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Review

Comparative Analysis of Research Trends and Hotspots of Foreign and Chinese Building Carbon Emissions Based on Bibliometrics

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Abstract: The construction industry has great potential for carbon emission reduction, which strongly impacts the peak of carbon emissions and carbon neutrality. This paper compares foreign and Chinese articles on building carbon emissions from publication objects, journals, subject categories, authors, and institutions. It discusses the differences in research trends and hotspots from keywords, reference co-citation analysis, and historical citation analysis. The results show that the number of publications on building carbon emissions steadily increased. The research on building carbon emissions in foreign articles is earlier and more systematic than that in China, and the output and influence of foreign articles are generally more prominent than those of Chinese articles. However, the production and influence of articles by certain Chinese authors and institutions have been remarkable. The topics of 'CO_2 emission', 'life-cycle assessment', 'environmental impact', 'greenhouse gas emission', and 'renewable energy' are essential subjects for foreign and Chinese articles in the research field of building carbon emissions and the development trend is similar. The thematic direction of Chinese articles is more divergent and lacks well-developed themes that greatly influence other research themes. Finally, based on the research results, this study puts forward the potential future research direction of building carbon emissions. The results of this study will provide a current and systematic overview of this field, which will be helpful for future researchers to promote the development of research on building carbon emissions.

Keywords: comparative analysis; building carbon emissions; China; foreign; bibliometric

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1. Introduction

Sustainable development is one of humanity's most significant challenges in the 21st century. With the deepening influence of greenhouse gases and the increase in global energy consumption, the problem between the environment and energy consumption has aroused widespread concern and research. Environmental protection and energy-saving measures have become highly concerning global issues. In 2020, in response to international calls to reduce greenhouse gas emissions, the Chinese government proposed reaching the peak of carbon dioxide emissions by 2030 and striving to achieve carbon neutrality by 2060. The United States has pledged to return to the Paris Agreement in 2021, which also proposes new policies to reduce carbon emissions. At the same time, the European Union passed the European Union Act, which sets a goal of carbon neutrality by 2050.

With the gradual urbanization and modernization of countries worldwide, the construction industry has developed rapidly, and the energy demand and carbon emissions of building construction and use have shown a rising trend. The building sector is highly energy-consuming. In 2020, construction activities consumed 36% of global energy, and building carbon emissions accounted for 39% of global carbon emissions [1]. At the same time, this field has excellent energy conservation and emission reduction potential, and the emission reduction cost is relatively low. It was found that by controlling building scale, selecting construction mode, reducing material supply-side emissions, and other measures, the embodied carbon emissions of China's construction industry can be reduced by approximately 50% in 2060 compared with 2020 [2,3]. Therefore, building emission reduction is considered a critical link to achieving the long-term goal of controlling the global temperature rise within 2 °C, and this field is attracting more and more attention [4,5].

Currently, the literature on building carbon footprints published by Chinese and foreign scholars is abundant and complicated. It includes (1) Accounting for building carbon emissions, including the accounting of carbon emissions from building monomers at the micro level and the accounting of carbon emissions from buildings at the macro level. Various carbon emission accounting systems have been developed for single buildings at home and in foreign locations [6–8]. At the micro level, the latest research focuses on the carbon emission accounting of different life-cycle stages of buildings [9], building materials [10], components [11], and structural forms [12]. Macro-level building carbon emissions accounting refers to the global, national, regional, provincial, and municipal scales of carbon emissions in the building sector. Its purpose is mainly to reflect regional building energy consumption and total carbon emissions and provide a basis for the government to formulate energy-saving and emission-reduction policies. Scholars at home and in foreign countries mainly use the input-output method (top-down) [13] and the process analysis method (bottom-up) [14] to measure embodied carbon emissions at the macro level. (2) The analysis model method of carbon emission influencing factors, such as IPAT model [15], the exponential decomposition method [16], the structural decomposition method, and other novel model methods [17,18]. (3) Research on influencing factors in building carbon emissions. The main factors that affect the carbon emission of buildings are energy structure, energy intensity, industry scale [19], population [20], income level [21], residential building area, and urbanization level [22].

The existing articles have various reviews of the research on building carbon emissions. Most review literature determined the research topics from a subjective point of view. These reviews often focus on household carbon emissions [23], the neural network prediction method [24], carbon reduction technology [25], energy conservation policy [26,27], energy performances [28], life cycle assessment [29,30], and the building act [31]. For example, Pomponi et al. systematically reviewed the academic knowledge system of strategies to mitigate embodied carbon in the built environment [32]. Chau et al. and Anand et al. have reviewed the application of LCA in the construction industry and pointed out the corresponding challenges and research directions [33,34]. Ma et al. carried out a systematic review of the implementation of the China Act on the Energy Efficiency of Civil Buildings (2008) [31].

Due to its intuitive image and elimination of subjective screening errors, bibliometric analysis has been widely used in literature reviews in many research fields [35]. Up until now, only a few bibliometric studies have focused on the carbon footprint of buildings. For example, Lu et al. systematically summarized green buildings' strategy, technology, and mode of carbon emission [36]. Luo et al. conducted a comprehensive and objective analysis of the research field of low-carbon buildings in 378 publications [37]. Onat et al. analyzed the research frontier and characteristics of building a carbon footprint from the global supply chain perspective [38]. Sun et al. summarized the construction sector's carbon peak and neutrality through bibliometric analysis [39]. We can find that the bibliometric analysis of the construction industry's carbon footprint has also appeared.

In summary, the existing research still lacks the following: (1) Most of the existing carbon footprint bibliometry studies are based on the relevant literature on the global carbon footprint and do not focus on a specific industry to grasp the knowledge structure and development trend of its carbon emissions. (2) The literature review on building carbon emissions identifies the research topic mainly from a subjective point of view and tends to focus on methods and techniques. The review on building carbon emissions needs more quantitative analysis from an objective perspective. (3) Most previous studies used the Chinese CNKI and the international WoS databases to compare Chinese and foreign studies. Therefore, it is necessary to distinguish Chinese and foreign literature on building carbon emissions from a unified global literature perspective by using bibliometric analysis.

The aims of this study are as follows: (1) This paper identifies individuals and institutions conducting in-depth research on building carbon emissions in Chinese and foreign articles. It identifies subject categories related to the field. (2) This paper identifies the knowledge base and research focus of building carbon emissions in Chinese and foreign articles through various methods to ensure the reliability of the research results. (3) This paper compares the development process of topics that aroused scholars' broad interest in Chinese and foreign articles.

This study is organized as follows: Section 2 introduces the data sources and the methods adopted in the follow-up research. Section 3 is a comparative analysis of the research situation on building carbon emissions, followed by keyword analysis and citation analysis. Section 4 discusses the content that needs further research. Section 5 summarizes the main conclusions. The research flowchart is shown in Figure 1.

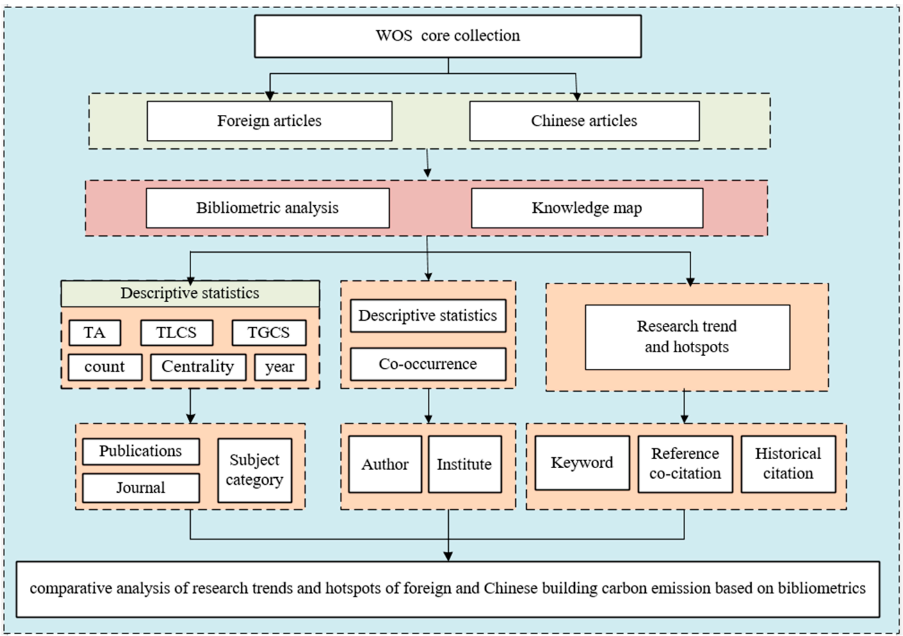

Figure 1. The research flow chart.

