total energy-related CO_2 emissions worldwide [2,3]. Thus, the construction sector has a significant impact on global carbon emissions. The carbon emissions and growth trends of specific different sectors are shown in Figure 1b [3].

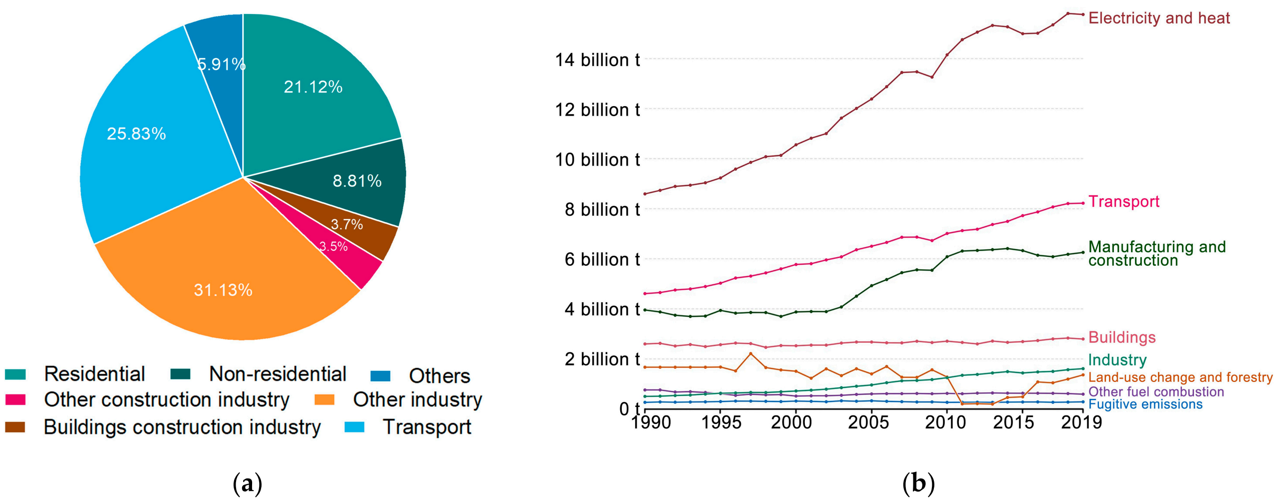


Figure 1. (**a**) Final energy consumption in the building sector, 2021; (**b**) worldwide CO_2 emissions by sector.

To address global climate change, it is crucial to prioritize energy efficiency and decarbonization in the construction sector. Various countries around the world must seize the opportunity to achieve a decarbonization transition in the building sector during the economic recovery from the coronavirus pandemic [4]. The ultimate decarbonization of the construction sector is closely linked to the use of raw materials in the construction industry [5]. The implicit energy and carbon emissions in construction materials are becoming an increasingly important consideration. Therefore, it is imperative to consider the selection of economical, low-carbon, and low-energy materials [6].

For decades, straw has served as an agricultural by-product in many fields, such as animal feeding, agriculture, bioenergy production, and construction materials [7]. Considering that grains can be replanted annually and produced in large quantities yearly and that their primary energy input is solar energy, straw qualifies as a renewable building material [8]. The chemical composition of straw is mainly cellulose and lignin, also the main components of wood [9]. Straw is often used as bedding for livestock, as burning material, as soil fertilizer, or as a supplement to animal feed [10,11]. Furthermore, it is a crucial biomass and renewable energy source for producing biomass fuels and materials, which play a positive role in sustainable development and reducing greenhouse gas emissions [12–14]. The use of straw as a building material dates back to ancient times and has experienced a revival in recent years, given the increasing emphasis on sustainable construction practices. As a renewable resource that is readily available and easily sourced, straw offers a cost-effective alternative to traditional building materials such as concrete, steel, and brick. The primary focus of this paper is to explore the application of straw in the field of building materials. Specifically, straw can be used as a means of storing carbon and reducing dependence on other energy-intensive materials in the field of construction materials [15]. Insulation materials made from straw are receiving increasing attention due to their superior hygrothermal properties, low life-cycle costs, and low carbon footprint [8].

Several studies have described the specific properties and applications of straw buildings [6,8,15–18]. The chemical and physical properties of straw materials have been quantified [6,8,18]. However, as a re-emerging material in the construction industry, there is a need for more systematization of current research results, further research on the development of straw building materials, and identification of future trends in the field. Consequently, scholars new to the field have only a vague understanding of the origin of the material and its overall development status, which could be improved to better grasp future research directions and development trends.

To clarify the development of straw building materials in the energy conservation field and to explore the latest research results and trends, this review employs a bibliometric analysis method. Bibliometrics is a popular research method that uses quantitative analysis and statistical methods to analyze publications and visualize relevant research results [19–23]. Compared with the manual extraction of valuable information from a large amount of the literature, the bibliometric method is more efficient in handling large literature databases for collation and analysis [21,22]. Therefore, we use bibliometrics to analyze publications in the field of straw building materials for energy efficiency; it is efficient and accurate and can help sort out the current stage of development and provide references for future applications of straw building materials. In this paper, we use the CiteSpace visualization analysis software, which is specifically designed to support the complete analysis process of the scientific literature [24–27]. This software has a user-friendly interface, is easy to use, and offers powerful visualization capabilities [25,28].

The rest of the paper unfolds as follows:

In Section 2, we provide a detailed overview of the methodological approach used in this study. This includes a description of the search strategy used to identify relevant publications, as well as an explanation of the key metrics and indicators used to analyze the literature.

In Section 3, we present the results and discussion of our analysis. This includes an examination of the most influential publications and authors in the field of straw building materials for energy efficiency, as well as an exploration of the key research themes and trends that have emerged in this area.

Finally, in Section 4, we provide concluding remarks and summarize the main findings of this study. We also highlight the potential implications of our findings for future research and the practical application of straw building materials in the construction industry. We believe that our study provides a valuable contribution to the field of energy-efficient building materials and that it can serve as a useful reference for researchers and practitioners alike.

The argumentative logic of this paper is shown in Figure 2, which provides a visual summary of the structure and content of the paper.

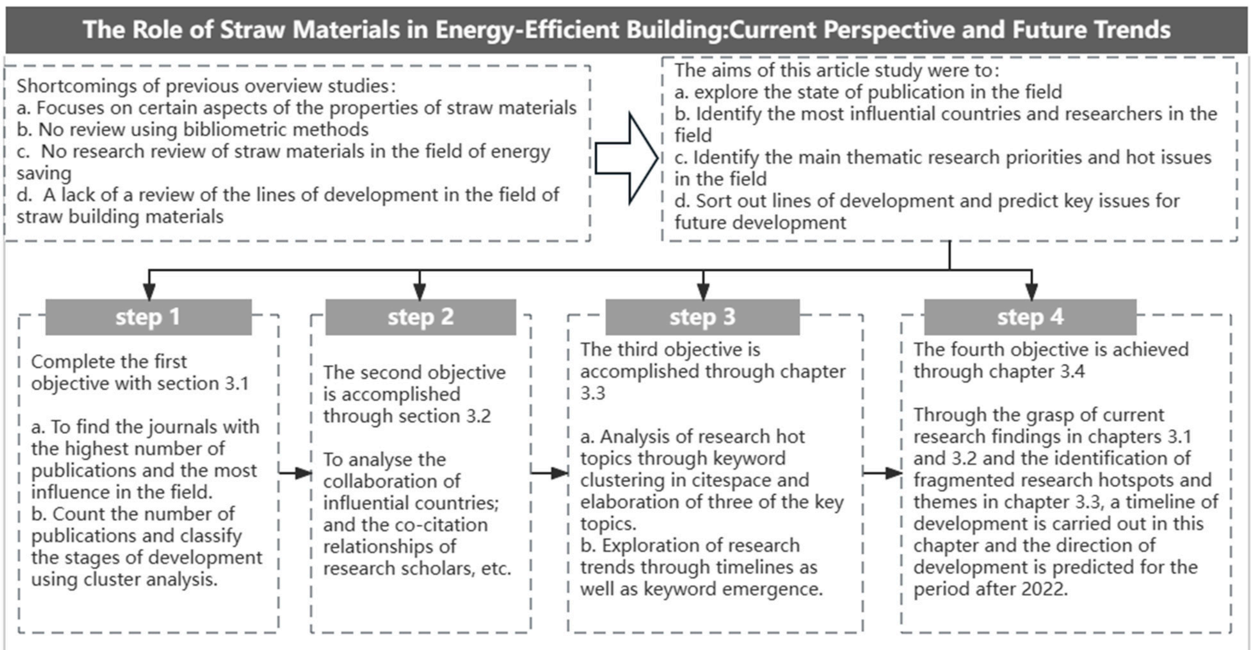


Figure 2. Logic diagram of the paper.

