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Visualization Analysis and Knowledge Mapping the Research of Aerogels Applied in Buildings

Xin Yu [1], Lei Wu [2,*] and Ming Li [2,*]

[1] Center for International Education, Philippine Christian University, Malate, Manila 1004, Philippines; yusihai1314@gmail.com
[2] Key Laboratory of Songliao Aquatic Environment Ministry of Education, School of Municipal and Environmental Engineering, Jilin Jianzhu University, Changchun 130118, China
* Correspondence: wulei830101@163.com (L.W.); mgvi@163.com (M.L.)

Abstract: With the deepening of aerogel research and the popularization of its application, the demands for energy saving in the construction field has brought aerogels into the limelight. To explore state-of-the-art research and development trends related to aerogels applied in construction, CiteSpace was used to conduct a quantitative analysis based on the Web of Science core database. Results show that: (1) in the past 10 years, the number of papers on aerogels in the field of constructions has increased significantly; (2) the top producing countries in the aerogel field are mainly China and the United States, and the top two research institutions are all Chinese institutions (Univ Sci & Technol China and Chinese Acad Sci); (3) the main publishing journals are ENERGY AND BUILDINGS, CONSTRUCTION AND BUILDING MATERIALS, and CHEMICAL ENGINEERING JOURNAL; (4) the hot keywords are thermal insulation, silica aerogel, thermal conductivity, phase change material, mechanical property, graphene aerogel, self-assembly, energy saving, etc.; (5) aerogel is mostly used in building insulation, mainly in the form of aerogel glass, aerogel mortar, aerogel felt, and aerogel coating. In summary, in addition to systematically strengthening theoretical research, it is necessary to optimize the technical process and reduce costs in order to effectively promote aerogels in construction energy conservation and carbon reduction. Through this study, the current situation, hot spots, and development trend of aerogel application in construction can be revealed systematically. Overall, this study helps advance research on aerogels applied in buildings and help in tackling energy efficiency challenges.

Keywords: aerogel; building; bibliometrics; CiteSpace; visual analysis

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1. Introduction

Aerogel (solid smoke or frozen smoke) has a three-dimensional mesh-like microstructure and is the lightest known solid material. This microstructure gives it unique properties such as low density, low thermal conductivity, high specific surface area, and high acoustic impedance [1,2]. Environmental degradation has been widespread since the 1990s, and more economical, energy-saving, environmentally friendly, and efficient materials have gradually become the key to solving the problem of high energy consumption in the construction industry. Currently, common and traditional inorganic thermal insulation materials include thermal insulation mortar, rock wool, and foam glass [3–5], while organic thermal insulation materials include extruded polystyrene board and foamed polyurethane [6,7]. These organic class insulation materials have low thermal conductivity and poor fire resistance, which are serious safety hazards in the face of a fire, and the gases released by combustion are harmful to human body and the environment. Aerogel materials have superior properties compared to these conventional materials [8,9]. Therefore, aerogels have a good prospect of replacing many construction materials. In addition, aerogels can be compounded with traditional materials, thus improving the energy efficiency of buildings, while effectively reducing the occurrence of safety hazards.

In summary, aerogels are an ideal new, lightweight and efficient thermal insulation material, with broad research prospects in thermal insulation, energy saving, and consumption reduction. With aerogel materials gradually gaining attention, the accumulation of related research literature has been grown too [10–12]. However, there is no comprehensive, quantitative, and in-depth analysis and generalization of this literature, which is not conducive to systematically comprehending the development status and research trends of aerogels in the field of construction. In addition, traditional review writing is more subjective comments without quantitative analysis and cannot accurately grasp the knowledge base and frontier trends in the field of aerogel. In the face of the rapidly growing research in the field of aerogels applied in construction, it is important to provide a quantitative summary of research evolution and trends using new methods.

Bibliometrics is a discipline that uses mathematical and statistical measures to quantitatively study the characteristics of literature and can explore the trends and hot frontier areas of the discipline from the evolution of research [13,14]. This method can comprehensively and quickly extract knowledge structures, research hotspots, and topic distributions from the existing mass of academic data, and has been widely used in environmental, medical, management, materials, agricultural, and other disciplines [15–19]. With the explosive growth of knowledge, the method is expected to gain more widespread applications. However, there are still insufficient quantitative studies on the research hotspots and development trends of aerogels in the construction field.

In this study, a literature review of aerogel research in the construction field was conducted using a bibliometric approach. The research power (countries, institutions, authors), research themes, and evolutionary trends are discussed in terms of publication trends, cooperative network analysis, journal double stacking analysis, keyword mutation analysis, literature co-citation analysis, and theme clustering analysis, aiming to provide a basis for understanding the development process and hot topics of the field.

2. Methodology

2.1. Data Retrieval

Data were obtained from the Web of Science Core Collection (WoS) in the Science Citation Index Extension (SCI-E) web database. It is a literature search platform that includes the most authoritative scientific articles [20–22]. The data used was based on article paper titles, abstracts, and keywords containing the terms "aerogel", "building", "architecture", or "construction" published up to 3 March 2023. A total of 862 articles were selected as raw data and downloaded under the name of "XXX_download. txt" for further bibliometric visual analysis.

2.2. Data Analysis

CiteSpace, one of the most popular bibliometric tools, is a citation visualization and analysis software for multivariate, time-stage, and dynamic literature information gradually developed in bibliometric, data, and information visualization. It has extremely powerful literature statistics and knowledge graph visualization capabilities [19,23–25]. In this study, CiteSpace 5.1 R3 software was used for visual mapping, using the options "Author", "Institution", "Country", "Keyword", "Cited Reference", and other options in the software to analyze the current status and frontiers of published research literature on aerogels applied in buildings in terms of countries, institutions, journals, and research directions. In addition, the "Analyze Search Results" function of WOS was used to analyze the distribution of subjects and the number of articles published.

3. Results and Discussion

3.1. Publication Trend Analysis

The trend of the number of publications is an important indicator of research development in a particular area of the discipline, which can effectively assess the research status of the discipline in that area and further predict its development dynamics and trends. The average annual publication volume of aerogel-related research in the field of construction on Web of Science for the past 30 years was 29.7 (Figure 1).

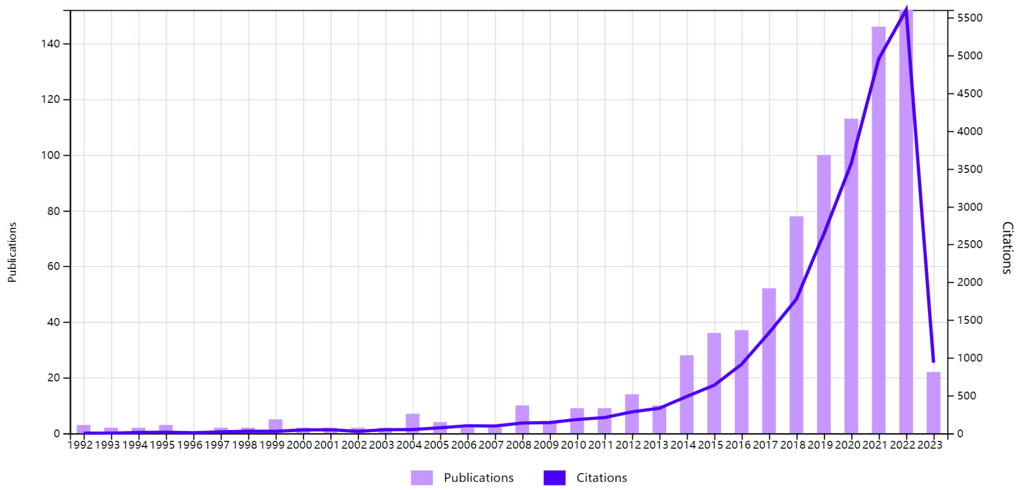

Figure 1. The distribution of the annual publications and citation from 1992 to 2023.