2. Data and Methods

2.1. Data Collection

The literature data on building carbon emissions research was gathered from the Web of Science Core Collection database. This paper compares a construction carbon emission research analysis between China and non-China. The retrieval formula TS = (('building industry' or 'building sector' or 'construction industry' or 'construction sector') and ('Carbon emission *' or 'Carbon dioxide emission *' or 'CO_2 emission *' or 'CO_{2e} *' or 'carbon emit *' or 'carbon dioxide emit *' or 'CO_2 emit' or 'carbon footprint *' or 'carbon dioxide footprint *' or 'CO_2 footprint *' or 'carbon budget' or 'carbon market' or 'greenhouse gas' or 'greenhouse gases' or 'greenhouse gas emission*' or 'greenhouse-gas emission *' or 'ghg emission*')), document types = (Article or Review), language = (English), PY = (2008–2022). An asterisk represents singular or plural. In this procedure, 6547 publications were obtained. In this study, the articles with author affiliations with "Not Peoples R China" are foreign articles, and the author affiliations with "Peoples R China" are Chinese articles. When there are multiple affiliations, the distinction between articles is based on the location of the first institution of the first author. Finally, 4993 foreign and 1768 Chinese articles were obtained from the WoSCC database on 31 December 2022. Two datasets of 4993 foreign and 1768 Chinese publications on construction carbon emissions were obtained. Table 1 summarizes the search results.

Table 1. Retrieval strategies to acquire data.

Database	WoS Core Collection	
Retrieval mode	TS = ((‘building industry’ or ‘building sector’ or ‘construction industry’ or ‘construction sector’) and (‘Carbon emission *’ or ‘Carbon dioxide emission *’ or ‘CO_2 emission *’ or ‘CO_{2e} *’ or ‘carbon emit *’ or ‘carbon dioxide emit *’ or ‘CO_2 emit’ or ‘carbon footprint *’ or ‘carbon dioxide footprint *’ or ‘CO_2 footprint *’ or ‘carbon budget’ or ‘carbon market’ or ‘greenhouse gas’ or ‘greenhouse gases’ or ‘greenhouse gas emission *’ or ‘greenhouse-gas emission *’ or ‘ghg emission *’))	
	Foreign articles	Chinese articles
Publication type	Article; Review	Article; Review
Country/Region	Not Peoples R. China	Peoples R. China
language	English	English
Year	2008–2022	2008–2022
Retrieval time	31 December 2022	31 December 2022
Retrieval results	4993	1768

Note: TS is the subject words, including the title, abstract, and keywords; * is singular or plural.

2.2. Research Tools

Common bibliometric software tools include VOSviewer, CiteSpace, HistCite, SciMat, BibExcel, and RefViz. VOSviewer is developed by Van Eck and Waltman [40]. Through the relationship construction and visualization analysis of literature knowledge units, VOSviewer can realize the drawing of a scientific knowledge graph and show the relationship between structure, evolution, and cooperation in the knowledge domain. Regarding co-occurrence map making, VOSviewer can select the number and type of nodes according to the requirements, and the graph adjustment ability is strong. CiteSpace is a knowledge map visualization tool developed by Chen Chaomei using Java that can analyze the structure of various networks of scientific publications and support networks with mixed node types and link types [35]. The drawing effect of CiteSpace is slightly worse than that of VOSviewer, and the adjustment process is relatively complicated. HistCite, developed by Eugene Garfield, can perform citation frequency statistics for source journals, authors, institutions, and individual papers in the WOS database [41]. Bibliometrix is a powerful literature analysis tool that relies on the R language [42]. It is an object-oriented and relatively easy programming tool that can help scholars to analyze the relevant literature in the field conveniently and visually.

To compare these foreign and Chinese publications, this paper used three bibliometric software tools, VOSviewer 1.6.16, HistCite Pro 2.1, and CiteSpace 5.7.R2, to develop the research results. HistCite is used to conduct journal, author, and institution analyses. VOSviewer is employed to perform the co-citation network analysis of cited references. CiteSpace is used to conduct subject category analysis and high-frequency keyword analysis. The Biblioshiny open-source R-package is engaged to conduct keyword cluster analysis and historical citation network analysis.

3. Results

3.1. Comparative Analysis of the Overview

3.1.1. Publications Analysis

The number and growth of publications in a field are critical indicators to measure the development of a domain. As presented in Figure 2, the number of foreign building carbon emissions articles increased by 21.91% from 44 in 2008 to 1008 in 2022. Chinese articles increased by 406%, from 1 in 2008 to 407 in 2022. The annual growth rates for foreign and Chinese articles are 2.53% and 27.44%, respectively. The numbers of foreign and Chinese publications have shown a steady upward trend. As can be seen from Figure 2, the average citations per year (AC) of foreign publications and Chinese publications reached the highest values in 2009 (96.52) and 2010 (88.69), respectively, and then began to decline in a fluctuating trend. The AC of foreign articles was lower than that of Chinese articles after 2018. Figure 3 shows that the total local citation score (TLCS) and total global citation score (TGCS) of foreign and Chinese articles began to fluctuate and decline after experiencing fluctuating rises for some time. The TLCS of Chinese articles reached its highest value of 624 in 2017 and has been declined since 2019. In 2017, 2019, and 2022, the TLCS of Chinese articles was higher than that of foreign articles. The TGCS of foreign publications was higher than that of Chinese publications during the study period, whereas the gap has gradually decreased since 2018.

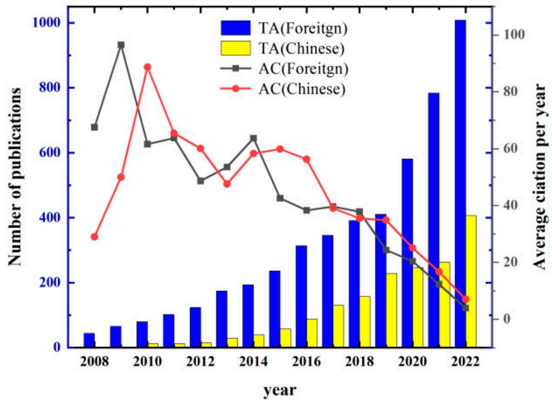

Figure 2. Annual distribution of TA and AC of foreign and Chinese articles.

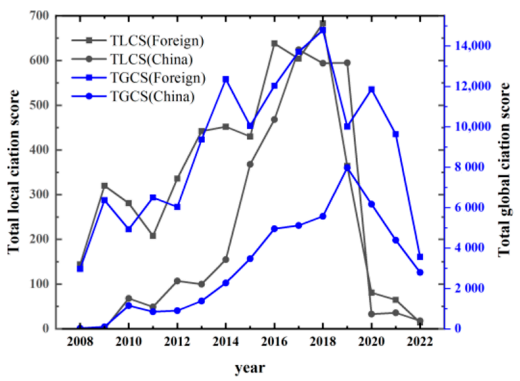

Figure 3. Annual distribution of TLCS and TGCS of foreign and Chinese articles.

The results of articles on building carbon emissions research indicate that foreign and Chinese articles presented a rising trend during 2008–2022, showing that the research on building carbon emissions has attracted increasing attention from foreign and Chinese scholars. Chinese research on building carbon emissions started later than foreign studies. The production and impact of foreign research on construction carbon emissions are generally higher than those of Chinese articles. However, the gap in global impact has gradually narrowed since 2018 due to the reduction of citation accumulation time.

3.1.2. Subject Category Analysis

Which disciplines are involved in carbon emissions in the construction industry? The 4993 foreign articles cover 331 subject categories, and the 1768 Chinese articles cover 182 subject categories. Table 2 shows the top 20 subject categories of foreign and Chinese articles.

Table 2. Top 20 subject categories of foreign and Chinese articles.