2. Methodology and Content

2.1. Data Collection

The data source selected for this paper is the WEB-based scientific core database of Thomson Scientific. The WOS Core database is considered the most comprehensive database globally, covering the most influential and relevant journals in the WOS database [23,29]. The WOS database includes more than 20,000 kinds of authoritative and high-impact academic journals and conference literature in the world [29]. Its inclusion criteria are very strict, with multiple considerations such as expert evaluation and measurement indicators. Users can search the data in WOS Core by specifying the topic and publication period, after which reliable data can be collected through keyword or term co-occurrence analysis [30].

This study searched the database for two topics: "straw building" and "energy". The search syntax used the Boolean operator "AND" to link the two fields when searching for topics. The search period was set to all years contained in the database, i.e., 1985 to 2022. Since the earliest publication year retrieved was 1992, the starting year for publications was calculated from 1992 to the end of 2022. The filtering process included publications in English and was limited to journals included in the SCI Extended Index (SCIE) and SSCI journals included in the Journal Citation Reports (JCR) database. The search resulted in 338 articles and the complete records of the literature and their references were derived as the primary data for this study. Table 1 shows the search parameters used for the article search.

Table 1. Data parameters used for article retrieval.

Parameters	Value
Title	(TS = (straw building)) AND TS = (energy)
Type	Articles or Comments
Time Span	1985–2022
Citation Index	SCIE, SSCI
Language	English

2.2. Bibliometric Methods and Visualization Tools

A bibliometric analysis was performed on the database obtained from the above data collection methods. Origin software was utilized to statistically analyze the number of publications in different years based on the 338 retrieved publications in the field and a growth curve of the published literature was fitted using linear regression. Citespace 6.2.R2 was then used for a series of analyses of the database, including co-occurrence analysis (such as country and author), research hotspot analysis (keyword co-occurrence), cluster analysis (keyword clustering), and outburst word analysis [24,27]. In the co-occurrence analysis networks, specific key terms are represented as nodes, with larger nodes indicating a higher frequency of occurrence. By detecting emergent terms, the evolutionary trend of research in a particular field can be revealed, from macro to micro and from single to diversified, reviewing when key branch technologies have become hot and even predicting which key technologies can continue the explosive trend in the future [26,28]. CiteSpace supports two types of burst detection: citation-based and occurrence-based burst detection [24].

CiteSpace allows for the study of changes in the literature over time by creating a network of "time slices" [24,27,28]. The time interval for the slices can be set in CiteSpace, with the standard unit of analysis for each slice being usually one year [27]. New publications that appear each year can strengthen existing connections between articles or can create new ones. By observing the changes in the time slices, it is possible to gain insight into how researchers' perceptions of concepts evolve in this field. CiteSpace uses different colors to represent nodes and edges within each time slice, with each color corresponding to a different year. The color of an edge in the network indicates the year in which the co-citation link was first established. The nodes consist of overlapping layers of rings of different colors and the thickness of each layer represents the number of times an article was cited in a given year. This bibliometric approach enables the analysis of research hotspots and development trends in the energy-saving potential of straw building materials.

3. Results and Discussion

3.1. Publishing Trends

3.1.1. Publication Statistics

In order to obtain only SCIE and SSCI journal publications, the authors checked each publication journal shown in Table 1 in the JCR database; the list of journals included in SCIE and SSCI is presented in Table 2. The authors chose to analyze only SCIE and SSCI data because the relevance of journals is assessed largely by their impact factor (IF) [31] and the magnitude of the IF is directly related to the accuracy and analytical value of the data analyzed in this case.

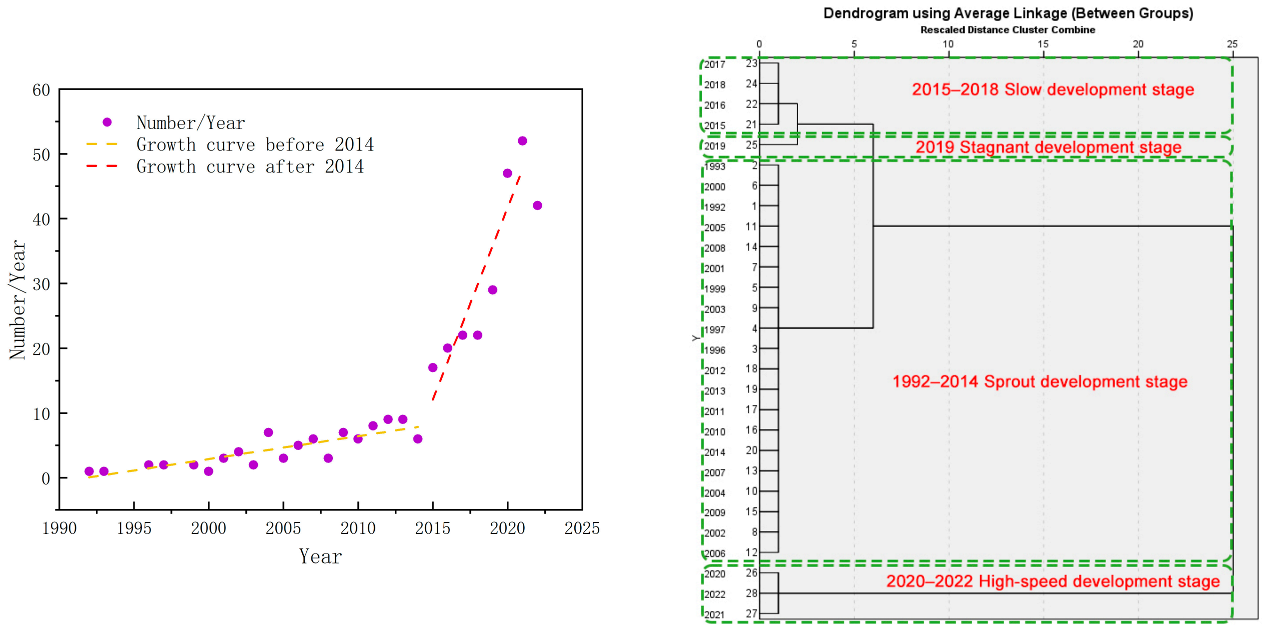
Table 2. Top 8 journals by number of publications.

Source Title	N	N (%)	IF-(Five Years)	H-Index	Country
Construction and Building Materials	19	5.81	8.194	198	UK
Energy and Buildings	14	4.28	7.129	198	Netherlands
Sustainability	14	4.28	4.089	109	Switzerland
Energies	13	3.98	3.333	111	Switzerland
Journal of Cleaner Production	11	3.36	11.016	232	UK
Biomass and Bioenergy	11	3.36	5.500	189	UK
Renewable and Sustainable Energy Reviews	8	2.45	17.551	337	UK
Journal of Building Engineering	6	1.83	6.991	54	Netherlands

The number of publications for which data were collected was analyzed and the top 10 journals are shown in Table 2. The number (N) and number share (N (%)) of straw energy conservation research published in these journals during the period 1985–2022, as well as the IF and high citation frequency (H-Index) of the journals, were counted. From the results presented, it can be seen that the top 10 journals contributed over 33% of the energy efficiency in straw building research published in the last 30 years. *Buildings and Building Materials* is the most influential journal, with 19 published articles (5.81%) related to straw building energy efficiency. *Energy and Buildings* and *Sustainability* are in second and third place, respectively. Among these journals, *Renewable and Sustainable Energy Reviews* ranks seventh in terms of the number of articles, but with an impact factor of 16.799 and an H-index of 337, which are the highest values among these eight journals. This shows that *Renewable and Sustainable Energy Reviews* is one of the journals that has a significant impact on research on energy efficiency in straw buildings.

3.1.2. Quantity Distribution

Figure 3a shows the number and growth trend of the published literature in the field of energy-efficient straw building materials from 1992 to 2022. The overall trend in the number of publications on energy efficiency in straw buildings has been increasing since 1992. The total number of the published literature on straw building materials' energy efficiency was only 87 during the 22 years from 1992 to 2014. However, after 2015, the number of publications increased to 251, representing 74.3% of the total number of publications. Although the data for 2019 deviate from the fitted curve, it is clear that the growth trend after 2015 is very different from the previous trend. The overall trend of linear growth in the literature (R^2 = 0.89) has an average annual growth rate of 19.4%.