Research on aerogels in the construction field has been developing and progressing continuously and can be divided into three stages. The first stage is the budding period, during the period from 1992–2010, in which aerogel research in the field of construction had just started, the average annual number of publications is only 3.63, and the academic community lacks attention to this field. The second stage is the stable development period, during the period from 2011–2017, in which the average annual number of aerogel publications in the field of construction reached 27.42. This shows that the research in this field was gradually gaining attention and its influence on the current academic and practical communities was gradually strengthening. The third stage is the explosive period, where the average annual publication volume reaches 118.8 articles in the period from 2018–2022. With the increasing requirements of low carbon and environmental protection in the construction industry and the in-depth research on aerogel applications, aerogels in buildings have now also become a research hotspot in the field, and many scholars have started to conduct comprehensive research on the technology, process, evaluation, and influencing factors of aerogels in construction [26–30]. By the third stage, the research of aerogels in the field of construction developed like never before and had a certain system and structure. Scholars focused on stable research directions and began to explore them in depth, leading to a certain steady growth rate of aerogel research in the field of construction in recent years. Meanwhile, according to the current research trend of aerogels in construction research, there will still be a great research space for this topic, and research will continue to grow in the next few years.

3.2. Analysis of Article Output Characteristics

3.2.1. Analysis of Countries

The global scientific communication and academic cooperation in various countries in this field can be explored through an econometric analysis of the posting countries. Country was selected as the analysis object in CiteSpace, the time slicing was set to "1995–2023", the years per slice was 3, the threshold was top 50, and the final country analysis map was obtained (95 network nodes and 74 lines with a density of 0.0166).

The nodes and circles in China are the largest, and much larger than those in other countries, indicating that aerogels are more intensively studied in China (Figure 2). China is the country with the most publications in this field (294), which is much larger than other countries, which indicates that China pays significant attention to aerogels in the field of construction and has accumulated more experience in the research of aerogels (Table 1). The aerogel technology in China is in the leading position in the construction field, which creates favorable conditions for the promotion and application of aerogel materials around the world. In addition, the centrality of China is 0.44, indicating that China has more frequent transnational cooperation and often exchanges and cooperates with other countries. In addition, the United States ranked 2nd in frequency (frequency of 121) and Italy ranked 3rd (frequency of 38). France has a high per-center degree of 0.5, which indicates that France is developing faster within the field and has a close relationship with other countries. Moreover, French researchers tend to cooperate with other countries to research aerogels in the construction field. Meanwhile, the half-life of the United States reached 24, which indicates that the research in the United States is slow to decline in value in the future and still has some frontier and value.

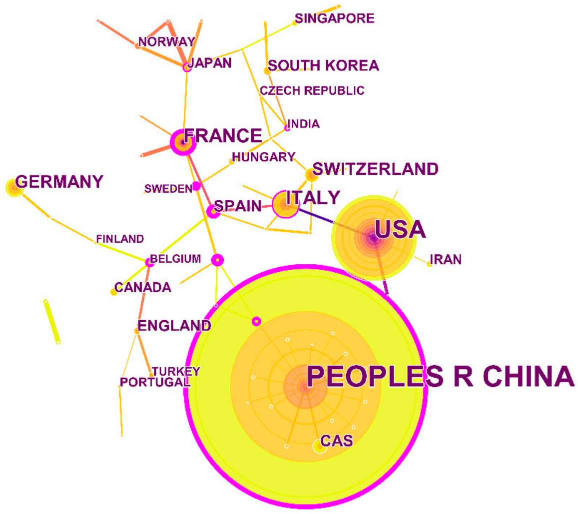

Figure 2. Visualization of country network analysis.

Table 1. Top 10 countries based on rank.

Rank	Frequency	Centrality	Country	Year	Half-Life Period
1	294	0.44	CHINA	2011	10
2	121	0.09	USA	1995	24
3	38	0.19	ITALY	1998	20
4	36	0.5	FRANCE	1998	18
5	28	0	GERMANY	2010	9
6	24	0.07	SWITZERLAND	2011	7
7	18	0	CAS	2016	4
8	17	0.48	SPAIN	2008	9
9	15	0.09	ENGLAND	2011	6
10	15	0.06	SOUTH KOREA	2016	3

Note: The location of the country and the richness of the research are represented by centrality. The greater the centrality, the greater the richness, and the location matters.

3.2.2. Analysis of Institutions

The institution was used as an object of analysis in CiteSpace, and an institution analysis profile, with 161 network nodes and 140 connected lines with a density of 0.0109, was obtained (Figure 3). The nodes are relatively dense, with a total of 140 connected lines. This shows that communication and cooperation among institutions are relatively frequent and the geographical differences in cooperation are significant. In summary, cross-institutional research on construction aerogels needs to continue to maintain transnational cooperation, and academic exchanges in the field of aerogels still need to be further strengthened. The University of Science and Technology of China, Chinese Academy of Sciences, University of Debrecen, University of Perugia, and Guangzhou University have larger nodal circles and are highly productive institutions for aerogel research in the field of construction.

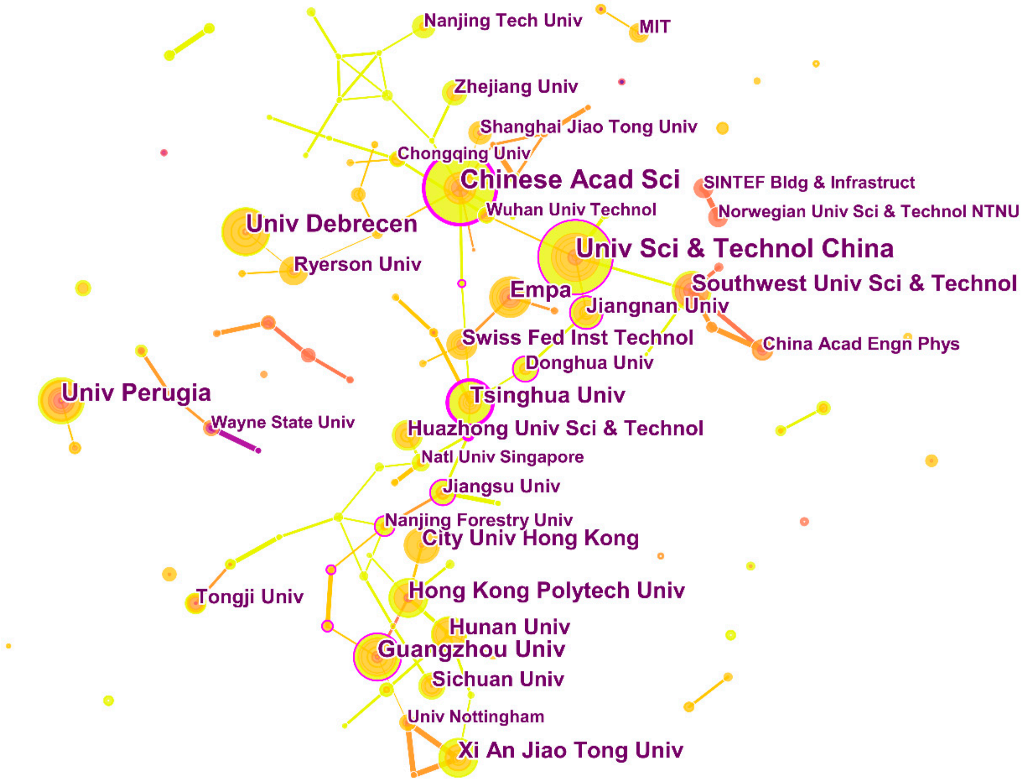

Figure 3. Visualization of institution network analysis.

Within the field of architecture, aerogels was included in the top 10 issuing institutions (Table 2). Among them, the University of Science and Technology of China (USTC) has the highest number of publications, with 25, and Vrije Univ Brussel institution is in the top (centrality of 0.11), which indicates that USTC not only publishes more frequently, but also cooperates with other institutions more frequently. The late publication of USTC indicates that it has made a large contribution to aerogel research in the field of construction in recent years. The Chinese Academy of Sciences and the University of Debrecen ranked second (frequency of 24) and third (frequency of 18), and the publication time of both was in 2016 and 2017. These two structural universities are late in focusing on aerogel research in architecture, but they are currently ranked high in terms of the number of papers, indicating that these two institutions have conducted more in-depth research on aerogel in architecture in recent years. By the centrality ranking, Tsinghua University and the University of Chinese Academy of Sciences are 0.27 and 0.2, ranking in the top two, indicating that they are the most central institutions in this field, and the cooperation with other institutions has led to more research output.