Foreign Articles				Chinese Articles			
Subject Categories	**Count**	**Centrality**	**Year**	**Subject Categories**	**Count**	**Centrality**	**Year**
Engineering	1822	0.07	2008	Environmental Science and Ecology	973	0.08	2009
Environmental Science and Ecology	1729	0.02	2008	Engineering	673	0.14	2010
Energy and Fuels	1506	0.05	2008	Environmental Science	628	0.16	2008
Science and Technology-other Topics	1270	0.02	2008	Science and Technology-other Topics	580	0.25	2009
Green and Sustainable Science and Technology	1178	0.01	2008	Green and Sustainable Science and Technology	542	0.05	2009
Environmental Science	842	0.18	2008	Engineering, Environmental	418	0.06	2009
Construction and Building Technology	759	0.03	2008	Energy and Fuels	422	0.21	2009
Engineering, Environmental	734	0.01	2008	Construction and Building Technology	144	0.06	2010
Engineering, Civil	564	0.08	2008	Business and Economics	119	0.15	2008
Materials Science	465	0.14	2008	Engineering Chemical	99	0.04	2010
Business and Economics	282	0.07	2008	Engineering, Civil	98	0.01	2011
Chemistry	229	0.06	2008	Thermodynamics	78	0.02	2010
Engineering Chemical	216	0.02	2008	Economics	73	0.21	2008
Economics	208	0.10	2008	Materials Science	59	0.23	2010
Thermodynamics	204	0.04	2008	Meteorology and Atmosphere Science	42	0.04	2015
Physics	131	0.02	2008	Materials Science, Multidisciplinary	35	0.07	2010
Chemistry, Physical	107	0.03	2008	Chemistry	34	0.31	2010
Environmental Studies	91	0.10	2008	Geology	32	0.13	2011
Chemistry, Multidisciplinary	82	0.05	2011	Geosciences, Multidisciplinary	19	0.01	2015
Mechanics	79	0.02	2008	Computer science	19	0.15	2013

The most common categories are ‘Engineering’, ‘Environmental Science and Ecology’, ‘Science and Technology-other Topics’, and ‘Green and Sustainable Science and Technology’ in foreign and Chinese articles. Studying subject categories in foreign articles are earlier than in Chinese articles. Research in the ‘Environmental Science’, ‘Business and Economics’ and ‘Economics’ fields began earlier than other categories in Chinese articles. In contrast, articles on ‘Engineering’, Construction and Building Technology’, ‘Engineering Chemical’, and ‘Engineering Civil’ were published relatively late, but these disciplines have developed rapidly.

This analysis indicates that building carbon emissions is an interdisciplinary research topic involving energy, environment, climate change, economics, chemistry, green development, and other natural sciences. From the perspective of informatics, this research field has significant interdisciplinary attributes.

3.1.3. Journal Analysis

On the one hand, the statistical analysis of journals on construction carbon emissions can help researchers lock down the core journals in this field to find relevant literature and understand the research status quickly. On the other hand, it can determine whether this field has cross-field characteristics.

Table A1 lists the top 10 journals with the most published foreign and Chinese articles. Seven top journals of foreign and Chinese articles (*Journal of Cleaner Production*, *Sustainability*, *Energy Policy*, *Applied Energy*, *Energy*, *Energy and Buildings*, *Energies*) overlap, indicating the most important sources of construction carbon emissions research in foreign and Chinese articles. *The Journal of Cleaner Production* is the most influential, regardless of foreign or Chinese articles. The journal *Renewable and Sustainable Energy Reviews*, one of the earliest sources in this research field, is also very influential.

As seen from Table A1, the number of articles published is related to the difficulty of the journals. For these top journals in the same ranking level, foreign articles performed better than the Chinese articles in H and TGCS, showing that foreign articles have more influential sources than Chinese articles on construction carbon emissions.

3.1.4. Authors Analysis

Table A2 shows that foreign authors Hong Taehoon and Kucukvar Murat rank first in TA (16, 0.32%) and H (13). The authors Pomponi Francesco and Kucukvar Murat rank first and second in TLCS (86, 80), indicating they also strongly influence foreign construction carbon emission research. In terms of Chinese authors, Cai Weiguang, from Chongqing University, ranks first in TA (40, 2.26%), H (28), TLCS (345), and TGCS (2264), indicating that he is the most authoritative scholar in Chinese construction carbon emission research. Cai Weiguang, Lin Boqiang, Ma Minda, Hong Jingke, and Geng Yong significantly influence Chinese research on construction carbon emissions, considering their high rankings in H and TLCS. Interestingly, the quantity and quality of these top Chinese authors in the field of construction carbon emissions performed better than those of top foreign authors.

The link strength of the authors of foreign and Chinese articles is 409 and 922 (Figures A1 and A2), respectively. The collaboration between Chinese authors is higher than that of foreign authors. Cai Weiguang, Ma Minda, Lin Boqiang, Gong Yong, and Hong Jingke have the highest frequency. However, Lin Boqiang has no connection with other authors, indicating they have yet to cooperate. As can be seen from Figures A1 and A2, some authors form an academic community, with the core authors making outstanding contributions. The authors are generally characterized by small concentrations and large dispersion. Therefore, on the whole, the degree of cooperation is not strong, and extensive collaboration has yet to be formed.

3.1.5. Institutions Analysis

The research institutions that contribute to the development of the discipline provide the soil for the growth of the theoretical foundation of the field, and the cooperation between the institutions can better reflect the spatial structure of the academic community than the researchers.

The top 10 productive institutions producing foreign and Chinese articles in the construction carbon emission field are listed in Table A3. The University of Cambridge has the highest scores of TA (51, 1.02%), TLCS (173), and Centrality (0.07), indicating it is the most influential institution in foreign countries. UCL and Swiss Fed Inst Tech rank second and third in TA (46, 0.92%; 44, 0.88%). For Chinese institutions, Tsinghua University obtains the highest TA (151, 8.54%), TGCS (4833), and centrality (0.29). Chongqing University ranks first in Chinese articles in TLCS (756) and TGCS (5662). An interesting finding is that foreign institutions generally outperformed Chinese institutions regarding TLCS and TGCS. However, among the 10 institutions in Table A3, Chinese institutions with the same ranking performed better than foreign institutions in these two aspects, possibly because Chinese articles focused on more specific fields and methods related to building carbon emissions.

The map density of foreign and Chinese articles is 0.0045 and 0.0115, respectively, (Figures A3 and A4). The cooperation between institutions and organizations studying carbon emissions from the building sector could be strong. In addition, the total number of articles published by institutions engaged in collaborative research is higher than that of non-collaborative research, suggesting that academic exchange and collaboration can effectively promote the development of expertise and increase productivity.

3.2. Comparative Analysis of the Conceptual and Intellectual Structure

3.2.1. Keywords Analysis

Keywords are the most direct clues to grasping the literature research topic. They reflect the hot topics that arouse public concern within a certain time [43]. This paper uses the authors' keywords to explore the knowledge structure in the field of construction carbon emissions because of the disputed issues on the keyword plus [44,45]. Some keywords showing the same meaning are combined to obtain accurate results; for example 'carbon emission', 'carbon emissions', 'carbon dioxide emissions', and others are merged as 'CO_2 emissions' [44]. Table A4 lists the top 25 high-frequency keywords. As can be seen from Table A4, circular economy, embodied carbon, green building, mechanical property, and geopolymer are the new hot areas of building carbon emissions research in foreign articles. The Chinese articles' research in 2008–2012 was characterized by using diverse approaches (input-output analysis, scenario analysis) to measure energy efficiency, carbon emission efficiency, greenhouse gas emission efficiency, etc., to assess the influence of energy and environmental systems. In addition, Beijing, province, city, and other keywords indicate that the research on building carbon emissions in Chinese articles has evident regional characteristics. The focus on urbanization, economic growth, investment, and land use indicates that the study of building carbon emissions in Chinese articles exhibits the characteristics of human science. Foreign articles mainly apply the input-output analysis method in terms of analysis methods of driving factors of carbon emission. In contrast, Chinese papers involve more diversified methods, such as scenario analysis, the Stirpat model, and the LMDI (Logarithmic Mean Divisia Index) method. In addition, foreign articles pay more attention to low-carbon building materials than Chinese articles.

Furthermore, to more intuitively understand the development and importance of the research hotspots, this study draws a thematic map of foreign and Chinese articles on construction carbon emissions using the bibliophily R-package tool. The x-axis in the figure is centrality; the y-axis is density. The higher the centrality, the more influential the topic is, and the greater the influence of this topic on other topics [46]. The higher the density, the better the development of the topic. Therefore, the topics in the upper-right quadrant are important and well developed. These themes, known as motor themes, have high centrality and density. The topics in the upper-left quadrant are very specialized, highly developed, and of marginal importance for the research area. These topics have highly developed internal connections but no significant external ties. The topics in the lower-left quadrant represent disappearing or emerging topics. These topics are marginal and weakly developed. The topics in the lower-right quadrant are important but not well developed for research and are known as the basic theme.

Figure 4 presents the thematic map for foreign articles in the construction carbon emission field. The topics in the upper-right quadrant mainly include 'energy efficiency', 'climate change', 'renewable energy', 'energy policy', and 'optimization', which indicates that the themes 'energy efficiency', 'climate change', and 'energy' are well developed and important. The topics in the upper-left quadrant are highly developed but unimportant, mainly including 'compressive strength', 'durability', and 'mechanical property'. Foreign articles have paid much attention to the performance and properties of building materials in recent years. The topics in the lower-left quadrant are disappearing or emerging themes, including 'concrete', 'recycle', and 'machine learning'. The topics in the lower-right quadrant are the core knowledge base of the construction carbon emissions field, mainly consisting of 'life cycle assessment', 'CO_2 emission', 'sustainability', 'greenhouse gas emission', and 'circular economy', and especially the topics that are closely related to building carbon emissions, including 'environmental impacts', 'energy consumption', 'built environment', and 'sustainable construction'.