(**a**) (**b**)

Figure 3. (**a**) Number of annual publications on the direction of straw building materials' energy efficiency; (**b**) the stages of research and development of straw building materials' energy efficiency from 1992 to 2022.

The present study examines the reasons for the substantial increase in the number of publications on straw building energy efficiency after 2015. To contextualize this increase, we looked at the policy developments in the construction industry, particularly the closing year of the UN Millennium Development Goals' (MDGs) program and the launch of the new Sustainable Development Goals (SDGs) [32,33]. Moreover, most of the 11 papers from the growth in 2015 compared with 2014 were publications by Chinese scholars on energy efficiency in straw brick buildings. This was due to the high priority given to the summit in China, where, on 24 July 2015, the Chinese government emphasized the critical role it would play in implementing the Sustainable Development Goals [34]. As can be seen, research on the energy efficiency of straw building materials responds to sustainable development (an important topic under the sustainable environmental development goals) and the research trend is increasing yearly in the context of the development of the times. This critical turning point also guides the lines of development in Sections 3.3 and 3.4.

Subsequently, the SPSS software was used for hierarchical cluster analysis to classify straw materials' research and development stages. A dendrogram serves as a graphical depiction of hierarchical clustering, which can reflect the relationships between diverse groups of data or variables in an intuitive manner [35]. Within the SPSS system, dendrograms are widely used as a chart type in cluster analysis [36]. The fundamental principle of hierarchical clustering involves constructing a nested cluster tree by computing the similarity between distinct categories of data points. The number of annual publications was divided into four different stages of development, as shown in Figure 3b. The first stage (before 1992 to 2014) was the embryonic development stage, with 0–10 publications per year. The second phase (2015–2018) was characterized by slow development, with 10–25 publications per year. The third phase (2019–2020) was also marked by slow development, but the year 2019 was divided into a separate phase because the trend in the number of published papers in the years before and after showed a clear difference in the data. The outbreak of the COVID-19 pandemic in 2019 had some impact on the research process in the field, which returned to a more normal level in 2020. The fourth stage (2020–2022) is a high-speed development stage, with 40–55 articles published annually, accounting for 43.7% of the total published articles.

3.2. Most Influential Countries and Research Scholars

Counting the number of articles published in different countries can help identify the countries that have made significant contributions to the field. In the graph, the connecting lines between countries represent collaborative relationships, with thicker lines indicating closer collaboration. The size of the nodes represents the number of articles published by each country. Larger nodes indicate a higher number of publications (Figure 4).

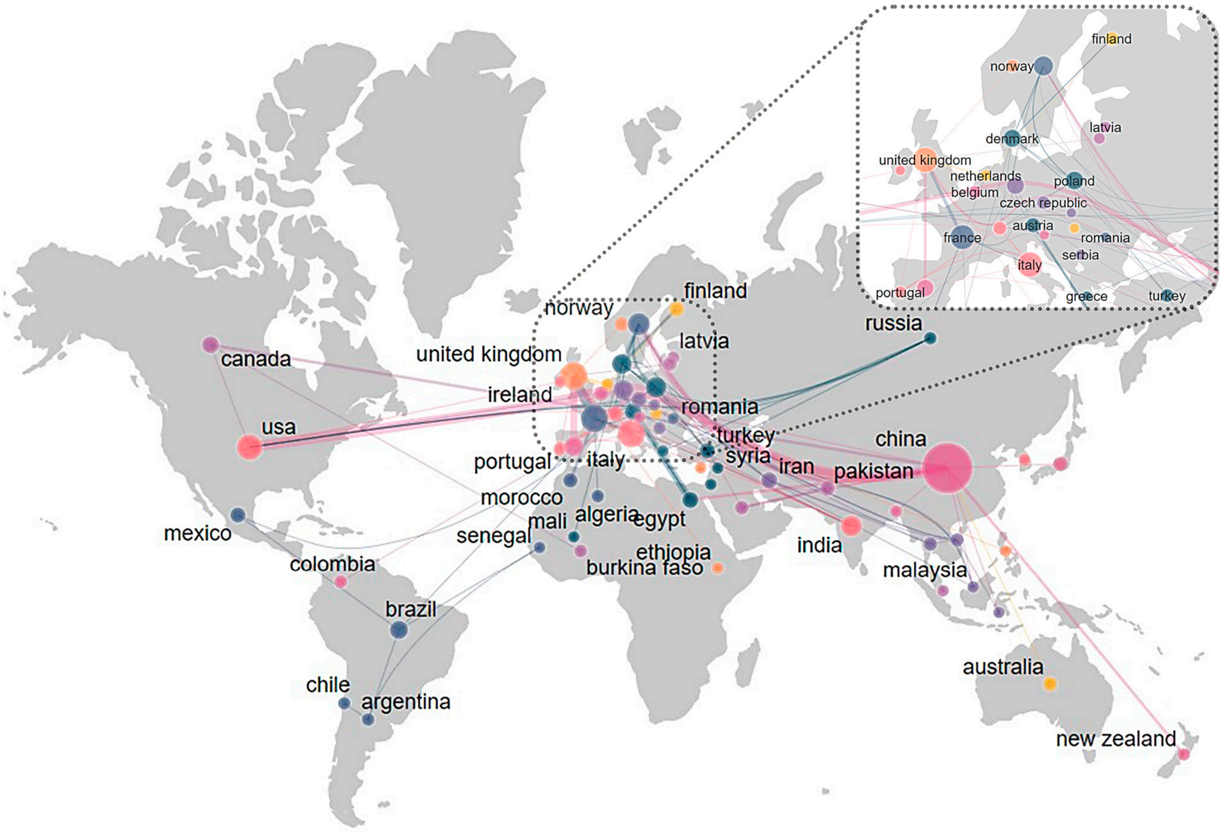


Figure 4. Visual map of collaboration by country/region.

According to the statistical analysis of the data in the database, it was found that articles related to energy-saving research on straw building materials have been published by 62 countries, with China being the most prolific, accounting for 29.36% of the total. The countries with >10% of published articles are China, France, Italy, the UK, and the USA. As shown in Figure 4, the co-occurrence map of national and international cooperation indicates that China plays a leading role in international cooperation in the field of energy efficiency in straw construction materials. The countries that China collaborates with are mainly the USA, France, the UK, Switzerland, and other European and American countries. The country that collaborates most closely with China is the USA, followed by Switzerland and the UK. However, statistically, most straw buildings are concentrated in countries that have regulations for such buildings. The country with the highest number is the USA, with 784 buildings, followed by France, with 700 [6]. The actual number of builds in these countries is much larger than in China. The number of published articles on the energy-efficient application of straw building materials in China far exceeds that of other countries, indicating that the theoretical research in this field is more systematic in China. However, more practical applications are needed.

There are 528 researchers in the field of straw building materials' research, with the top 10 authors and co-cited authors summarized in Table 3. If the number of articles is the same, the authors are ranked based on the chronological order of publication. Zuohe Zhang and Zehong Chen are the authors with the highest number of articles, followed by Xunzhi

Yin, Yuanchen Chen, and T. Ashour. T. Ashour, a scholar from Austria, has the highest number of co-citations, with 31, and S. Goodhew and H. Binici are highly cited, ranking second and third, respectively. As shown in Table 3, although eight of the top ten scholars ranked by the number of publications are from China, most of the top ten co-cited authors are from European countries and only one is from China. The leading research interests of Chinese scholars in the field include energy fuels, environmental science, and materials' multi-science, with a concentration of publications between 2015 and 2022. In contrast, the proportion of straw building construction technology and civil engineering construction in this field is much greater abroad; research in this area started earlier, showing a slow growth phase from 1992 to the present. This suggests that, although the number of publications by Chinese scholars is the highest in this field, the start of research in this field in China may have been later than that in European countries; further extensive research is needed to build on preliminary research results in European countries.

Table 3. Top 10 active and co-cited authors.