Table 2. Top 10 institutions in terms of number of articles issued and centrality.

Rank	Publications	Year	Institution	Centrality	Year	Institution
1	25	2016	Univ Sci & Technol China	0.27	2019	Tsinghua Univ
2	24	2016	Chinese Acad Sci	0.2	2016	Chinese Acad Sci
3	18	2017	Univ Debrecen	0.18	2017	Nanjing Forestry Univ
4	18	2012	Univ Perugia	0.16	2018	Jiangsu Univ
5	17	2015	Guangzhou Univ	0.13	2015	Guangzhou Univ
6	15	2018	Xi An Jiao Tong Univ	0.12	2020	Donghua Univ
7	15	2012	Empa	0.11	2016	Univ Sci & Technol China
8	14	2015	Hong Kong Polytech Univ	0.11	2019	Jiangnan Univ
9	14	2013	Southwest Univ Sci & Technol	0.09	2015	Hong Kong Polytech Univ
10	14	2019	Tsinghua Univ	0.05	2019	Hunan Univ

3.2.3. Analysis of authors

The metrological analysis of authors can identify the core authors of aerogel research in the field of architecture and reflect the academic communication and cooperation among researchers in this field. Author was used as the analysis object in CiteSpace, the time slicing was set to "1995–2023", years per slice was 3, the threshold was top = 50, and the analysis map with 326 network nodes, 559 connections, and a density of 0.0106 was constructed (Figure 4).

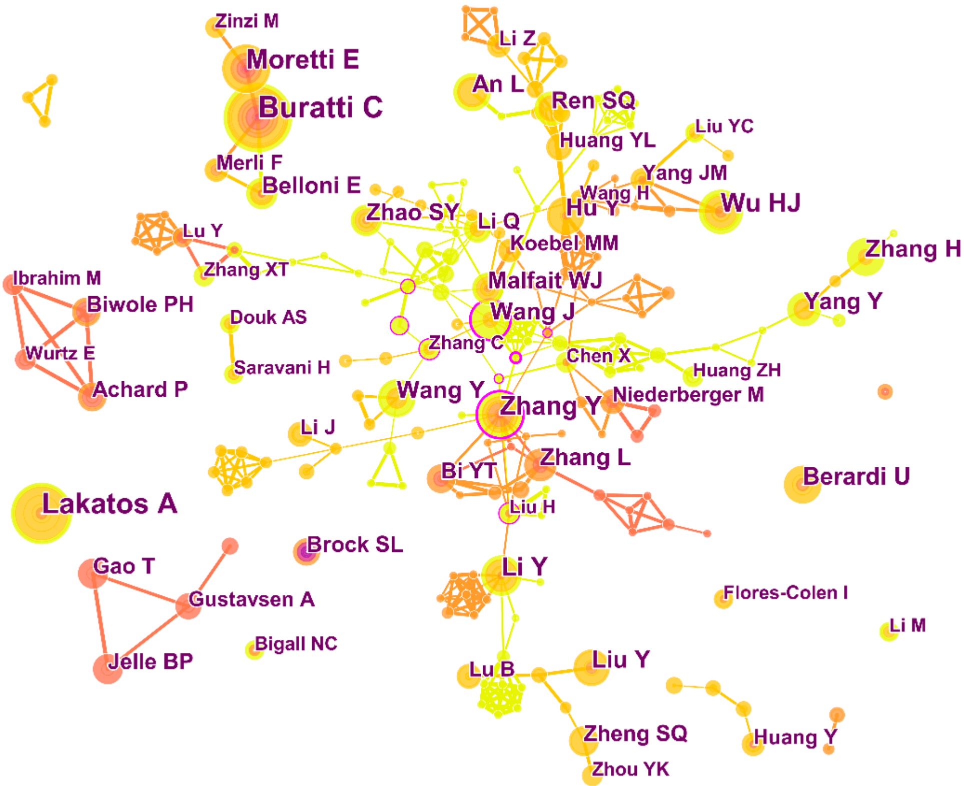

Figure 4. Visualization of author network analysis.

There are more nodes of authors, and most of them have collaborative relationships, indicating that authors in this field cooperate more closely. According to Price's law, when the number of core authors in a field reaches more than 50% of the total number of articles published in that field, a more stable core group of authors can be considered to have formed in that field [31]. In the same field, half of the papers are authored by a group of highly productive authors, and this set of authors is approximately equal to the square root of the total number of all authors. From 1995 to 2023, the total number of authors engaged in research on aerogels in construction was 3887, whose square root is 62.3, indicating that the number of core authors in our field is 63. Statistically, the number of publications of these core authors is 407, accounting for about 47.2% of the total number of papers, indicating that aerogels are gradually forming a stable core group of authors in this field. The top three most prolific authors are Buratti C (17 publications), Lakatos A (15 publications), and Moretti E (12 publications). Zhang Y has a centrality of 0.34, the highest centrality in the field (Table 3), which indicates that Zhang Y is the most central author in the field and the author who has made the highest contribution promoting the research in this field.

Table 3. Author ranking with higher number and centrality of publication.

Rank	Publications	Year	Author	Centrality	Year	Author
1	17	2012	Buratti C	0.34	2015	Zhang Y
2	15	2017	Lakatos A	0.21	2019	Wang J
3	12	2012	Moretti E	0.19	2017	Liu H
4	11	2015	Zhang Y	0.16	2019	Zhang C
5	11	2017	Wu HJ	0.11	2022	Liu CY
6	10	2016	Li Y	0.09	2016	Li Y
7	9	2018	Hu Y	0.09	2022	Wang YJ
8	9	2017	Liu Y	0.08	2018	Hu Y
9	9	2019	Zhang H	0.08	2019	Li Q
10	9	2019	An L	0.08	2022	Feng J

3.2.4. Analysis of Subject and Journals

From the bibliometric point of view, the disciplinary association analysis mainly establishes the connection between the citer and cited literature by the discipline of the cited literature. We selected the JCR journal map in the overlay map option of CiteSpace and overlayed the information service data onto the original citation-citation literature discipline base map using addoverlay to obtain a two-map overlay map of discipline distribution (Figure 5). In this figure, the main distribution of which journals aerogels in construction research in Web of Science database is cited in can be identified, revealing the knowledge flow dynamics of foreign journals in this field.

The left side of Figure 5a refers to the main journal distribution clusters of aerogels in construction in Web of Science database, and the right side refers to the main cited journal clusters. It can be obtained that the research of aerogels in the field of construction is mainly concentrated in the journal groups of physics, chemistry, materials science, ecology, and science. The citations of aerogels in foreign architecture are concentrated in journal clusters of environmental, biological, chemical, physical, mathematical, computer, and systematics journal clusters. Among them, physical, chemical, and material sciences have two out-citation paths in the citation field, and this category is the most dominant citation category. Meanwhile, when the category environmental, toxicology and nutrition was used as a source journals, the corresponding category physics, chemistry and materials had the highest number of citations with the highest z-value (7.128).

The journals with more than 20 publications in this field are ENERGY AND BUILDINGS, CONSTRUCTION AND BUILDING MATERIALS, and CHEMICAL ENGINEERING JOURNAL, whose frequencies are 64, 27, and 20, respectively (Table 4). The number of publications in the table accounts for 26.45% of the total number of article tables, which to some extent indicates the lack of concentration of articles published in this field. The average impact factor of the top 10 journals is 10.07, and some journals even exceed 15, such as the impact factors of CHEMICAL ENGINEERING JOURNAL (16.744) and ACS NANO (18.027). This shows that the research of aerogels in the field of construction is concerned by highbrow press. In general, the research fields of high yielding journals are mainly concentrated in architecture, chemistry, and materials.