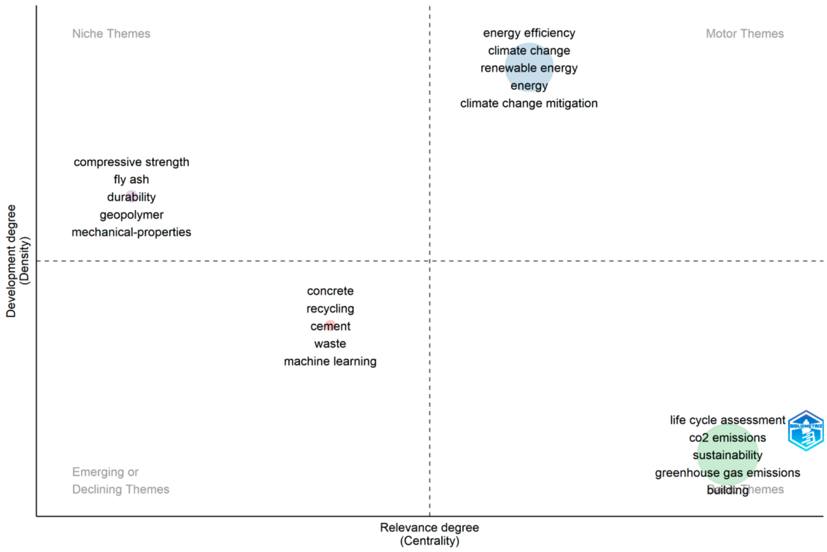

Figure 4. Thematic map for foreign articles.

Figure 5 shows that Chinese articles' mature and important themes in the construction carbon emission field are 'sustainable development', 'renewable energy', 'energy conservation', 'iron and steel industry', and 'emission reduction'. It is indicated that these topics are important and well developed in the field of study. The topics in the upper-left quadrant mainly include 'green building', 'optimization', 'mechanical property', and 'land use'. The topics in the lower-left quadrant are few, including 'compressive strength' and 'carbon tax'. These topics are disappearing or emerging. The topics in the lower-right quadrant mainly include 'CO_2 emission', 'China', 'life-cycle assessment', 'greenhouse gas emission', 'input-output analysis', and 'economic growth', which form the core knowledge base of the Chinese building carbon emissions research.

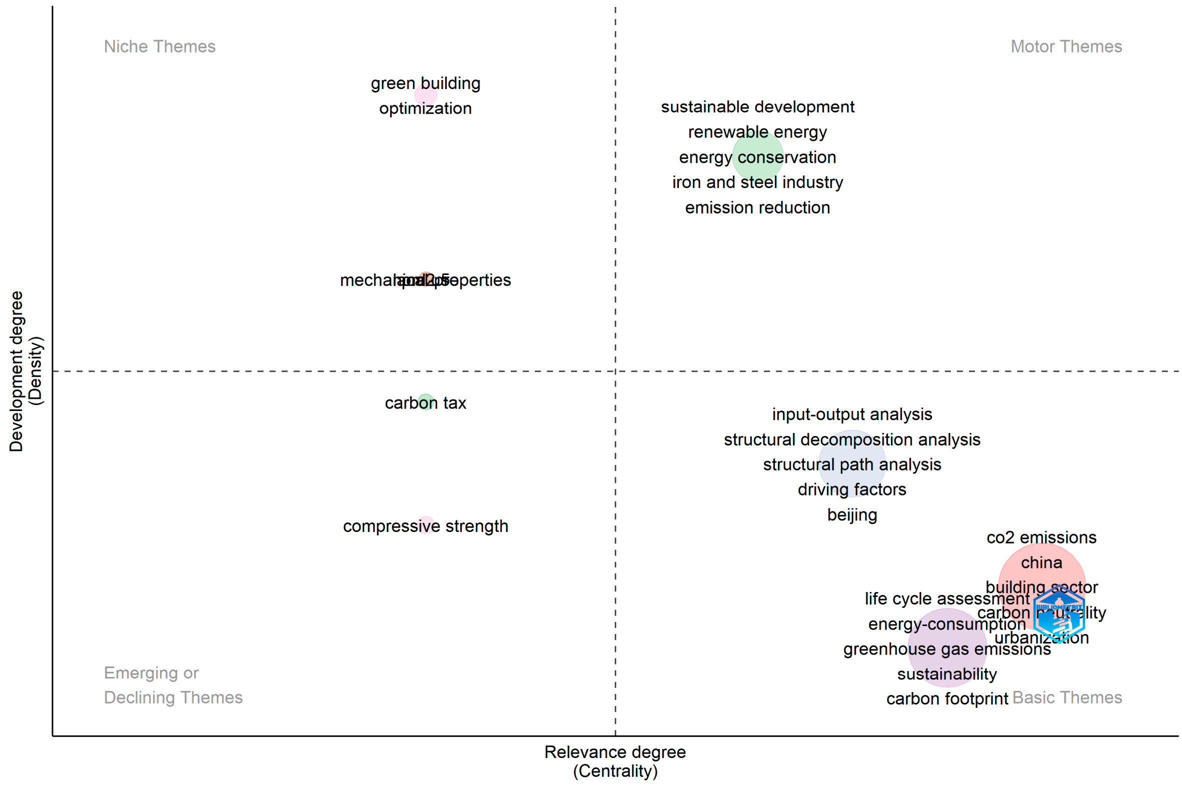

Figure 5. Thematic map for Chinese articles.

Compared to Figures 4 and 5, the topics of 'renewable energy', 'CO_2 emission', 'life cycle assessment', 'greenhouse gas emission', and 'environmental impact' are important subjects for foreign and Chinese articles, and the development trend is similar. 'Climate change' is an important topic in foreign and Chinese articles, but the development trends are markedly different. Specifically, the topic 'climate change' in foreign articles is both important and highly developed, whereas the topic 'climate change' in Chinese publications is important but not well developed. The topics 'carbon tax' and 'compressive strength' are emerging in Chinese articles. The synergy between the construction industry and the steel industry is also a mature and important research topic in Chinese articles. Compared to foreign publications on the construction of carbon emissions that concentrated on a few themes, the thematic direction of Chinese articles is more divergent. It lacks well-developed themes that greatly influence other research themes. The topics of the core knowledge base of Chinese articles are more affluent than those of foreign articles.

3.2.2. Reference Co-Citation Analysis

Co-citation analysis is a reliable and effective way to explore similar conceptual knowledge structures by finding high-impact articles and determining their co-citation relationships [47]. This study applied the VOSViewer software to conduct a co-citation network analysis of cited references in building carbon emissions.

A total of 220,211 cited references were identified from the 4993 foreign articles. We chose 20 as the minimum number of citations, and 257 cited references meet this threshold. These 257 nodes are divided into 5 clusters, including a red cluster (77 items), a green cluster (52 items), a blue cluster (47 items), a yellow cluster (40 items), and a pink cluster (33 items), presented in Figure 6. Items means the number of articles included in this cluster. Unlike the close relationship between the yellow, blue, and pink clusters, the red and green clusters stand more alone.

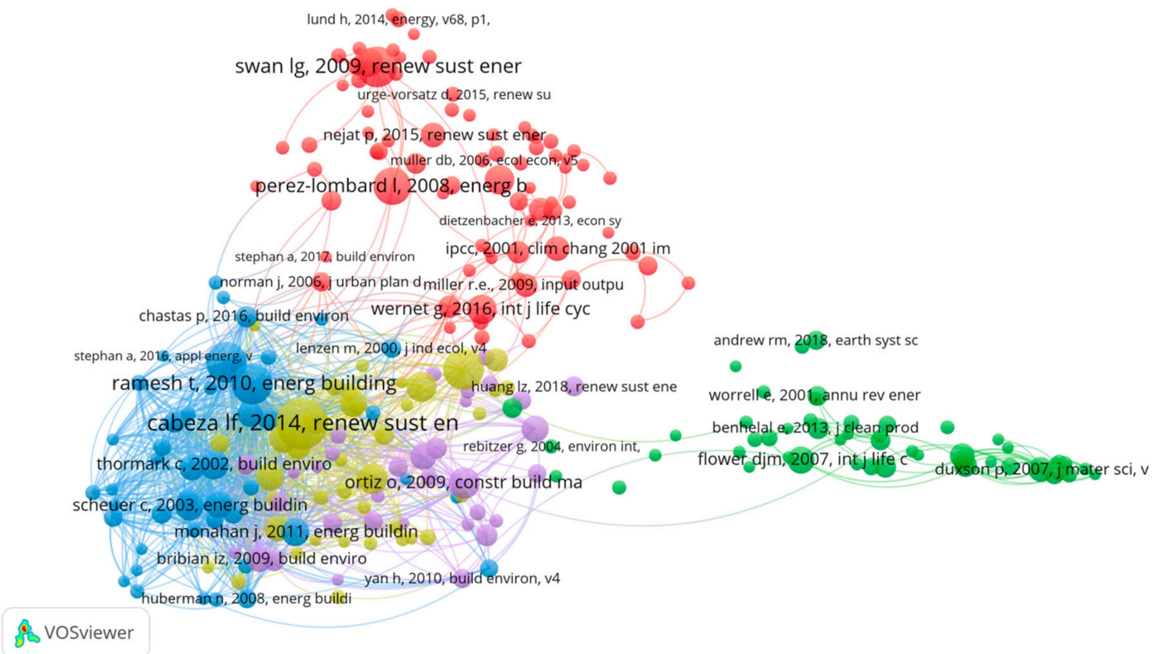

Figure 6. The five clusters map of co-citation references for foreign articles.