Author	Country	Quantity	Co-Cited Authors	Country	Quantity
Zuohe Zhang	China	5	T. Ashour	Austria	31
Zehong Chen	China	5	S. Goodhew	UK	24
Xunzhi Yin	China	4	H. Binici	Turkey	22
Yuanchen Chen	China	4	M. Lawrence	UK	20
T. Ashour	Austria	4	A.D. González	Chile	19
Minzhi Chen	China	4	F. D'Alessandro	Italy	18
Hongbin Liu	China	4	F. Asdrubali	Italy	16
Jiaqi Yu	China	3	A. Shea	UK	16
Hu Li	China	3	S. Cascone	Italy	14
S. Cascone	Italy	3	Xunzhi Yin	China	13

3.3. Research Directions and Hot Spots

3.3.1. Research Direction Analysis

The disciplinary classification in the WOS database reveals that, over the past 31 years, straw-building energy efficiency research has involved 40 disciplinary research directions. As shown in Figure 5, materials science, concrete science, energy and fuel science, and sustainability science dominate the field. The materials science direction is in first place, with 71 published papers. Straw material, as an agricultural by-product, is a biomass material and the leading research direction regarding building energy efficiency and material performance. In addition, since most new building structures are composed of concrete, the application of straw materials with the current building structure system is a critical issue to consider. Thus, the number of research publications in the concrete discipline is higher, with the second highest number of publications at 58. The above analysis shows that there has been an increase in research on issues such as building construction technology, environmental science, and green sustainability. This shift in research focus towards practical application in construction indicates that scholars recognize the importance of straw materials for achieving sustainable development in green buildings and seek to further explore the energy-saving potential of straw materials.

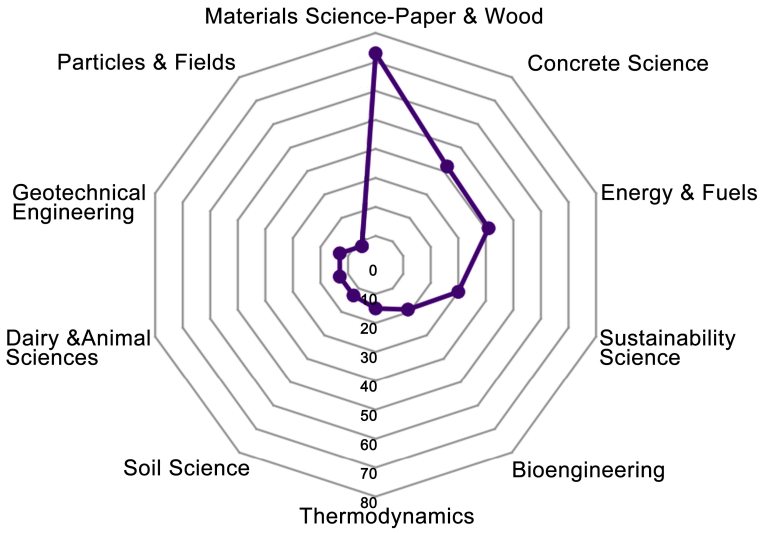


Figure 5. Statistical graph of the top 10 disciplines in terms of the number of published papers.

3.3.2. Research Hot Topic Analysis

The 338 papers selected in this study were analyzed using the keyword co-occurrence analysis function in CiteSpace; high-frequency keywords reflected the hot issues and development directions of the research field. First, two keywords—energy and straw—were filtered out since they were used as the main search keywords for the papers. Based on this filtering, a keyword co-occurrence network was generated by identifying the keywords of publications in the database and executing the keyword co-occurrence matrix with CiteSpace, as shown in Figure 6a.

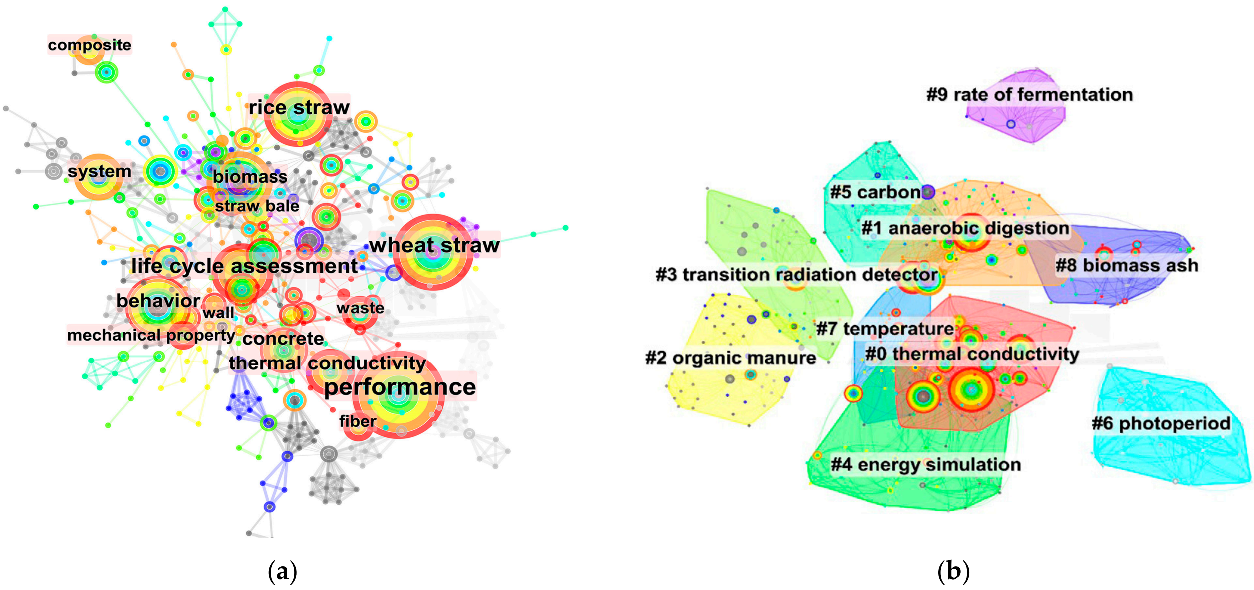


Figure 6. (**a**) Keyword co-occurrence network; (**b**) keyword clustering analysis profile.

High-frequency keywords that appeared more than ten times in energy efficiency studies in straw building materials between 1992 and 2022 included performance, wheat straw, life-cycle assessment, straw, and thermal conductivity. The keyword co-occurrence mapping was then clustered to generalize further and analyze the keywords, as shown in Figure 6b. One of the essential features of CiteSpace is the clustering of the information vocabulary and automatic labeling of the clusters [37]. Clustering analysis was performed using the CiteSpace clustering function to identify the main research themes in the topic of straw building energy efficiency.

Through clustering calculation, the keywords were grouped into 10 categories, numbered from 0 to 9, as shown in Table 4. The size of each cluster varied, with smaller numbers representing larger clusters; each cluster comprised several closely related keywords [27,38]. In this network, two critical values, namely the Q value and the S value, should be noted, as they characterized the quality of the clustering grid. Generally, the Q value represented the degree of modularity, with a value >0.3 indicating a significant clustering structure. On the other hand, the average contour value (S-value) represented the degree of contouring of the clusters, with a value >0.5 being considered reasonable and >0.7 being more plausible [27,39]. In this paper, the Q value was found to be 0.65 (>0.3), indicating a significant clustering structure, while the S value was 0.85 (>0.7), suggesting that the clustering is credible. Further analysis was conducted on the most significant clusters.

Table 4. Keyword clustering table.

Cluster ID	Most Frequent Keyword	Size	Silhouette	Top Keywords (Frequency)
Cluster #0	Performance	88	0.707	performance (44); life-cycle assessment (28); behavior (19); thermal conductivity (19); concrete (18); fiber (12); mechanical property (12); composite (11); wall (11); wood (10); impact (9); building material (9); bio-based material (9); conductivity (9); agricultural waste (9); composite (11); wall (11); wood (10); impact (9); building material (9); bio-based material (9); conductivity (9); agricultural waste (8); energy efficiency (8); construction (8); thermal insulation (10)
Cluster #1	Wheat straw	77	0.819	wheat straw (29); rice straw (24); biomass (16); pretreatment (9); renewable energy (9); biogas production (7)
Cluster #2	Greenhouse gas emission	42	0.965	greenhouse gas emission (6); biofuel (5); energy metabolism (3); manure (4); embodied energy (3); fuel (3)
Cluster #3	System	41	0.901	system (15); agricultural residue (6); energy production (3); biomass energy (2)
Cluster #4	Straw bale	40	0.909	straw bale (12); design (5); carbon (5); consumption (4); environment (5); energy balance (2)
Cluster #5	Mission	36	0.86	mission (10); growth (5); physical property (5); architecture (2)
Cluster #7	Building	26	0.82	building (9); storage (9); cellulose (5); corn straw (4); phase change material (4)

Performance

The main keywords in this cluster are performance (44), life-cycle assessment (28), thermal conductivity (19), concrete (18), fiber (12), and others. This cluster is the largest and most significant, encompassing various straw material performances, properties, characteristics, and the whole life-cycle aspects of the keywords.