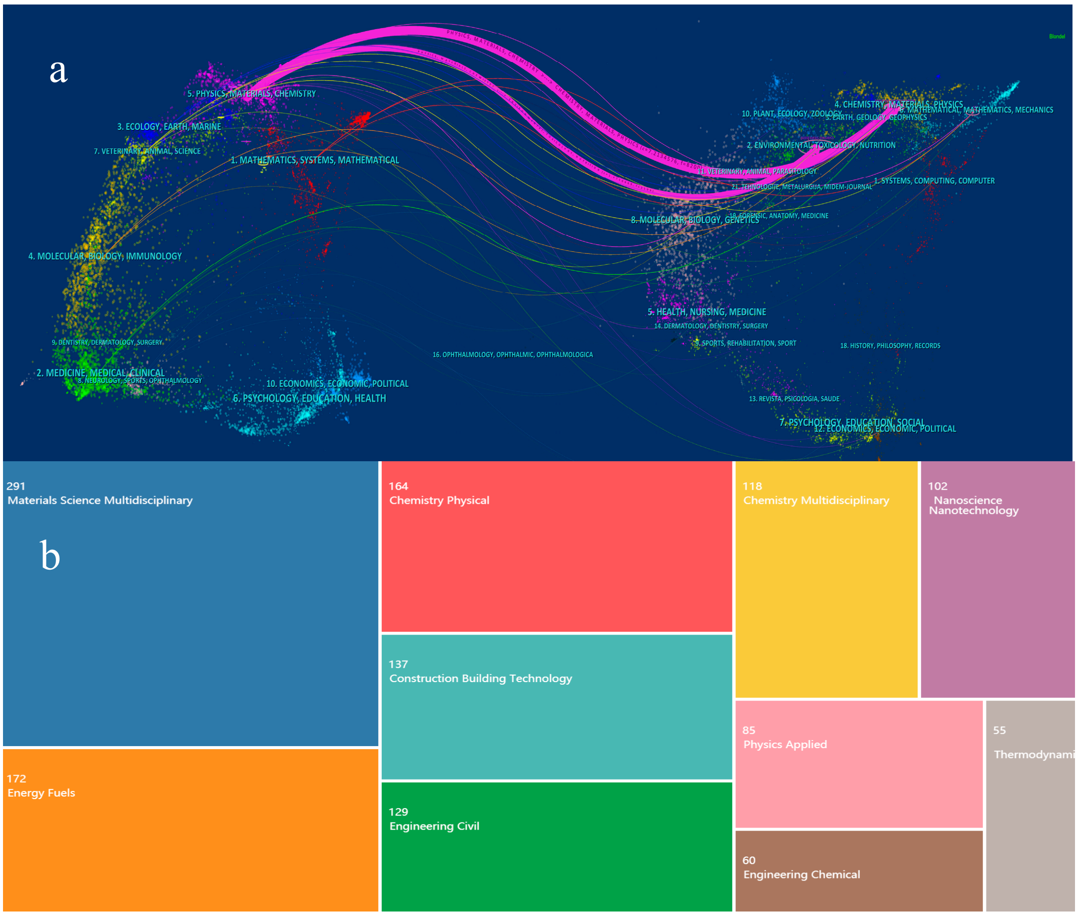

Figure 5. (**a**) Discipline double stacking, (**b**) discipline categories based on Web of Science top 10. Note: The left half takes the distribution of cited literature disciplines as the current research status of aerogels in construction; the right half takes the discipline to which the cited literature belongs as the research base of aerogels in construction. The wave curve connects the relationship between the research status and the research base, and the inner numbers of the oval indicate the number of publications in each discipline.

Table 4. Top 10 journals of publication.

Rank	Journal	Publication	Percentage	IF
1	ENERGY AND BUILDINGS	64	7.42%	7.201
2	CONSTRUCTION AND BUILDING MATERIALS	27	3.13%	8.194
3	CHEMICAL ENGINEERING JOURNAL	20	2.32%	16.744
4	ACS APPLIED MATERIALS INTERFACES	19	2.20%	10.383
5	JOURNAL OF MATERIALS CHEMISTRY A	18	2.09%	14.511
6	ACS NANO	17	1.97%	18.027
7	JOURNAL OF NON-CRYSTALLINE SOLIDS	17	1.97%	4.458
8	JOURNAL OF SOL GEL SCIENCE AND TECHNOLOGY	16	1.86%	2.606
9	APPLIED ENERGY	15	1.74%	11.446
10	JOURNAL OF BUILDING ENGINEERING	15	1.74%	7.144

3.3. Analysis of Research Hotspots

3.3.1. Analysis of KEYWORD NETWORK

The keyword co-occurrence graph includes 163 nodes, 196 connection lines, and a density of 0.0148 (Figure 6). The color change shows the characterization of the studied keyword nodes at different time periods; a color closer to purple indicates the nearest hot topic to the current research. The size of the keyword node label represents the frequency of the keyword, while the large node circles and tags characterize the high frequency keywords. The co-occurrence frequency and year between the keywords were characterized by the thickness of the lines and the line color, respectively.

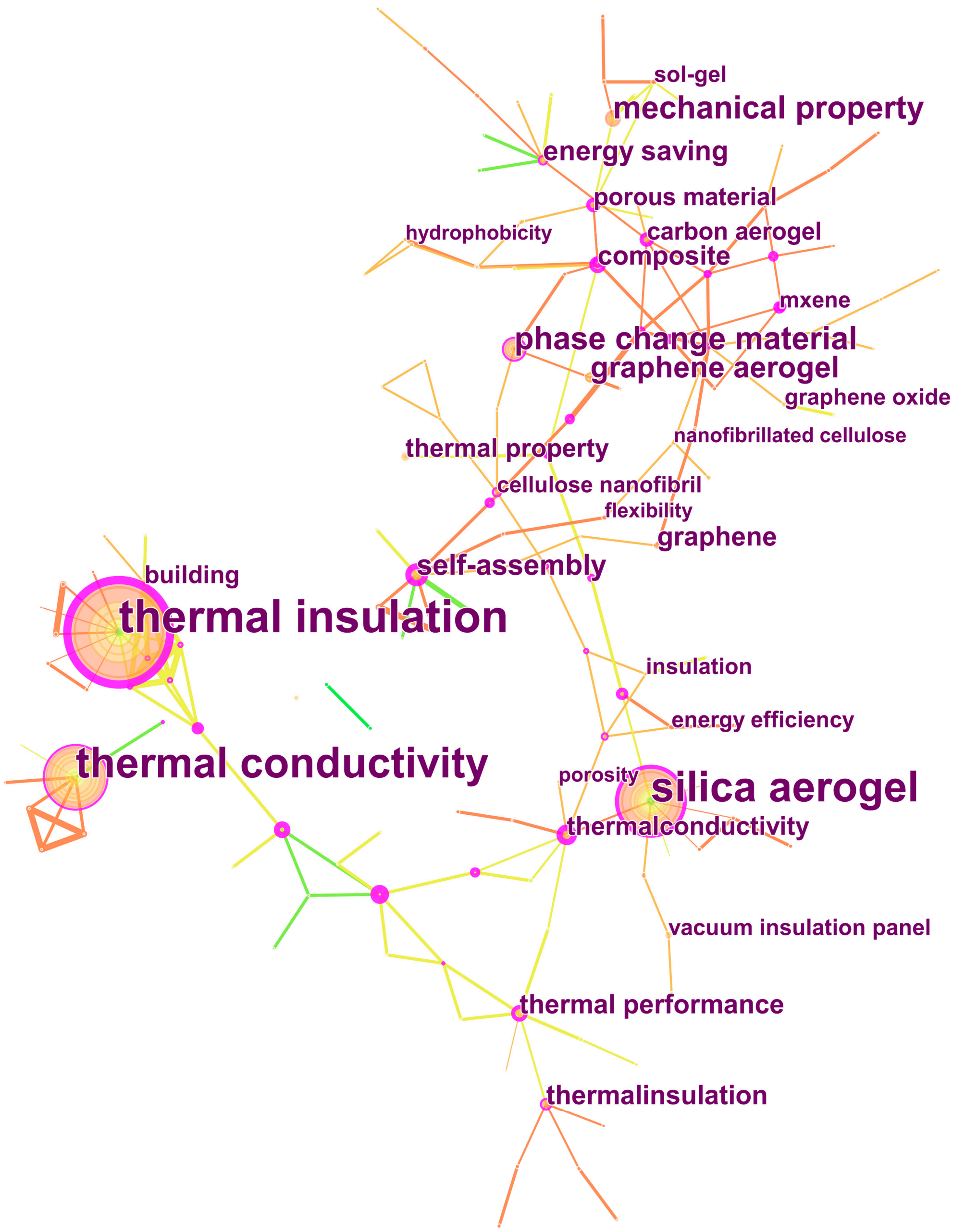

Figure 6. Visualization of keyword network analysis.