The red cluster primarily focuses on input-output analysis [48] and its applications to greenhouse gas emissions [49] and carbon emissions [13]. The yellow and blue clusters mainly concentrate on life-cycle assessment [50–52] and its applications to embodied carbon [53] and greenhouse gas emissions [54]. Some articles especially investigate the case of China [55,56]. Articles in the green cluster discuss the properties of cement, concrete, clay, and other building materials [57,58]. It is worth mentioning that the pink cluster only focused on hybrid life-cycle inventory methods [59,60] and their applications to embodied energy in buildings [61,62].

Moreover, 68,750 cited references were identified from the 1768 Chinese articles. We also chose 20 as the minimum number of citations, and 165 references are shown in the co-citation network. These 165 nodes are divided into 4 clusters, including a red cluster (56 items), a green cluster (32 items), a blue cluster (51 items), and a yellow cluster (24 items), as shown in Figure 7. The four clusters of co-citation networks of cited references for Chinese articles are more alone than those for foreign articles. The red and yellow clusters of Chinese articles mainly concentrate on the driving factors of building carbon emissions in China. The methods used include the LMDI model [63,64]), the IPAT-LMDI model [65], the STIRPAT model [20], decoupling analyses [66], and scenario analysis [67]. The green cluster mainly focuses on input-output analysis [68] and its applications on a global scale [13]. Some publications in the green cluster also concentrate on multi-region input-output analysis and its applications to the energy supply chain [69] and embodied energy [70]. The blue cluster mainly focuses on life-cycle assessment and its applications to energy [52], carbon emissions [71], and building materials [72]. Some articles in the blue cluster focus on the combination of life-cycle assessment and input-output analysis [73,74].

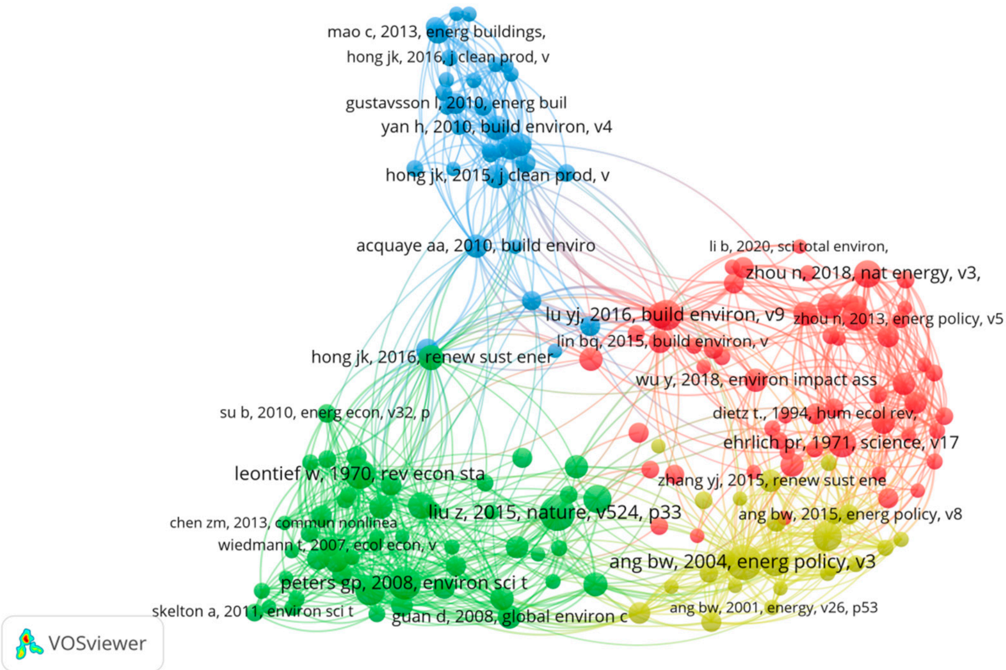

Figure 7. The four clusters map of co-citation references for Chinese articles.

3.2.3. Historical Citation Analysis

To better understand the evolution in the field of construction carbon emissions, this paper conducted a historical citation network analysis to obtain the key literature's relationships and conclude the evolution of research hotpots in the construction carbon emissions field. Figures 8 and 9 show foreign and Chinese publications' historical citation networks.

Figure 8 shows the citation relationships among the top 15 key articles of foreign research. Five of the articles were about greenhouse gas emissions. Upton et al. studied the impact of wood-based building materials on greenhouse gas emissions and energy consumption [75]. By applying input-output and LCA methods, the direct and implied carbon emissions of 238 cases have been studied, including the construction sector in Ireland and the United Kingdom [49,54,76]. Aye et al. found that steel structure prefabricated systems significantly reduce material consumption and carbon emissions compared with traditional concrete construction [77]. Two of the articles were about embodied carbon. De et al. reviewed the existing research methods, tools, and data sets on embodied carbon emissions from buildings [78]. Chastas et al. analyzed the range of embodied emissions in 95 residential buildings and determined the proportional relationship between embodied energy and carbon under different building energy efficiency levels [79]. Using LCA technology, the two papers discuss the differential impacts of the design, construction, use, and demolition of houses on the environment [80,81]. Four of the articles are reviews. Pomponi et al. systematically reviewed the academic knowledge system of strategies to mitigate embodied carbon in the built environment [32]. The application of LCA in the construction industry has been systematically reviewed and pointed out the corresponding challenges and research directions [29,30,34]. Unlike their focus, Giesekam et al. discussed the barriers to using low-carbon building materials in building the economy, technology, practice, and culture [82]. Huang et al. used input-output technology to compare the carbon dioxide emissions of the construction sector in 40 countries around the world [13]. In addition, five papers disconnected from other articles are not presented in Figure 8. The research focuses on environmentally friendly cement and concrete research [58,83], sustainable development of the concrete industry [84], and the carbon dioxide performance of cement [85].

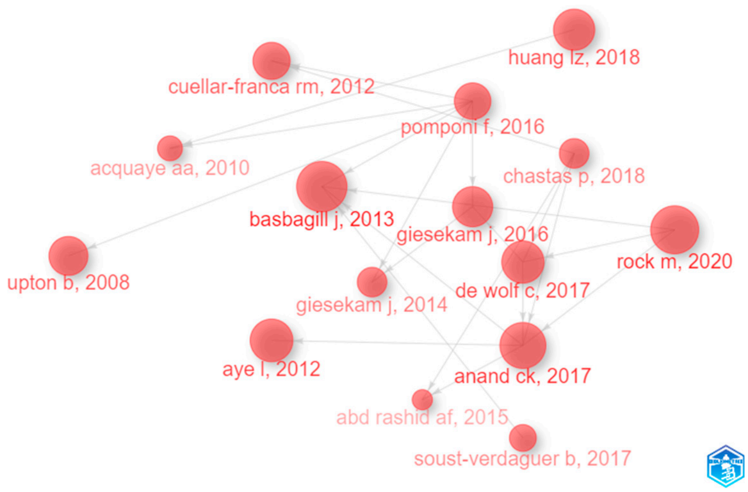

Figure 8. The historical citation network of foreign articles.

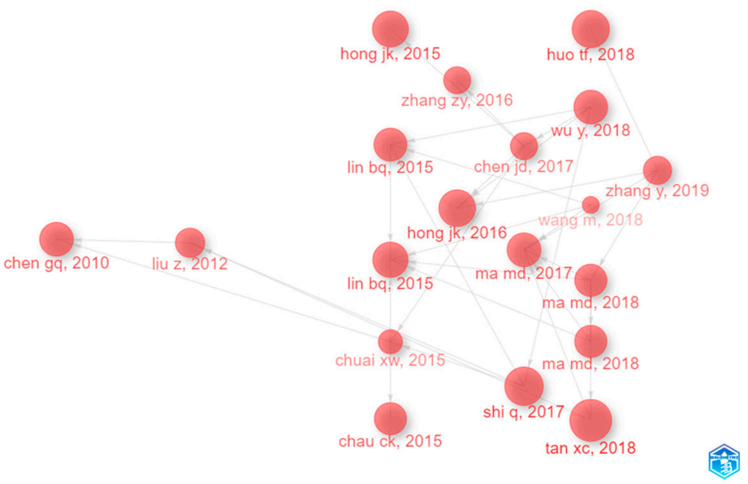

Figure 9. The historical citation network of Chinese articles.