After a comprehensive analysis of straw construction research, it was found that the study of fundamental properties of straw construction materials, including density, moisture content, heat capacity, mechanical properties, thermal performance, sound insulation, and durable fire resistance, is essential. Most research on straw materials focuses on the moisture and heat properties of straw materials, as it is closely related to building energy saving. Thermal conductivity of straw materials has been tested and verified in several publications [15–18,40–42]. Two experimental measurement methods are steady-state and transient [18,43–45]. Although the transient method is relatively faster, it requires a more complex analytical procedure compared with the steady-state method [15,43]. The thermal conductivity of straw generally increases with increasing stack density (ρ), but the relationship is not always perfectly linear [46–49]. Moreover, the thermal conductivity is related to the orientation of the straw within the material, with parallel, perpendicular, and random directions of the straw affecting it [50–52]. Compared with parallel-aligned straws, straws with vertical or random heat flow of fibers showed lower thermal conductivity [46,53–55]. The physical structure of the suction tube structure within the straw bale also affects its thermal conductivity. Vėjelienė's experiments showed that peeled straw had lower thermal conductivity compared with chopped straw, which was lower than unprocessed straw [46]. Notably, straw load-bearing and insulating materials are categorized as pure straw materials, which are derived from straw waste compressed with a baler immediately after harvesting the crop, and straw composites [56].

Despite its benefits of low cost, low carbon, and thermal insulation, straw suffers from drawbacks such as diminished strength, enhanced thermal conductivity, and vulnerability to moisture and mold because of its high moisture content. The factors that influence the moisture content of straw materials include density, porosity, fiber length, and fiber content [57]. The moisture content decreases as these factors decrease. Moreover, the preparation process and post-treatment methods of straw materials affect their moisture content. For instance, prestressing straw enhances its compressive strength and minimizes its drying shrinkage; coating straw improves its waterproof performance and protects it from external moisture intrusion [58–60]. Furthermore, the use environment and time of straw materials affect their moisture content. In a hot and humid environment, straw materials absorb moisture from the air, increasing their moisture content; in a dry and cold environment, straw materials lose their internal moisture, decreasing their moisture content [57,61]. Additionally, over time, straw materials deteriorate and degrade, compromising their moisture content stability.

Another important keyword in this cluster is life-cycle assessment (LCA), which evaluates the overall environmental impact of construction materials from "cradle to grave" and in the context of sustainable development. LCA helps in selecting an optimal solution by evaluating various alternatives for different products or facilities [62]. In a full LCA of straw material buildings, several scholars compared the LCA of straw walls with conventional double brick walls and found that straw walls had twice the thermal resistance of conventional walls and a lower environmental impact in all categories except for land use and water use [63–66]. Compared with traditional insulation materials, straw materials show a better sustainability potential. The method of LCA analysis enables the comparison of environmental impacts of bio-based construction materials under various future scenarios. When conducting a scenario analysis, it is crucial to account for the temporal dimension, along with factors that impact the different stages of the life-cycle, such as energy consumption, waste disposal, and the supply of raw materials. Table 5 presents a comprehensive comparison of the entire life-cycle across different scenarios.

Table 5. LCA results of straw material buildings in different scenarios.

Project	Building Type	Floor Area	Location	Key Findings
Hemp concrete for green building applications [67]	Residential and non-residential buildings	Not specified	Europe, North America, Australia, Asia	Hemp concrete has low embodied energy, high thermal insulation, good hygrothermal performance, and carbon sequestration potential.
Straw-bale housing [68]	Single-family houses	100–200 m^2	UK, USA, Canada, Australia, New Zealand	Straw-bale houses have lower embodied energy and carbon emissions than conventional houses. They also have high thermal performance and fire resistance.
Straw bale constructions [69]	Single-family houses and public buildings	50–300 m^2	Italy, Spain, France, UK	Straw bale constructions have low environmental impact, high thermal insulation, and good hygrothermal behavior. They also have high durability and fire resistance if properly designed and maintained.
An innovative straw bale wall package for sustainable building [6]	Residential building	100 m^2	Pescara, Italy	The straw wall package has excellent energy performance and low environmental impact compared with a traditional wall package. The embodied energy is about half and the CO_2 emissions differ by more than 40%.
A case study on bio-based and non-bio-based walls [6]	Residential building	100 m^2	France	The bio-based walls have lower global warming potential (GWP) than the non-bio-based walls over a 100-year time horizon. The GWP of the walls varies depending on the temporal dynamics of greenhouse gases (GHGs). The straw bale wall has the lowest GWP among the four walls.
Impact of insulation and wall thickness in compressed earth buildings in hot and dry tropical regions [70]	Residential building	100 m^2	Ouagadougou, Burkina Faso	The insulation material and thickness have significant effects on the thermal performance and energy consumption of the CEB buildings. The straw bale insulation has the best thermal performance and the lowest energy consumption among the three insulation materials.
Assessing the embodied carbon reduction potential of straw bale rural houses by hybrid life-cycle assessment [71]	Rural houses	80–120 m^2	Spain	The straw bale rural houses have lower embodied carbon than the conventional rural houses by 50–70%. The hybrid life-cycle assessment method can capture more carbon emissions than the process-based method.
Hygrothermal performance, energy use, and embodied emissions in straw bale buildings [72]	Residential building	100 m^2	London, Athens, Stockholm	Straw bale buildings show robust hygrothermal performance and low risk of mold growth when properly designed. Straw bale buildings achieve very low energy use at a minimum of embodied emissions compared with conventional buildings.
Energy sustainability of bio-based building materials in the cold and severe cold regions [73]	Residential buildings	100 m^2	Hailar, Harbin, Urumchi, Lanzhou, and Beijing	Both cross-laminated timber and straw bale buildings are more efficient than reinforced concrete with a reduction in energy consumption during the operational phase. The straw bale has the best thermal insulation performance among the three materials.

Table 5. *Cont.*

Project	Building Type	Floor Area	Location	Key Findings
Multi-case study on the carbon emissions of the ecological dwellings in cold regions of China over the whole life-cycle [74]	Three dwellings constructed at different times	100 m^2, 120 m^2, 150 m^2	Yinchuan City, China	The carbon emissions are mainly from the material production stage and the use stage. The use of ecological building materials (straw bales and logs) and solar photovoltaic system can significantly reduce the carbon emissions of buildings.

The keyword "concrete" was ranked and the publications under this phase focus on composite material performance and energy efficiency. Concrete is generally used as the object to be compounded and straw is added as the main mixture to carry out the compounding of the materials [75]. The study of composite material properties allows us to assess whether the composite material meets the thermal requirements established for low-energy buildings [76]. Experimental measurements on composite straw materials focus on achieving energy savings and reducing emissions by reducing the use of high-carbon-emitting building materials such as clay bricks, steel, concrete, lime, and cement [71,77].

Wheat Straw

The main keywords in this cluster were: wheat straw (29), rice straw (24), biomass (16), pretreatment (9), renewable energy (9), biogas production (7), etc. This cluster ranks as the second-largest core cluster. Studies have shown that in the thermal conductivity of different sources of straw, including barley straw, wheat straw, and rice straw, does not exhibit any significant variation [15,57,78–83]. Straw has a multi-layered and porous structure and is generally known as a hygroscopic material [84]. Among the different types of straw, wheat straw has a higher fibrous content and, in comparison with rice straw during experiments, exhibits more prominent cells with a larger size and an asphyxiated variable surface [15,18]. Additionally, rice straw has less hysteresis after water uptake than wheat straw, indicating that rice straw recovers more quickly after wetting with water. Therefore, rice straw has better hygrothermal properties and durability [52,85,86].

Greenhouse Gas Emission

The keywords in this cluster are: greenhouse gas emissions (6), biofuels (5), energy metabolism (3), fertilizers (4), embodied energy (3), fuels (3), etc. While smaller in size compared with the previous clusters, this cluster encompasses publications that focus on livestock and soil science, with some interdisciplinary intersections with construction materials.