The nodes and tags for thermal insulation, silica aerogel, and thermal conductivity are large, indicating that they are current hot topics in the field of aerogels in construction (Figure 6). The key words in the outer circle, insulation and silica aerogel, are closest to purple, indicating that these research topics are the current frontiers of aerogels in the construction field. Thermal insulation was the most frequent term (84), silica aerogel ranked 2nd (62), and thermal conductivity ranked 3rd (60), all three of which are important topics of interest (Table 5). In addition, thermal insulation has the highest centrality (0.64) and is closely related to other keywords. Self-assembly has the second highest centrality (0.57) and thermal conductivity has the third highest centrality (0.54). Silica aerogel has the highest half-life (12), indicating that it still has much room for development.

Table 5. Keywords with high search frequency.

Rank	Frequency	Centrality	Country	Half-Life Period
1	84	0.64	thermal insulation	7
2	62	0.38	silica aerogel	12
3	60	0.54	thermal conductivity	7
4	19	0.1	phase change material	2
5	19	0.05	mechanical property	5
6	16	0.02	graphene aerogel	4
7	15	0.57	self-assembly	5
8	13	0.16	energy saving	4
9	12	0.22	thermal performance	4
10	12	0.12	thermal insulation	4
11	11	0.38	composite	2
12	11	0.03	graphene	4
13	10	0.12	thermal conductivity	2
14	10	0	thermal property	3
15	9	0.38	porous material	4
16	9	0.05	building	3
17	9	0.2	carbon aerogel	2
18	7	0.02	graphene oxide	3
19	7	0.02	vacuum insulation panel	2
20	7	0.05	sol-gel	2

3.3.2. Analysis of Keyword Clustering

CiteSpace software was used for clustering analysis of keywords, the cluster option was selected, and the pathfinder algorithm was used to crop the concatenation to ensure the classification rationality of clusters [20,32,33]. The research themes in the field of aerogels in the last 30 years were revealed by Figure 7, and a total of 11 clusters were obtained (Table 6). Q and S values are indicators that describe the network structure and clustering, where Q represents the module value and S represents the average profile value. Q > 0.3 indicates a clear delineation structure and S > 0.7 indicates valid clustering results [34,35]. The clustering results of this study were reasonable (Q = 0.8269, S = 0.828) and could be followed up for analysis.

Table 6. Cluster information.

#	Size	Silhouette	Year	Representative Terms
0	21	0.938	2016	thermal performance; historic building; internal insulation
1	20	0.948	2019	thermal management; SiO_2 aerogel; emi shielding;
2	18	0.853	2019	chitosan; sensing; electromagnetic interference shielding;
3	16	0.807	2018	self-assembly; nanofibrillated cellulose; flexibility;
4	16	0.95	2018	reaction kinetics; heat transfer; building insulation materials;
5	15	0.978	2018	thermal insulation; envelope; annual energy consumption;
6	14	0.928	2019	graphene aerogel; thermal energy storage; cellulose aerogel;
7	14	0.98	2016	radiative cooling; advanced glazing; aerogel;
8	8	0.991	2017	energy saving; energy performance; aerogel glazing system;
9	7	0.946	2018	thermal conductivity; graphite polystyrene; specific heat capacity;
10	6	0.985	2021	geopolymer; microstructure; composite aerogel

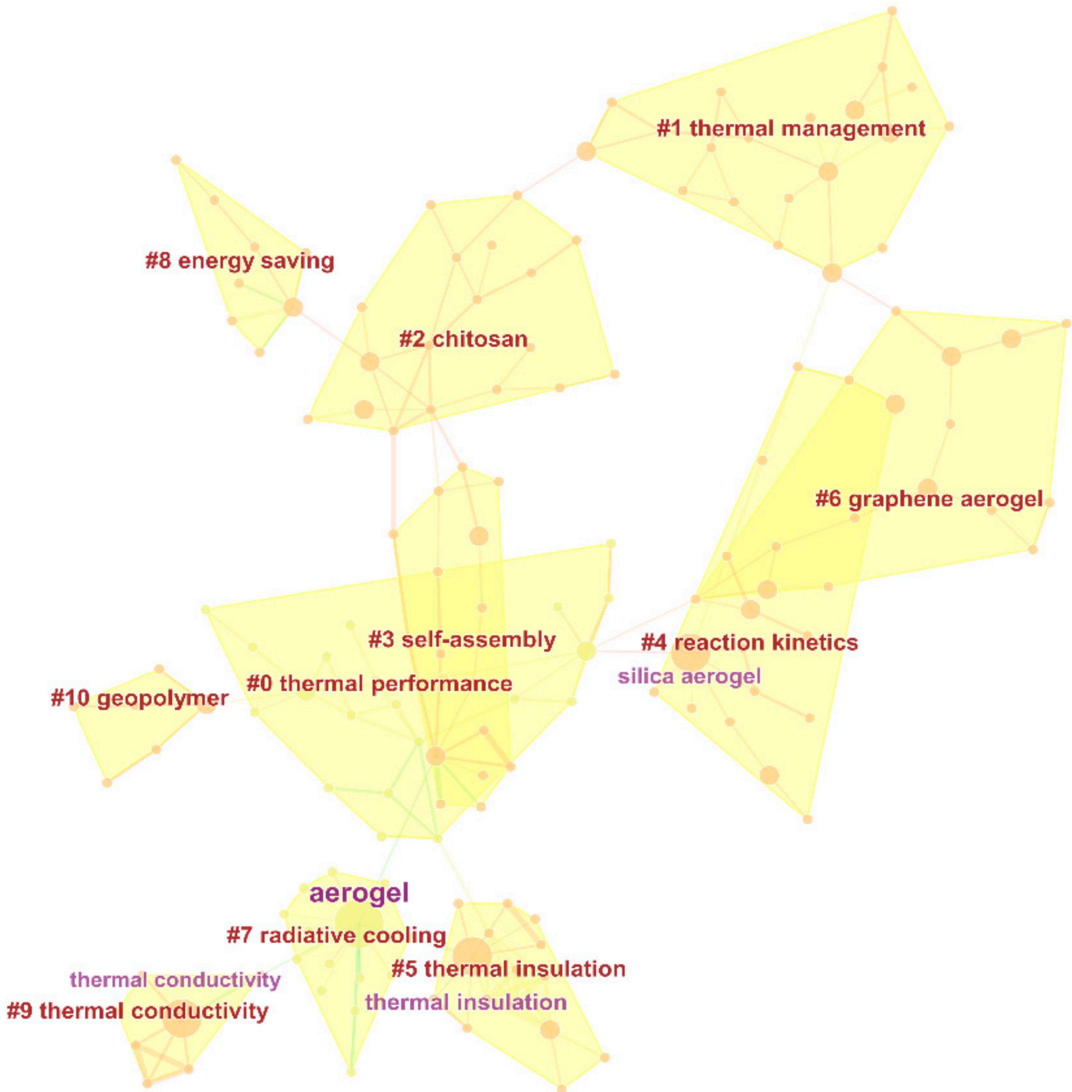

Figure 7. Co-occurrence clusters of the keyword.

A total of 14 research themes were generated from this study as #0 thermal performance, #1 thermal management, #2 chitosan, #3 self-assembly, #4 reaction kinetics, #5 thermal insulation, #6 graphene aerogel, #7 radiative cooling, #8 energy saving, #9 thermal conductivity, and #10 geopolymer (Table 6). The mean profile values were all greater than 0.7, indicating that the effect of each cluster is consistent with the study. The average year for group 10 is 2021, indicating to some extent that cluster 10 research topics are relatively close to cutting-edge research. However, the average year for cluster 0 and cluster 7 is 2016, indicating that these two groups are more traditionally studied. In a word, the theme of aerogels is the development and application of thermal insulation properties in different fields.

3.4. Analysis of Research Trends

3.4.1. Research Frontiers

The bursts detection algorithm of the CiteSpace software was employed to obtain the keyword hotspot evolution mapping of aerogels in the field of construction domain processing, i.e., keyword emergence (Table 7).

Table 7. Top 25 keywords with the strongest citation bursts (1995–2023). The time period of the citation burst is indicated by the red line.