The top 20 locally cited articles of Chinese research are shown in Figure 9. Two articles were about greenhouse gas emissions. Using input-output analysis, Chen et al. studied embodied greenhouse gas emissions in final consumption and international trade [86]. Two articles forecast the carbon reduction potential of the construction sector. Considering low-carbon building policies and emission factors, Tan et al. developed a CAS bottom-up model to evaluate the CO_2 emission reduction potential of the construction industry from 2016 to 2050 [67]. Eight articles analyzed the influencing factors of carbon emissions from commercial and residential buildings using different methods, such as LMDI, structural decomposition analysis, production theory decomposition analysis, and econometric model. For example, Lin et al. studied the driving factors influencing energy-related carbon dioxide emissions from commercial and residential buildings in China using three-dimensional LMDI mode [63]. Six articles studied building carbon emissions from the perspective of direct or indirect energy consumption. Hong et al. studied embodied energy in the consumption, interregional trade, and energy use of different building phases in China's building sector by using a multi-regional input-output model [70,87]. Unlike their focus, Chau et al. systematically reviewed the life cycle carbon emission and energy assessments in building assessments [33]. Ma et al. examined the implementation of the China Act on the Energy Efficiency of Civil Buildings (2008) [31].

Compared to Figures 8 and 9, China's research on construction carbon emissions lags behind foreign research. After 2014, Chinese articles began to pay more attention to the study of building carbon emissions. We can further find that Chinese articles focus more on the factor decomposition of building carbon emissions. In contrast, foreign articles were not only interested in the factorization of building carbon emissions but also focused on carbon emissions from the construction phase of the construction industry.

4. Discussion

By analyzing the research status of building carbon emissions in Chinese and foreign articles, we find that the current research results are very rich, and the research methods are diversified. However, there are still many research directions worth further exploration.

Clarify the system boundaries of building carbon emissions. Many articles use the life-cycle assessment method to estimate building carbon emissions [52,71–74]. However, the system boundary of building carbon emissions is not clear, and there are differences in the definition of the building life cycle [80,81]. Different methods and models for analyzing building life cycle carbon emissions lead to different carbon emission results in the whole life cycle of buildings. It is urgent to clarify the boundaries of the life-cycle assessment system to conduct more in-depth research on building carbon emissions in the future. A comprehensive carbon factor database needs to be improved. Most studies use the inventory method to calculate building carbon emissions. Different calculation methods, years, and regions result in significant differences in calculation results. There still needs to be more research on the applicability of carbon emission accounting methods to different types of buildings. In the future, a building carbon emissions calculation based on a specific accounting method should be formed quickly to match building types with carbon emission accounting methods.

Green building, low-carbon building, and zero-carbon building assessment standards should be formulated globally. This includes expanding the scope of assessment from commercial buildings to rural residential buildings, so that all countries can measure and report their building carbon emissions in a consistent and comparable manner. In 2006, the UK announced the planning of ecological towns, requiring new buildings to be "zero-emission" by 2016 [88]. The foreign green building evaluation system is relatively perfect; a relatively good evaluation system is the American LEED system (Leadership in Energy and Environmental Design) [89], as is the German DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen). However, the green building evaluation system needs to pay more attention to the building carbon emissions index [90]. Compared to developed countries, studies in developing countries started relatively late in green, sustainable, and low-carbon buildings and have yet to establish widely recognized evaluation standards for low-carbon buildings. Developing countries need to increase policy support for low-carbon research, encourage enterprises to voluntarily comply with the requirements of low-carbon buildings through taxation and other means, strengthen the audit and supervision of the low-carbon status of buildings, and clarify the low-carbon standards. At the same time, researchers need to learn from historical development experience, promote the further development of low-carbon building research, improve the low-carbon building evaluation system, and enrich the research content.

The potential of individual energy conservation and emission reduction. The development of low-carbon buildings and life reflects residents' pursuit of green life to some extent. However, the public's understanding of low-carbon awareness is not comprehensive enough, resulting in insufficient trust in low-carbon buildings [91]. Promoting of low-carbon buildings needs to be led by the government and considered from the two aspects of raising public awareness and establishing incentive mechanisms [92]. To ensure end-user participation, the real estate housing market must introduce financial incentives to buy low-carbon buildings [93]. The study found that the public is willing to learn more about renewable resource knowledge and hoped that the government could take corresponding measures to raise awareness of low-carbon buildings [94]. Countries should take the government's lead to publicize the advantages and benefits of low-carbon buildings, advocate a low-carbon lifestyle, enhance the awareness of low-carbon buildings, and thus increase the market demand for low-carbon buildings. With the shift of emission reduction policy to the consumer side, residents will play a crucial role in reducing carbon emissions.

Building carbon emissions in developing countries. Building carbon emissions is a comprehensive research field with strong practicability, but current research is mainly concentrated in China, the United States, the United Kingdom, Australia, and other major economies. With the improvement of economic development and urbanization, the energy consumption and carbon emissions of non-developed countries worldwide will experience unprecedented levels [95]. China's urbanization rate has risen from 38% in 2001 to 61% in 2019 [96]. The consumption of large amounts of building materials during urbanization is an important factor driving China's rapid surge in energy consumption and carbon emissions [97]. India is the world's fourth-largest emitter, and its energy demand increases with its economy and population [98]. From 2000 to 2017, indirect emissions in India's construction industry almost tripled. In 2019, the Indian construction sector accounted for 24% of the country's carbon dioxide emissions. India's urbanization level will reach 40% in the next decade, which will significantly drive the increase in building carbon emissions [99]. The research on carbon emissions from the building industry in developing countries cannot be ignored [95]. With the decline in the growth rate of the total building stock and the increase in the proportion of recycled building materials, the coordinated development of the construction sector and industry sectors will be more important [2]. The synergy of the emission reduction effect between the construction and building materials manufacturing industries should be considered. Therefore, it is necessary to actively develop interdisciplinary research platforms, establish comprehensive research teams, strengthen openness and cooperation, strengthen connections with foreign universities, and promote transnational and inter-institutional collaborative research.

Carbon tax and carbon trading system. Scholars study allowance allocation from the perspective of efficiency [100,101] or fairness [102,103], trying to establish a reasonable and acceptable allocation scheme. The researchers proposed more than 20 allocation options, but none were widely accepted by climate conference [104]. Moreover, in developing countries such as China, the allowance allocation is led by the government and currently only involves the power sector. Ref. [105] points out that long-term use of the free method will reduce the efficiency of the emission trading system, and proposes a more effective carbon emission trading by auction. Allowance allocation through auction helps to improve the efficiency of emissions trading systems and maximize government revenue [106]. Carbon markets may be the best way to balance development and emissions. With the development of carbon markets, future allowance allocations will be covered by other industries or sectors. Under the market mechanism, how to achieve a fair and effective allowance allocation is a subject worthy of research.

Low-carbon properties of building materials. With the proposal of the "double carbon" goal and the continuous popularization of the concept of green environmental protection, the development of the construction industry has gradually developed in the direction of sustainable development, and the construction side has increasingly recognized the application of green building materials. Energy conservation and emission reduction in the building industry are closely related to the development of building materials. The construction sector has the characteristics of "low carbon on the surface, high carbon hidden" [107]. In the construction industry, the waste of resources and environmental pollution caused by traditional building materials have become urgent problems to be solved. Developing countries lag behind developed countries in the research of low-carbon building materials. However, developing countries are undergoing economic restructuring, and green and low-carbon building materials have enormous development potential. All parties should seize the opportunity, increase investment in the research and development of green and low-carbon building materials, strengthen the ability of technological innovation, improve production efficiency, and save resources by optimizing the production process.

5. Conclusions

This study compares the bibliometric differences between foreign and Chinese articles on building carbon emissions research. Two data sets of 4993 foreign and 1768 Chinese articles from 2008 to 2022 are analyzed using the Web of Science Core Collection database. Specifically, this paper compares aspects of publication object, journal, subject category, author, and institution. It discusses the differences in research trends and hotspots regarding keywords and citation analysis.