Rice straw can be used as a renewable energy source to reduce the use of fossil fuels and greenhouse gas emissions, including methane [87,88]. Various technologies have been developed to harness the energy potential of rice straw, such as direct combustion, densification of rice straw into pellets, agglomeration, gasification, pyrolysis, and bioethanol production [89]. Rice straw has been used as a renewable energy source for electricity and heat production (direct combustion) in Denmark, the UK, Spain, and India [90–92]. Research studies have also demonstrated the effectiveness of straw bales in reducing carbon emissions from buildings, considering carbon sinks [88,93,94]. Using straw as a renewable resource, straw-bale houses offer a low-carbon construction method that minimizes carbon dioxide emissions and maximizes carbon sequestration throughout their lifespan [95]. Research indicates that each semi-detached straw-bale house can store over 15 tons of carbon dioxide, with straw accounting for about 6 tons and wood and wood products for the rest. This implies that renewable construction materials have a high carbon lock-up potential, which can lower the whole-life carbon dioxide emissions of the case study house by 61% over its 60-year design life, relative to the case without carbon sequestration [69]. Another study also demonstrates that, in contrast to the reference rural houses, straw-bale houses with wood or light-steel structures can slash net carbon emissions by 96.75% and 76.92%, respectively [71].

3.3.3. Research Trends and Outburst Word Analysis

In the timeline co-occurrence analysis of high-frequency keywords in the energy-saving development of straw materials, the two phases of 2020 to 2022 and 2019 were combined for the convenience of observation and analysis. Based on the clustering timeline, the analysis of emergent words in each phase, as shown in Figures 7 and 8, helps to establish a development order for the research hotspots in this field in the past three decades and to grasp the logical relationship between the keywords, laying the foundation for research in Section 3.4.

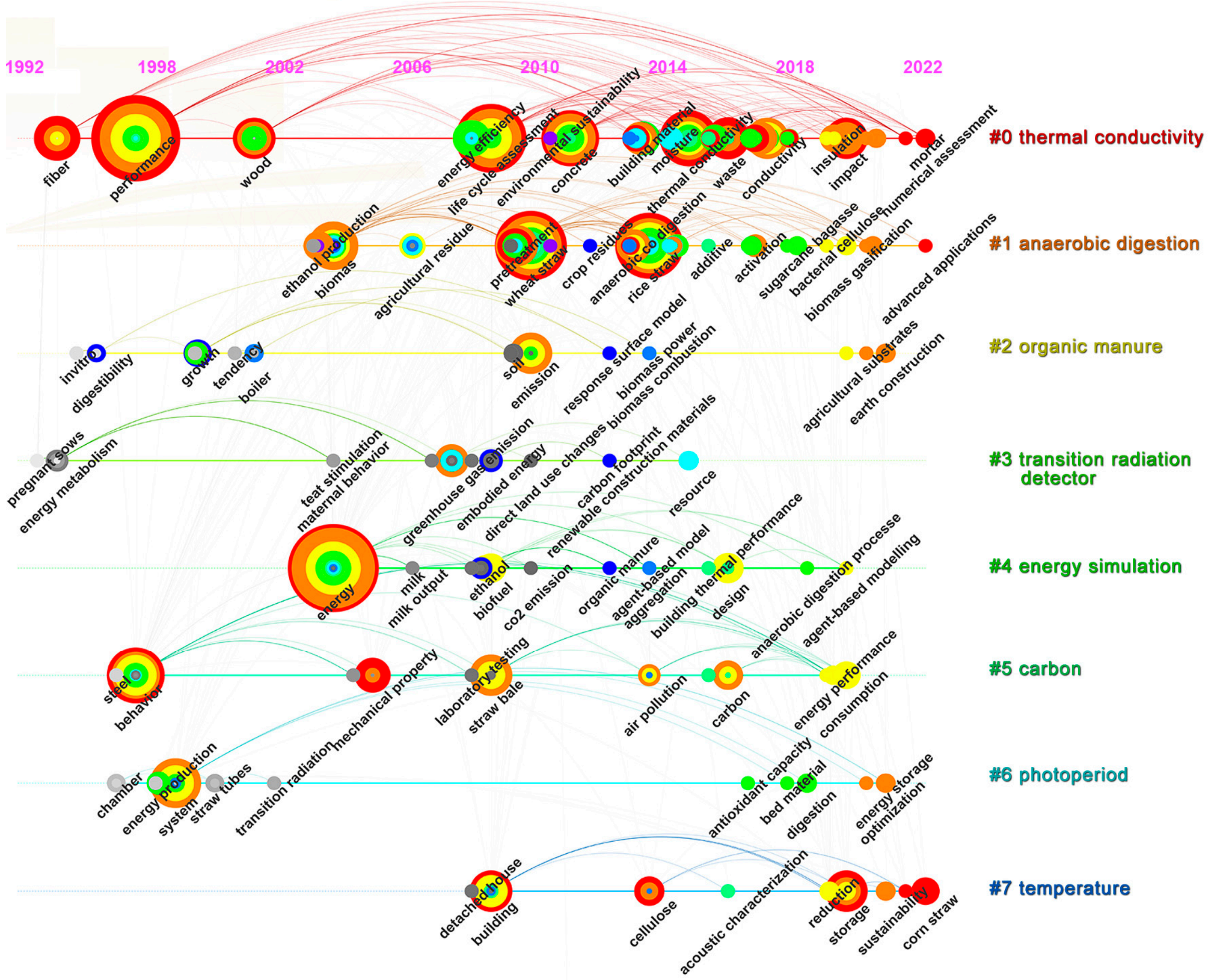


Figure 7. Analysis of hot trends of keyword time mapping research.

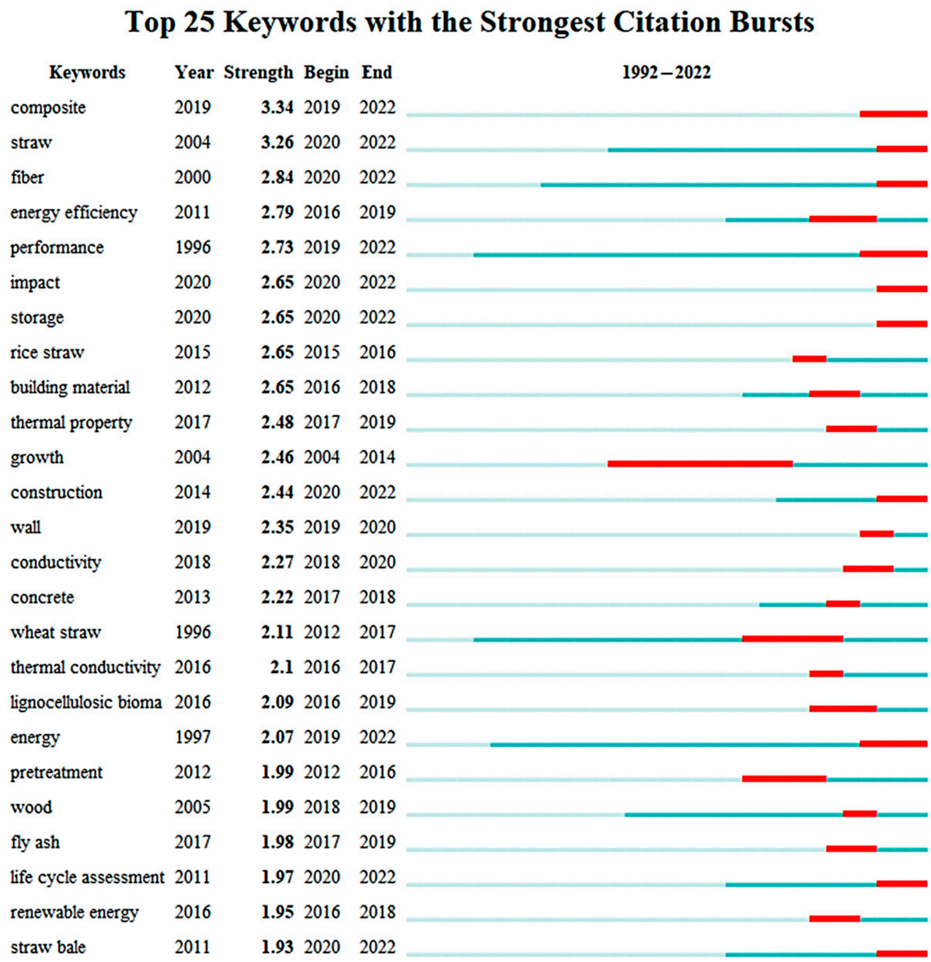


Figure 8. Analysis of the top 25 keywords with the strongest citation burst.