Keywords	Strength	Begin	End	1995–2023
aerogel	10.5147	1995	2014	
silica aerogel	1.3316	2013	2014	
concrete	1.2686	2014	2015	
gold nanoparticle	1.2686	2014	2015	
sol-gel processes	1.2686	2014	2015	
durability	1.2686	2014	2015	
aerogel glazing	1.2686	2014	2015	
window	2.2113	2014	2016	
historical building	1.2686	2014	2015	
nanocomposite	1.7491	2015	2016	
u-value	1.6713	2015	2018	
ambient pressure drying	1.3431	2016	2018	
aerogel blanket	1.3431	2016	2018	
historic building	2.2447	2016	2018	
thermal comfort	1.3431	2016	2018	
building insulation	1.508	2017	2018	
thermal property	1.278	2018	2021	
porosity	1.4412	2018	2019	
thermal performance	1.6651	2019	2021	
aerogel glazing system	1.6401	2019	2020	
vacuum insulation panel	2.1903	2019	2021	
cellulose nanofiber	1.5603	2019	2021	
building envelope	1.5603	2019	2021	
flame retardance	1.399	2019	2020	
cellulose aerogel	1.687	2020	2021	

A total of 25 top keywords of aerogels in construction domain emergent intensity were generated in this study. The duration of the research hotspots was 1995–2021. However, the earliest hotspot studies from 1995–2013 are search terms, so 2013–2021 was used as the hotspot duration in this study. Silica aerogel, concrete, gold nanoparticle, sol–gel processes, durability, and aerogel glazing were the hot spots of research during the period from 2013–2015 [36–39], with emergent intensities of 1.3316, 1.2686, 1.2686, 1.2686, 1.2686, 1.2686, and 1.2686, respectively. The intensity of the emergence of each hotspot is relatively close and the duration is 2 years, indicating that the research on these hot topics was relatively even at this stage. Windows, historical building, nanocomposite, u-value, ambient pressure drying, aerogel blanket, historical building, thermal comfort, building insulation were the main research focuses during 2016–2018 [40–45], with emergent intensities of 2.2113, 1.2686, 1.7491, 1.6713, 1.3431, 1.3431, 2.2447, 1.3431, and 1.508, respectively. The highest emergent intensity of historic building and window indicates that these two themes were focused on during this phase [42,46,47].

The major themes during 2019–2021 include thermal property, porosity, thermal performance, aerogel glazing system, vacuum insulation panel, cellulose nanofiber, building envelope, flame retardance, and cellulose aerogel, with emergent intensities of 1.278, 1.4412, 1.6651, 1.6401, 2.1903, 1.5603, 1.5603, 1.399, and 1.687, respectively. During this period, vacuum insulation panel had the highest emergent intensity and continued to until 2021, indicating that vacuum insulation panel is the current frontier topic for aerogels in construction [48].

3.4.2. Research Trends

The keyword time series evolution of aerogels in buildings is shown in Figure 8, where years per slice is 2, the threshold is g-index = 5, the number of nodes is 119, the number of connections is 259, and the density is 0.0369.

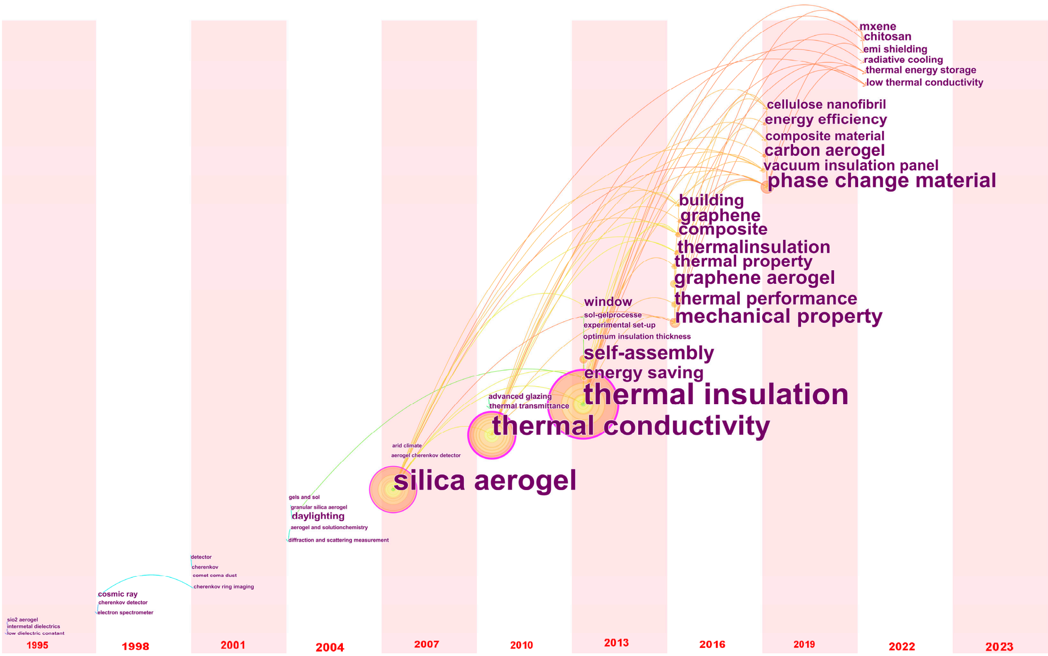

Figure 8. Time zone view of keywords.

In terms of distribution, the keywords of aerogels for construction are concentrated in 1995–2023, which indicates that the research on aerogels for construction was more adequate and abundant in this time period. Specifically, in the period of 1992–2010, the research of aerogels in the field of construction was in the early stage of research and received less attention and lower frequency of key words, and research themes such as low dielectric constant, SiO_2 aerogel, intermetal dielectrics, and drift chamber appeared in the field of construction research [49–51], indicating that the structure and basic properties of the material are the basic research of aerogel. There are various types of aerogels, such as silica, carbon, metal, and cellulose systems. At present, the most common is SiO_2 aerogel, with density of 0.003–0.15 g/cm^3, more than 90% nanoscale porosity, and size less than 50 nm, which shows superior properties in thermal acoustics and optics. Thermodynamically, SiO_2 aerogel at room temperature has efficient thermal insulation and very low thermal conductivity (0.02~0.03 W/(m K)); its unique pore grid structure can play an effective role in suppressing the heat conduction of solid and gas, and this porous network structure can be well maintained at high temperature of 950 °C. It can be seen that SiO_2 aerogel is currently recognized as the optimal lightweight thermal insulation or super insulation material, which has broad research prospects and application development value in building energy saving and emission reduction.

During 2011–2017, aerogel research in the construction field began to develop gradually, with the emergence of thermal conductivity, thermal insulation self-assembly, energy saving, mechanical property, graphene aerogel, thermal performance, thermal insulation, composite, graphene, and other research topics [52–56]. Moreover, the amount of literature in this field was steadily increasing, and scholars began deepening and expanding the applications of aerogels in different building fields during this period. During 2018–2023, with the advent of the nano-age, various new materials have been continuously applied in the construction industry, and research on aerogels in construction has emerged with phase change material, carbon aerogel, vacuum insulation panel, graphene oxide, energy efficiency, cellulose nanofibril, composite material, cellulose, and other research topics in the field of construction [29,30,57–61].

4. Conclusions

In the past 10 years, the number of papers on aerogels in the field of construction has increased significantly, and the academic influence has gradually improved. As far as the development trend is concerned, the field involves multidisciplinary cross-fertilization, and the journals also tend to be diversified and multidisciplinary, with a greater potential for development. China is the country with the highest number of publications in this field (294), and the output and impact of the results are outstanding internationally, contributing greatly to the development of this research field. Univ Sci & Technol China is the most published institution and Buratti C is the most published author, though there is still a need to further improve international cooperation among institutions and scholars. The research of aerogels in the field of construction involves multidisciplinary cross-fertilization. ENERGY AND BUILDINGS is the journal with the largest number of articles and a high impact in this field. Research on the thermal insulation properties of silica aerogel is a hot research topic in the field of aerogels in construction. Research on graphene, cellulose modification, nanotechnology, self-assembly, flame retardance, and aerogel glazing systems of existing materials is becoming the frontier. In addition, future research should focus on elasticity that does not change with temperature, highly stable aerogels with high fatigue resistance, and the development of low-cost aerogel preparation technologies, such as inexpensive raw materials and normal temperature and pressure preparation. With the development of the field of building energy saving, the performance of aerogel insulation materials is gradually subjected to a great test, and the development of more systematic basic research on aerogel materials, as well as engineering application technology, is the top priority to promote energy saving and carbon reduction in the building field.