(1) The research on building carbon emissions shows a steady upward trend from 2008 to 2022. During the study period, the output and impact of foreign studies on building carbon emissions were generally higher than those of Chinese studies. Building carbon emissions is an interdisciplinary research topic involving the environment, energy, climate change, economics, green development, chemistry, and other natural sciences. The cooperation between institutions and organizations studying carbon emissions from the building sector is relatively weak. The influence of foreign articles on publications, journals, authors, and institutions is generally greater than that of Chinese articles. However, Chinese articles outperformed foreign articles for a few authors and institutions.

(2) Through keyword and citation network analysis, we found that the similarities and differences in conceptual and knowledge structure between foreign and Chinese articles are intertwined. For example, carbon footprint, energy, climate change, environmental impact, and greenhouse gas emissions are the common focus of both foreign and Chinese articles. However, foreign articles tend to focus on the impact of the whole life cycle of buildings on the environment. The low-carbon performance of cement, concrete, and other building materials is a new hot area of building carbon emissions in foreign articles. From the overall characteristics of the publication, the research on building carbon emissions in Chinese articles has prominent regional characteristics.

(3) In terms of the importance of the subject and maturity, the topic of 'climate change' in foreign articles is both important and highly developed. In contrast, the topic 'climate change' in Chinese publications is important but not well developed. The topics 'carbon tax' and 'compressive strength' are emerging in Chinese articles. Synergy between the construction industry and the steel industry is also an important research topic in Chinese articles. The topics of the core knowledge base of Chinese articles are more affluent than those of foreign articles. Overall, the thematic direction of Chinese articles is more divergent and lacks well-developed themes that greatly influence other research themes.

Finally, potential future research directions are proposed. Compared with the papers of Sun et al. [39], this study combines VOSviewer, CiteSpace, HistCite, and the latest bibliophily R-package tools, with the help of new search strategies, to more accurately dig out academic hotspots and research trends. More importantly, this paper compares

Chinese and foreign literature on building carbon emissions to reduce the subjectivity and one-sidedness of the research on building carbon emissions. Exploring the differences between foreign and Chinese articles on building carbon emissions can further improve the researchers' ability to explore building carbon footprint research.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

See Tables A1–A4 and Figures A1–A4.

Table A1. The top 10 influential journals of foreign and Chinese articles.

Foreign Articles						Chinese Articles					
Journal	TA	H	TLCS	TGCS	PY	Journal	TA	H	TLCS	TGCS	PY
Journal of Cleaner Production	362 (7.25)	58	551	12,565	2011	*Journal of Cleaner Production*	286 (16.17)	54	901	10,604	2010
Sustainability	345 (6.91)	27	11	3095	2011	*Sustainability*	105 (5.94)	18	10	1022	2014
Energy and Buildings	236 (4.72)	49	588	8092	2008	*Applied Energy*	69 (3.90)	33	238	3302	2011
Energies	220 (4.40)	21	17	1744	2011	*Environmental Science and Pollution Research*	59 (3.33)	15	53	786	2013
Renewable and Sustainable Energy Reviews	180 (3.60)	55	664	11,443	2008	*Energy Policy*	58 (3.28)	33	359	3209	2008
Energy Policy	171 (3.42)	46	331	6282	2008	*Energy*	58 (3.28)	29	154	1925	2010
Applied Energy	140 (2.80)	41	183	5935	2009	*Science of the Total Environmental*	55 (3.11)	28	212	2560	2010
Construction and Building Materials	140 (2.80)	41	163	5998	2008	*Renewable and Sustainable Energy Reviews*	48 (2.71)	32	178	2753	2008
Energy	105 (2.10)	35	167	3150	2008	*Resource Construction and Recycling*	44 (2.49)	25	139	1710	2016
Building and Environment	96 (1.92)	35	342	3675	2009	*Energies*	40 (2.26)	12	15	396	2011

Note: TA (%) total articles and percentage; H h-index; PYS the start of publications year.

Table A2. The top 10 productive authors of foreign and Chinese articles.

Foreign Articles						Chinese Articles					
Author	**TA(%)**	**H**	**TLCS**	**TGCS**	**PYS**	**Author**	**TA(%)**	**H**	**TLCS**	**TGCS**	**PYS**
Hong Taehoon	16 (0.32)	13	37	505	2009	Cai Weiguang	40 (2.26)	28	345	2264	2017
Kucukvar Murat	16 (0.32)	13	80	792	2013	Lin Boqinag	30 (1.70)	22	159	1346	2015
Hewage Kasun	14 (0.28)	10	35	548	2015	Zuo Jian	23 (1.30)	16	53	1005	2013
Tae Sungho	13 (0.26)	11	56	313	2009	Ma Minda	21 (1.19)	21	253	1491	2017
Sadiq Rehan	12 (2.24)	9	12	212	2015	Hong JingKe	21 (1.19)	17	212	1048	2015
Cabeza Luisa F	12 (0.24)	8	17	632	2011	Geng Yong	21 (1.19)	17	137	1204	2011
Pomponi Francesco	11 (0.22)	12	86	583	2015	Chen Bin	21 (1.19)	15	67	877	2011
Duic Meven	11 (0.22)	8	12	222	2013	Du Qiang	18 (1.02)	11	34	345	2017
Habert Guillaume	11 (0.22)	10	54	1,018	2009	Huo Tengfei	17 (0.96)	14	101	883	2017
Lenzen manfred	10 (0.20)	9	24	629	2012	Ren Hong	16 (0.90)	11	92	598	2017

Table A3. Top 10 productive institutions of foreign and Chinese articles.

Foreign Articles						Chinese Articles					
Institution	**TA**	**TLCS**	**TGCS**	**Centrality**	**PYS**	**Institution**	**TA**	**TLCS**	**TGCS**	**Centrality**	**PYS**
University Cambridge	51 (1.02)	173	2460	0.07	2009	Tsinghua University	151 (8.54)	337	4833	0.29	2010
UCL	46 (0.92)	98	2728	0.02	2014	Chinese Academy of Sciences	139 (7.86)	400	4827	0.23	2010
Swiss Fed Inst Tech	44 (0.88)	47	1390	0.05	2016	Chongqing University	126 (7.13)	756	5662	0.12	2010
University Seville	43 (0.86)	11	942	0.01	2015	Beijing Normal University	86 (4.86)	155	2276	0.20	2011
Politecn Milan	42 (0.84)	49	868	0.02	2015	Hong Kong Polytechinc University	75 (4.24)	429	3556	0.08	2013
University Calif Berkeley	40 (0.80)	64	2686	0.03	2009	North China Electric Power University	66 (3.73)	49	1410	0.05	2013
University Leeds	38 (0.76)	130	1690	0.02	2014	Tianjin University	64 (3.62)	182	1599	0.06	2013
University Melbourne	36 (0.72)	93	2555	0.02	2010	Beijing Inst Technol	58 (3.28)	80	1629	0.07	2009
University Utrecht	34 (0.68)	37	1202	0.02	2011	University of Chinese Academy of science Cas	51 (2.88)	127	1837	0.10	2013
Chalmers Universuty Technoligy	32 (0.64)	111	1037	0.02	2012	Peking University	46 (2.60)	142	1647	0.11	2010

Table A4. The top 25 keywords by frequency of foreign and Chinese articles.

Foreign Articles				Chinese Articles			
Keywords	**Frequency**	**Centrality**	**PYS**	**Keywords**	**Frequency**	**Centrality**	**PYS**
CO_2 emission	368	0.21	2008	CO_2 emissions	268	0.39	2010
sustainability	287	0.08	2009	China	228	0.37	2009
energy efficiency	265	0.12	2008	life-cycle assessment	52	0.16	2015
life-cycle assessment	247	0.07	2008	energy-consumption	50	0.18	2011
climate change	213	0.07	2008	input-output analysis	43	0.09	2012
renewable energy	116	0.04	2010	sustainability	33	0.03	2017
greenhouse-gas emissions	107	0.12	2009	carbon footprint	30	0.08	2010
carbon footprint	101	0.09	2010	climate change	28	0.07	2012
circular economy	95	0.03	2013	energy efficiency	26	0.07	2008
energy consumption	91	0.07	2009	carbon neutrality	26	0.01	2021
environmental impact	80	0.04	2009	scenario analysis	22	0.07	2011
concrete	79	0.04	2008	driving force	19	0.02	2016
embodied energy	77	0.04	2010	urbanization	19	0.02	2016
residential buildings	64	0.09	2011	greenhouse-gas emissions	17	0.02	2010
compressive strength	57	0.02	2012	Stirpat model	16	0.03	2016
embodied carbon	55	0.02	2016	environmental impact	15	0.04	2018
energy policy	55	0.06	2010	Beijing	15	0.04	2011
cement	53	0.06	2011	residential buildings	15	0.03	2017
geopolymer	50	0.01	2018	structural path analysis	14	0.03	2017
durability	47	0.05	2012	economic growth	14	0.03	2019
optimization	43	0.05	2008	lmdi	12	0.02	2013
green building	41	0.06	2013	supply chain	11	0.03	2018
heat pump	38	0.05	2014	renewable energy	10	0.00	2008
built environment	35	0.02	2008	carbon tax	10	0.02	2018
mechanical property	35	0.02	2017	land use	10	0.03	2015