The outburst words depicted in Figure 8 scrutinize the frequency of occurrence of words and phrases utilized in the referenced literature during the time frame of 1992 to 2022. The year of appearance for the keyword is highlighted in dark blue. The words that transition to red signify the forefront of research. The "Begin" and "End" labels indicate the initiation and termination years for the frontier. The "Strength" label signifies the magnitude of emergence, where a larger number indicates a greater intensity of emergence. The graph elucidates the research frontiers during different periods of time. For instance, "Composite" is the research frontier for 2019 to 2022. Analyzing the emergent terms can offer a lucid picture of evolving research trends and hotspots at each stage. This paper has selected the top 25 keywords with the highest strength and conducted trend analysis for different time periods in conjunction with Figure 7.

- Research on straw properties and wheat straw started early, but the number of publications was limited before 2000. The research on the built environment, energy consumption, and buildings started later and all began to develop after 2000, with a focus on the availability of cereal straw materials, the initial exploration of straw composite synthesis materials, and the use of straw as a biomass fuel. As shown by Figures 7 and 8, the keywords before 2000 were mainly focused on the utilization of biomass. Recycling straw by filling it into the soil is beneficial for better crop growth, such as rice [14,96,97]. Wheat straw and its pre-treatment started to come to the forefront and developed mainly in the next phase. This research stage was less dynamic and represented the primary development stage for each research direction. The effectiveness of energy-saving strategies was initially verified by using renewable materials and energy sources to improve the sustainability of buildings. Experiments were selected for straw material buildings and solar energy supply [98].

- Between 2015 and 2018 (Figures 7 and 8), keywords such as energy efficiency, rice straw, construction materials, thermal performance, concrete, wheat straw, thermal conductivity, wood fiber biomass, wood, fly ash, and renewable energy became increasingly prominent. The main research areas focused on energy fuels, building construction technologies, and green sustainable technologies. Research has revealed that wheat straw and rice straw exhibit significant microstructural differences; however, both types of straw exhibit similar water absorption properties regardless of the straw species [57]. Moreover, understanding the water absorption isotherms of rice straw can ensure a high degree of confidence in the hygroscopicity conditions in straw bale wall structures made of rice straw [99]. Given the increased importance of sustainable development strategies, some scholars have begun to explore the potential of using straw building materials as a renewable energy source, which has intensified further research on the specific properties of straw and the possibilities of insulation materials.
- As shown in Figures 7 and 8, between 2019 and 2022, keywords such as composite, straw bale, fiber, performance, impact, storage, building, wall, energy, and life-cycle assessment emerged. Various studies have confirmed that straw is a promising raw material for cost-effective and environmentally friendly building insulation [6,8,15,100]. However, straw insulation materials still possess some drawbacks and issues, for example, their durability and fire resistance when compared with traditional building materials have some gaps, which has been a hot issue of concern in recent years [42,101,102]. In addition, further study is required to investigate the risk of straw degradation. The current emergence of relevant straw composites aims to achieve better use of straw in construction and represents an important research direction in this field, enabling the exploitation of the performance characteristics of straw materials. In the future, the relevant properties of straw materials or straw composite-related products could be microscopically analyzed to optimize their design [43,103]. Furthermore, more scholars are using life-cycle assessment methods to examine the life-cycle carbon emissions of straw buildings [104]. Differences in carbon emissions throughout the life-cycle of various eco-houses, particularly in energy consumption and carbon emissions during construction and operation, are significant [74]. Research focuses on multiple aspects and stages of building and construction, management, and components [7,105].

3.4. Development Overview and Future Research Forecast

Based on the analysis of the above chapters for the development stage, outburst word analysis, research hotspots, development trend, and co-citation of the literature, the authors summarized and composed the temporal development pulse of the straw building materials' energy saving field, as shown in Figure 9.

Figure 9 shows the development of straw building materials in the field of energy efficiency from 1992 to 2022, with 2015 marking a crucial turning point. While the field's development was slow during the period from 1992 to 2014, there have been significant breakthroughs in both the breadth and depth of research areas since 2015, with a focus on straw as a building material.

In 1992, straw was first used as a warming material in cattle barns and experiments were conducted to test the effect of laying straw in slatted cattle beds and fences on changes in the diet of cattle [11]. The experiment demonstrated that the straw had an influence on the nutrient intake of the livestock by changing their living environment, making it the first time straw was used as an insulating material in a building. From 1996 to 1997, Sweden and other places pioneered research on using straw as agricultural waste, with the suggestion that replacing fossil fuels with biomass such as straw could reduce Swedish carbon dioxide emissions by about 65%, equivalent to 20% of the electricity produced at the time [88]. The additional transport costs associated with this agricultural waste were also considered, laying the groundwork for a later systematic life-cycle view of the problem.

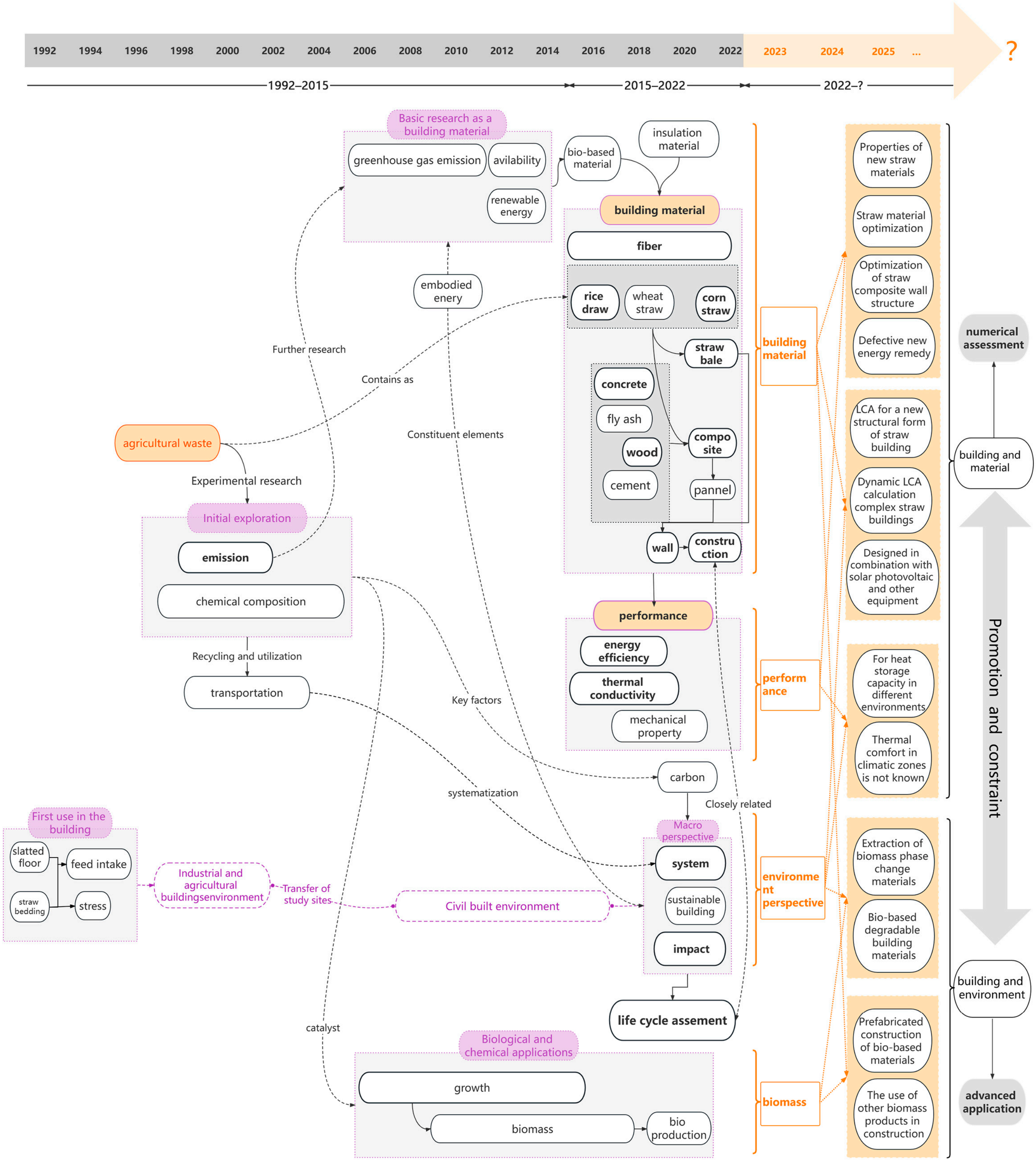


Figure 9. Development of straw building materials in the field of energy efficiency composed between 1992 and 2022.