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References

1. Wan, C.; Jiao, Y.; Wei, S.; Zhang, L.; Wu, Y.; Li, J. Functional nanocomposites from sustainable regenerated cellulose aerogels: A review. *Chem. Eng. J.* **2019**, *359*, 459–475. [CrossRef]
2. Sun, H.; Xu, Z.; Gao, C. Multifunctional, ultra-flyweight, synergistically assembled carbon aerogels. *Adv. Mater.* **2013**, *25*, 2554–2560. [CrossRef] [PubMed]
3. Yan, Q.; Meng, Z.; Luo, J.; Wu, Z. Experimental study on improving the properties of rock wool and glass wool by silica aerogel. *Energy Build.* **2021**, *247*, 111146. [CrossRef]
4. Zhang, J.; Chen, B.; Yu, F. Preparation of EPS-Based Thermal Insulation Mortar with Improved Thermal and Mechanical Properties. *J. Mater. Civ. Eng.* **2019**, *31*, 04019183. [CrossRef]
5. Smirnov, Y.M.; Baidzhanov, D.O.; Imanov, E.K.; Zhurunova, M.A. Energetics Metrics for Foam-Glass Concrete Building Products. *Glas. Ceram.* **2020**, *77*, 267–271. [CrossRef]
6. Zhang, W.; Zhang, J.; Ding, Y.; He, Q.; Lu, K.; Chen, H. Pyrolysis kinetics and reaction mechanism of expandable polystyrene by multiple kinetics methods. *J. Clean. Prod.* **2021**, *285*, 125042. [CrossRef]
7. Amaral, C.; Vicente, R.; Ferreira, V.; Silva, T. Polyurethane foams with microencapsulated phase change material: Comparative analysis of thermal conductivity characterization approaches. *Energy Build.* **2017**, *153*, 392–402. [CrossRef]
8. Huang, Y.; Gong, L.; Pan, Y.; Li, C.; Zhou, T.; Cheng, X. Facile construction of the aerogel/geopolymer composite with ultra-low thermal conductivity and high mechanical performance. *RSC Adv.* **2018**, *8*, 2350–2356. [CrossRef]
9. He, J.; Li, X.; Su, D.; Ji, H.; Wang, X. Ultra-low thermal conductivity and high strength of aerogels/fibrous ceramic composites. *J. Eur. Ceram. Soc.* **2016**, *36*, 1487–1493. [CrossRef]
10. Cuce, E.; Cuce, P.M.; Wood, C.J.; Riffat, S.B. Toward aerogel based thermal superinsulation in buildings: A comprehensive review. *Renew. Sustain. Energy Rev.* **2014**, *34*, 273–299. [CrossRef]

11. Baetens, R.; Jelle, B.P.; Gustavsen, A. Aerogel insulation for building applications: A state-of-the-art review. *Energy Build.* **2011**, *43*, 761–769. [CrossRef]
12. Sheng, Z.; Liu, Z.; Hou, Y.; Jiang, H.; Li, Y.; Li, G.; Zhang, X. The Rising Aerogel Fibers: Status, Challenges, and Opportunities. *Adv. Sci.* **2023**, *10*, e2205762. [CrossRef] [PubMed]
13. Li, M.; Han, N.; Zhang, X.; Wang, S.; Jiang, M.; Bokhari, A.; Zhang, W.; Race, M.; Shen, Z.; Chen, R.; et al. Perovskite oxide for emerging photo(electro)catalysis in energy and environment. *Environ. Res.* **2022**, *205*, 112544. [CrossRef]
14. Chen, C. Searching for intellectual turning points: Progressive knowledge domain visualization. *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 5303–5310. [CrossRef]
15. Pierre, M.S.; Grawe, P.; Bergstrom, J.; Neuhaus, C. 20 years after To Err Is Human: A bibliometric analysis of 'the IOM report's' impact on research on patient safety. *Saf. Sci.* **2022**, *147*, 105593. [CrossRef]
16. Li, Y.; Feng, T.-T.; Liu, L.-L.; Zhang, M.-X. How do the electricity market and carbon market interact and achieve integrated development?—A bibliometric-based review. *Energy* **2023**, *265*, 126308. [CrossRef]
17. Shi, C.; Qu, L.; Zhang, Q.; Li, X. A systematic review on comprehensive sloping farmland utilization based on a perspective of scientometrics analysis. *Agric. Water Manag.* **2021**, *244*, 106564. [CrossRef]
18. Li, M.; Wang, Y.; Xue, H.; Wu, L.; Wang, Y.; Wang, C.; Gao, X.; Li, Z.; Zhang, X.; Hasan, M.; et al. Scientometric analysis and scientific trends on microplastics research. *Chemosphere* **2022**, *304*, 135337. [CrossRef]
19. Jiang, H.; Wang, M.; Shu, X. Scientometric analysis of post-occupancy evaluation research: Development, frontiers and main themes. *Energy Build.* **2022**, *271*, 112307. [CrossRef]
20. Cai, M.; An, C.; Guy, C. A scientometric analysis and review of biogenic volatile organic compound emissions: Research hotspots, new frontiers, and environmental implications. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111317. [CrossRef]
21. Wang, X.; Zhang, Y.; Zhang, J.; Fu, C.; Zhang, X. Progress in urban metabolism research and hotspot analysis based on CiteSpace analysis. *J. Clean. Prod.* **2021**, *281*, 125224. [CrossRef]
22. Liu, H.; Hong, R.; Xiang, C.; Lv, C.; Li, H. Visualization and analysis of mapping knowledge domains for spontaneous combustion studies. *Fuel* **2020**, *262*, 116598. [CrossRef]
23. Li, M.; Wang, Y.; Shen, Z.; Chi, M.; Lv, C.; Li, C.; Bai, L.; Thabet, H.K.; El-Bahy, S.M.; Ibrahim, M.M.; et al. Investigation on the evolution of hydrothermal biochar. *Chemosphere* **2022**, *307*, 135774. [CrossRef] [PubMed]
24. Kamali, M.; Jahaninafard, D.; Mostafaie, A.; Davarazar, M.; Gomes, A.P.D.; Tarelho, L.A.; Dewil, R.; Aminabhavi, T.M. Scientometric analysis and scientific trends on biochar application as soil amendment. *Chem. Eng. J.* **2020**, *395*, 125128. [CrossRef]
25. Wei, J.; Li, J.; Zhao, J.; Wang, X. Hot Topics and Trends in Zero-Energy Building Research—A Bibliometrical Analysis Based on CiteSpace. *Buildings* **2023**, *13*, 479. [CrossRef]
26. Berardi, U. Aerogel-enhanced systems for building energy retrofits: Insights from a case study. *Energy Build.* **2018**, *159*, 370–381. [CrossRef]
27. Cuce, E.; Cuce, P.M.; Wood, C.J.; Riffat, S.B. Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings. *Energy Build.* **2014**, *77*, 28–39. [CrossRef]
28. Liu, K.S.; Zheng, X.F.; Hsieh, C.H.; Lee, S.K. The Application of Silica-Based Aerogel Board on the Fire Resistance and Thermal Insulation Performance Enhancement of Existing External Wall System Retrofit. *Energies* **2021**, *14*, 4518. [CrossRef]
29. Zhou, Y. Artificial neural network-based smart aerogel glazing in low-energy buildings: A state-of-the-art review. *iScience* **2021**, *24*, 103420. [CrossRef]
30. Ahankari, S.; Paliwal, P.; Subhedar, A.; Kargarzadeh, H. Recent Developments in Nanocellulose-Based Aerogels in Thermal Applications: A Review. *ACS Nano* **2021**, *15*, 3849–3874. [CrossRef]
31. Chen, C. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *J. Am. Soc. Inf. Sci. Technol.* **2006**, *57*, 359–377. [CrossRef]
32. Li, Q.; Long, R.; Chen, H.; Chen, F.; Wang, J. Visualized analysis of global green buildings: Development, barriers and future directions. *J. Clean. Prod.* **2020**, *245*, 118775. [CrossRef]
33. Carve, M.; Allinson, G.; Nugegoda, D.; Shimeta, J. Trends in environmental and toxicity research on organic ultraviolet filters: A scientometric review. *Sci. Total. Environ.* **2021**, *773*, 145628. [CrossRef]
34. Chen, C. Science Mapping: A Systematic Review of the Literature. *J. Data Inf. Sci.* **2017**, *2*, 1–40. [CrossRef]
35. Li, M.; Jia, X.; Wang, J.; Wang, Y.; Chen, Y.; Wu, J.; Wang, Y.; Shen, M.; Xue, H. Quantitative Analysis of the Research Development Status and Trends of Tannery Wastewater Treatment Technology. *Catalysts* **2022**, *12*, 1317. [CrossRef]
36. Tan, H.; Ma, X.; Fu, M. Preparation of continuous alumina gel fibres by aqueous sol-gel process. *Bull. Mater. Sci.* **2013**, *36*, 153–156. [CrossRef]
37. Gao, T.; Jelle, B.P.; Gustavsen, A.; Jacobsen, S. Aerogel-incorporated concrete: An experimental study. *Constr. Build. Mater.* **2014**, *52*, 130–136. [CrossRef]
38. Heiligtag, F.J.; Cheng, W.; de Mendonca, V.R.; Süess, M.J.; Hametner, K.; Günther, D.; Ribeiro, C.; Niederberger, M. Self-Assembly of Metal and Metal Oxide Nanoparticles and Nanowires into a Macroscopic Ternary Aerogel Monolith with Tailored Photocatalytic Properties. *Chem. Mater.* **2014**, *26*, 5576–5584. [CrossRef]
39. Gao, T.; Jelle, B.P.; Ihara, T.; Gustavsen, A. Insulating glazing units with silica aerogel granules: The impact of particle size. *Appl. Energy* **2014**, *128*, 27–34. [CrossRef]