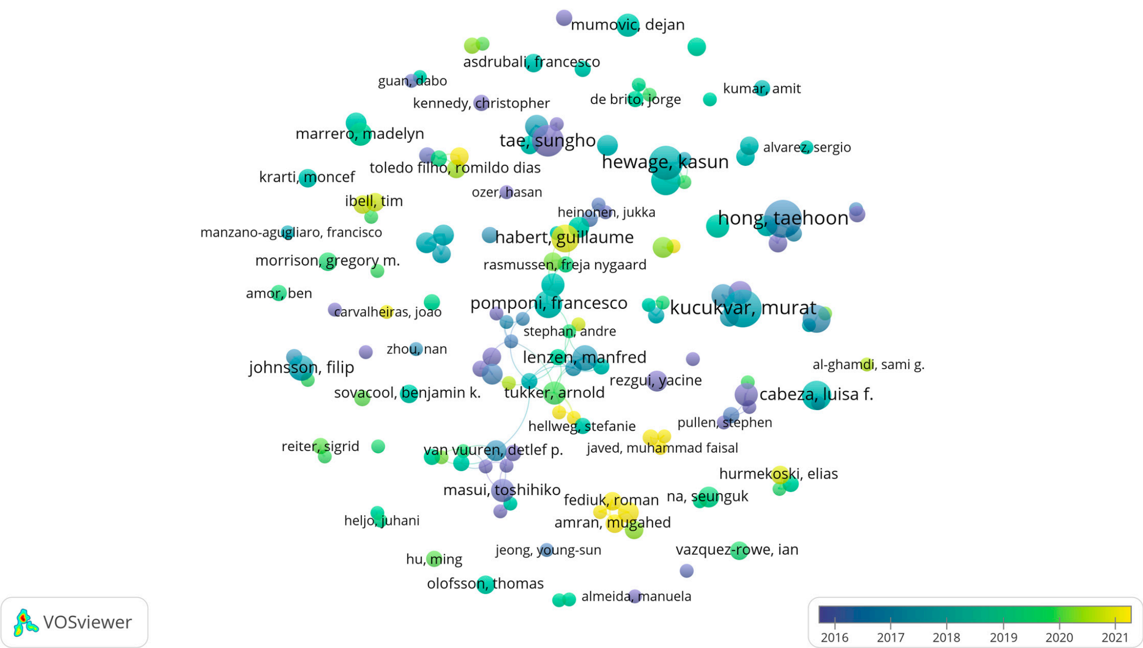

Figure A1. Overlay visualization map of co-authors of foreign articles.

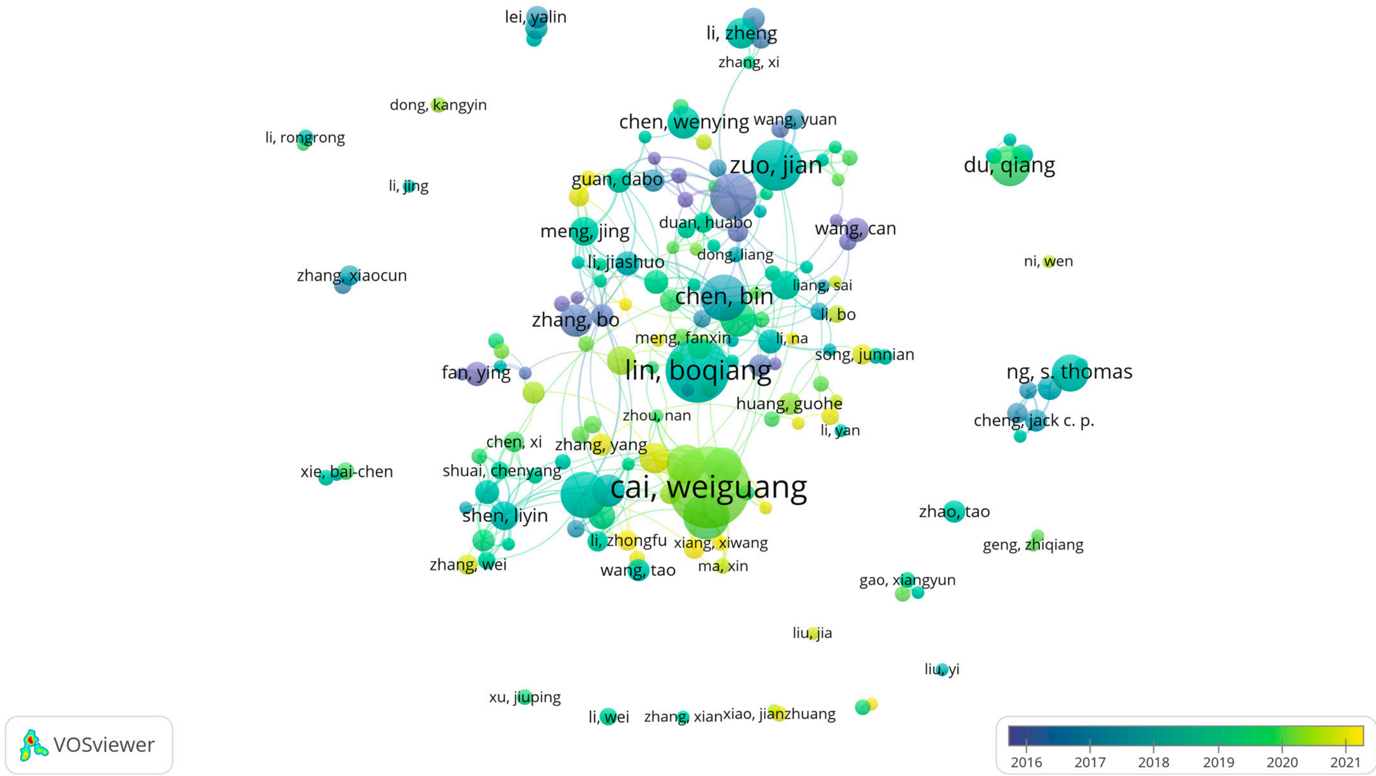

Figure A2. Overlay visualization map of co-authors of Chinese articles.

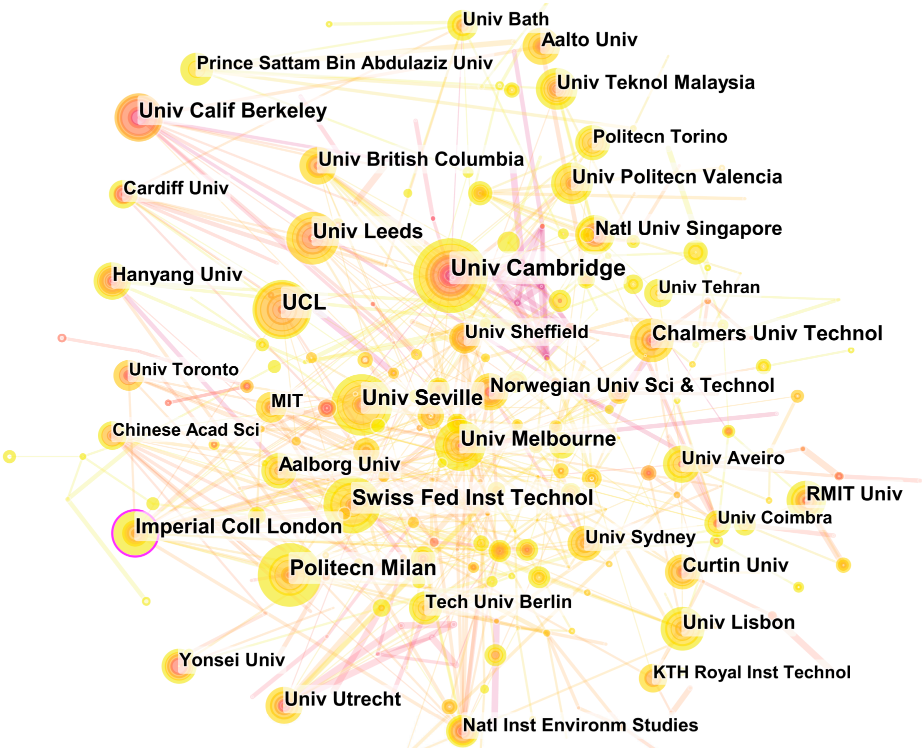

Figure A3. Co-occurrence knowledge map of cooperative institutions for foreign articles.

Figure A4. Co-occurrence knowledge map of cooperative institutions for Chinese articles.

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