Following the initial qualitative study of straw as crop waste between 1992 and 2014, research scholars conducted a series of biological and chemical experimental studies on the composition of straw. While there has been a steady stream of research on various products such as chemical fertilizers and biomass fuels in the following twenty to thirty years, this paper does not focus on these topics. Since the first suggestion of the advantages of straw materials in reducing emissions, research in the field of straw has been further investigated in terms of greenhouse gas emissions and renewable energy [69,106]. The implicit energy issues included in all aspects of transportation, construction, and production throughout the construction process have sparked the research on systemic issues in this field [88,107]. Based on research from 1992 to 2014, after 2015, research on straw materials for construction has gradually accelerated, with straw being used in many buildings based on renewable energy bio-based construction materials and a shift in focus from industrial and agricultural building environments to residential buildings. According to the keyword emergence analysis, scholars are limited to the study of a single straw material and the composite study of straw material. It can be seen that the straw composite material has a deep concern hot spot and has substantial development potential [8]. With the progress of the construction industry, the construction of straw buildings has also become a concern for scholars, for example, the prefabricated straw composite panels that have become more popular in some European countries in recent years [108].

Research into the properties of straw materials has been closely linked to the evolution of construction techniques utilizing this natural resource. The study of material properties in this field covers four areas: from small to large straw fiber scale, straw bale scale, envelope scale, and overall building scale, for experimental studies on performance [16]. Numerous studies have shown the excellent thermal insulation properties of straw materials in building envelopes due to their small heat transfer coefficient [6,8,18,109]. In addition, research focus has recently shifted towards mechanical properties, fire resistance, sound insulation, and durability [41,101,102]. Straw materials' moisture absorption performance, which affects the mechanical properties, dimensional stability, durability, fire resistance and other characteristics, is also a growing concern. Therefore, suitable environmental conditions and protective measures should be chosen when using straw materials to minimize moisture-induced deformation and degradation. On an architectural scale, there is an increasing focus on the issue of the indoor comfort of straw materials [110].

As sustainable development becomes an increasingly urgent priority and energy crises continue to mount, exemplified by the signing of the Paris Agreement, energy efficiency research in building materials is increasingly focused on the impact on and adaptation to the physical environment. Straw is an important area of low-carbon materials and some scholars have begun to use methods such as objective measurements and software simulations to evaluate and compare the adaptability of more mature straw-building systems to different climate zones [70,72,73,103,111]. These scholars have evaluated and compared the adaptation of straw building materials to specific climatic zones using more mature methods such as measurement and software simulation [73,103]. The goal is to provide theoretical support for better adaptation of straw building materials to specific environments.

With the advancement of research on the characteristics of straw and the growing need for low-carbon and energy-efficient buildings, novel straw-based materials are emerging rapidly. Various new materials with specific functions and properties are being developed by scholars using straw as a raw material and applying different techniques. These include straw fiber concrete, straw building panels, straw biomass ash, etc., which are all innovative building materials derived from agricultural waste through different processes [112]. Moreover, straw materials can be integrated with other renewable energy sources or low-carbon technologies to form holistic solutions for energy conservation and emission reduction, such as producing geopolymers from straw biomass ash, creating biorefineries from livestock manure, and constructing solar houses from straw building panels, etc. [113].

With the substantial growth in the number of straw buildings, the standardization and institutionalization of construction have become a top priority at this stage. Some scholars have explored problems in straw construction, such as the economy and construction cycle [111,114]. Furthermore, as the popularity of straw building materials increases, more research on the entire life-cycle, including straw material and component fabrication, straw house planning and design, construction, and transportation, will become increasingly important [114].

Based on the analysis, as shown in Figure 9, the authors divided them into four groups: building materials, performance, environmental perspective, and biomass. For instance, in the connection between building materials and environmental perspectives, future research may focus on studying the entire life-cycle of straw-insulated buildings in new structures, calculating the dynamic whole life-cycle of complex straw brick buildings, and exploring straw brick buildings integrated with photovoltaic power systems. The future is predicted based on previous developments, which will serve as a reference for scholars in the field.

In summary, the authors used Citespace software's burst detection and timeline logic to summarize nearly seven years of research results from 2015 to 2022 in this field. The results were categorized into two parts: straw building and materials; straw building and environment. For the improvement of straw buildings and materials, further research should be conducted on the qualitative analysis of data performances. In terms of the relationship between straw buildings and the environment, applied research should focus on low-carbon and energy-saving strategies throughout the building's entire life-cycle. Specific materials and construction should be considered to minimize the environmental impact on a particular building design. Both areas should be promoted and developed in an integrative manner.

4. Conclusions

The conclusions on the current status of research in the area of energy efficiency in straw building materials are as follows:

- Upon analysis, it has been observed that articles in the field of straw building materials' energy efficiency have made significant progress over the past 31 years, with 2015 being a pivotal year. This progress is closely linked to the Sustainable Development Goals' (SDGs) policy. Using the cluster analysis method, the development stages were classified into four stages, including the sprout developments stage, the slow development stage, the stagnant development stage, and the high-speed development stage. The current stage has been in the high development stage from 2020 to 2022.
- *Construction and Building Materials* is the journal that publishes the most articles related to energy efficiency in straw building materials. *Renewable and Sustainable Energy Review* and *Sustainability* are also promising journals. The top ten journals are concentrated in European countries such as the UK and the Netherlands.
- So far, 62 countries, 361 institutions, and 528 researchers have published articles on energy-saving research on straw building materials. Chinese scholars have contributed the most publications in this field. However, it started much later than overseas research and lags significantly behind the United States and Europe regarding building engineering technology practices in this field. The main shortcoming of the research in Europe and the United States is the lack of unified planning and policy support for the development and utilization of straw materials. In addition, the cooperation between countries is not close enough.

The research findings on hot directions and research trends in the area of energy efficiency in straw building materials are as follows:

- This review has shown that research on straw materials has progressed from basic exploration to practical application in construction. Following various research outcomes, novel straw-based materials have been developed, such as straw fiber concrete, straw building panels, straw biomass ash, etc. These novel materials have demonstrated superior performance in terms of thermal insulation, sound absorption, fire resistance, seismic resistance, etc., and can significantly reduce the energy consumption and carbon emission of buildings. Compared with other conventional or alternative materials, such as cement, steel, wood, etc., straw materials have lower environmental impact, higher economic feasibility, and greater social acceptability. Therefore, straw materials are essential for achieving green and sustainable buildings in the context of low-carbon economy and circular bioeconomy.

- Based on the analysis of the main hot keywords in the field of straw building materials between 2019 and 2022, such as composite, life-cycle assessment, straw bale, performance, storage, construction, wall, etc., it can be concluded that future research should focus on the following aspects: (1) evaluating the whole life-cycle environmental and economic impacts of straw materials; (2) optimizing the performance and structure of straw materials under different conditions; (3) developing innovative techniques and methods for storing and processing straw materials. By addressing these issues, straw materials can play a more important role in the transition to a low-carbon economy and sustainable development.
- This paper reviews the development of straw building materials from 1992 to the present. It highlights the evolution of knowledge from a qualitative understanding of the energy-saving and emission-reducing advantages of straw building materials to the large amount of experimental and simulated data proving the physicochemical properties of straw building materials. The application of straw building materials has evolved from their initial use in the agro-industrial building environment to their development and adoption in civil buildings worldwide. The paper summarizes the research results of the last seven years (2015–2022). The application of straw building materials for energy saving is summarized into two parts: straw building and materials and straw building and environment, emphasizing the interdependence between the two and the importance of their joint development.

This study presents a novel perspective on the research of energy efficiency in straw building materials, offering a comprehensive understanding of their relevant characteristics. This study serves as valuable insights for researchers seeking to explore specific areas of energy efficiency in straw building materials and related research methods. This paper is the first systematic review of the literature using bibliometric methods in this field; we chose to use journal articles as the main basis because journal articles usually go through a more rigorous peer review process and have a higher recognition in this field. However, we acknowledge that conference proceedings also have very rich research results in this field and we will further study the results of conference papers in the future.

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