40. Zhou, X.; Carmeliet, J.; Derome, D. Influence of envelope properties on interior insulation solutions for masonry walls. *Build. Environ.* **2018**, *135*, 246–256. [CrossRef]
41. Dong, L.-Y.; Zhu, Y.-J. A New Kind of Fireproof, Flexible, Inorganic, Nanocomposite Paper and Its Application to the Protection Layer in Flame-Retardant Fiber-Optic Cables. *Chem.—A Eur. J.* **2017**, *23*, 4597–4604. [CrossRef] [PubMed]
42. Lolli, N.; Andresen, I. Aerogel vs. argon insulation in windows: A greenhouse gas emissions analysis. *Build. Environ.* **2016**, *101*, 64–76. [CrossRef]
43. Lv, Y.; Wu, H.; Liu, Y.; Huang, Y.; Xu, T.; Zhou, X.; Huang, R. Quantitative research on the influence of particle size and filling thickness on aerogel glazing performance. *Energy Build.* **2018**, *174*, 190–198. [CrossRef]
44. Martinez, R.G.; Goiti, E.; Reichenauer, G.; Zhao, S.; Koebel, M.; Barrio, A. Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale. *Energy Build.* **2016**, *128*, 111–118. [CrossRef]
45. Wakili, K.G.; Remhof, A. Reaction of aerogel containing ceramic fibre insulation to fire exposure. *Fire Mater.* **2017**, *41*, 29–39. [CrossRef]
46. Lucchi, E.; Becherini, F.; Di Tuccio, M.C.; Troi, A.; Frick, J.; Roberti, F.; Hermann, C.; Fairnington, I.; Mezzasalma, G.; Pockelé, L.; et al. Thermal performance evaluation and comfort assessment of advanced aerogel as blown-in insulation for historic buildings. *Build. Environ.* **2017**, *122*, 258–268. [CrossRef]
47. Stahl, T.; Wakili, K.G.; Hartmeier, S.; Franov, E.; Niederberger, W.; Zimmermann, M. Temperature and moisture evolution beneath an aerogel based rendering applied to a historic building. *J. Build. Eng.* **2017**, *12*, 140–146. [CrossRef]
48. Buratti, C.; Belloni, E.; Merli, F.; Zinzi, M. Aerogel glazing systems for building applications: A review. *Energy Build.* **2021**, *231*, 110587. [CrossRef]
49. Leventis, N.; Sotiriou-Leventis, C.; Zhang, G.; Rawashdeh, A.-M.M. Nanoengineering Strong Silica Aerogels. *Nano Lett.* **2002**, *2*, 957–960. [CrossRef]
50. Jo, M.H.; Hong, J.K.; Park, H.H.; Kim, J.J.; Hyun, S.H.; Choi, S.Y. Application of SiO_2 aerogel film with low dielectric constant to intermetal dielectrics. *Thin Solid Film* **1997**, *308*, 490–494. [CrossRef]
51. De Lange, D.J.J.; Steijger, J.J.M.; De Vries, H.; Anghinolfi, M.; Taiuti, M.; Higinbotham, D.W.; Norum, B.E.; Konstantinov, E. A large acceptance spectrometer for the internal target facility at NIKHEF. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **1998**, *406*, 182–194. [CrossRef]
52. Buratti, C.; Moretti, E.; Zinzi, M. Cinzia Buratti, High Energy-Efficient Windows with Silica Aerogel for Building Refurbishment: Experimental Characterization and Preliminary Simulations in Different Climate Conditions. *Buildings* **2017**, *7*, 8. [CrossRef]
53. Huang, H.; Chen, P.; Zhang, X.; Lu, Y.; Zhan, W. Edge-to-edge assembled graphene oxide aerogels with outstanding mechanical performance and superhigh chemical activity. *Small* **2013**, *9*, 1397–1404. [CrossRef] [PubMed]
54. Scaffaro, R.; Maio, A.; Lopresti, F.; Giallombardo, D.; Botta, L.; Bondì, M.L.; Agnello, S. Synthesis and self-assembly of a PEGylated-graphene aerogel. *Compos. Sci. Technol.* **2016**, *128*, 193–200. [CrossRef]
55. Chen, K.; Neugebauer, A.; Goutierre, T.; Tang, A.; Glicksman, L.; Gibson, L. Mechanical and thermal performance of aerogel-filled sandwich panels for building insulation. *Energy Build.* **2014**, *76*, 336–346. [CrossRef]
56. Liang, Y.; Wu, H.; Huang, G.; Yang, J.; Wang, H. Thermal performance and service life of vacuum insulation panels with aerogel composite cores. *Energy Build.* **2017**, *154*, 606–617. [CrossRef]
57. Shah, S.N.; Mo, K.H.; Yap, S.P.; Radwan, M.K. Towards an energy efficient cement composite incorporating silica aerogel: A state of the art review. *J. Build. Eng.* **2021**, *44*, 103227. [CrossRef]
58. Zheng, D.; Chen, Y.; Liu, Y.; Li, Y.; Zheng, S.; Lu, B. Experimental comparisons on optical and thermal performance between aerogel glazed skylight and double glazed skylight under real climate condition. *Energy Build.* **2020**, *222*, 110028. [CrossRef]
59. Zhai, T.; Li, J.; Wang, X.; Yan, W.; Zhang, C.; Verdolotti, L.; Lavorgna, M.; Xia, H. Carbon-based aerogel in three-dimensional polyurethane scaffold: The effect of in situ unidirectional aerogel growth on piezoresistive properties. *Sens. Actuators A Phys.* **2022**, *333*, 113306. [CrossRef]
60. Cao, Z.; Zhang, C.; Yang, Z.; Qin, Q.; Zhang, Z.; Wang, X.; Shen, J. Preparation of Carbon Aerogel Electrode for Electrosorption of Copper Ions in Aqueous Solution. *Materials* **2019**, *12*, 1864. [CrossRef]
61. Zhao, K.; Ren, C.; Lu, Y.; Zhang, Q.; Wu, Q.; Wang, S.; Dai, C.; Zhang, W.; Huang, J. Cellulose nanofibril/PVA/bamboo activated charcoal aerogel sheet with excellent capture for $PM_{2.5}$ and thermal stability. *Carbohydr. Polym.* **2022**, *291*, 119625. [CrossRef]