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Analysis on the Research Trend of Carbon Capture, Utilization and Storage (CCUS) Technology Based on Bibliometrics

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Abstract:
In recent years, carbon capture, utilization and storage (CCUS) technology has attracted worldwide attention. In order to understand the latest hotspots and development trends in the field of carbon capture, utilization and storage (CCUS), through the Web of Science core collection database, advanced search was conducted with the theme of “CCUS”. A total of 6753 English literatures published by global scholars from 2000 to 2024 were selected, and visual analysis software VOSviewer, HistCite and Biblioshiny were used to analyze the annual number of publications, subject distribution, journal distribution, research countries, research institutions, research hotspots and development trends. The innovation of this research is reflected in revealing the global CCUS technology research pattern and development direction: for the first time, it quantitatively points out that although China started late, the number of achievements has jumped to the first place, breaking through the dominant mode of traditional technology power; three frontier directions in the future are proposed : energy transformation coupled with geological energy storage, molecular dynamics-enabled storage safety assessment, and economic feasibility optimization path. Breaking through the existing single carbon storage research framework, an integrated technology system of ’capture-utilization-energy storage’ is constructed. In particular, through the interdisciplinary integration of molecular dynamics, it provides atomic-scale theoretical support for deep geological storage, promotes the transformation of CCUS from engineering verification to intelligent design, and fills the theoretical gap of large-scale application.

1 Introduction

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) study show that to achieve the goal of controlling global temperature rise within 2°C by the end of this century, up to 14% of CO_2 reduction in the optimal scenario needs to be achieved by carbon capture, utilization and storage (CCUS) technology (Xin and Wang, 2021; Zhang et al., 2021; Song et al., 2023; Chen et al., 2023); if CCUS technology is not considered at all, the global emission reduction cost will increase by 138%. Carbon capture, utilization and storage (CCUS) refers to the technical system that separates carbon dioxide from the emission source or the atmosphere, uses it geologically, chemically or biologically, or transports it to a suitable storage site to isolate it from the atmosphere for a long time (Fan et al., 2020; Laurent et al., 2020; Parmesan and Yohe, 2003). In recent years, CCUS technology has received extensive attention worldwide, as shown in Fig. 1. In November 2016, CCUS was included in one of the seven major innovation challenges of the “Innovation Mission (MI)”. Driven by the temperature rise target and emission reduction pressure, CCUS related research has different emphases in different periods, and the regional differences are obvious. Based on the above analysis, this paper makes a systematic data statistics on the scientific literature of global CCUS technology in engineering research since 2000-2024.

Through the data of the publication process, the distribution

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of main research institutions, the international cooperation and the development and evolution of research hotspots of CCUS technology, this paper reveals the overall scientific research status, research focus and future development direction of CCUS technology, in order to provide reference for the future policy formulation of CCUS technology (Wang et al., 2018; Peng et al., 2022; Li et al., 2022; Zhang et al., 2023; Wu et al., 2023).

Based on the systematic statistical analysis of the global CCUS technology engineering research literature from 2000 to 2024, this paper points out the key of CCUS emission reduction and cost control under the temperature control target. The research situation is affected by the emission reduction pressure and has regional differences. It aims to provide reference for policy formulation, provide a new perspective and empirical support for subsequent CCUS technology research and policy planning, and is of great significance to improve the relevant research system. Compared with previous studies, the time span is longer and the data is more comprehensive, which can more accurately reflect the development trend of technology and the change of research focus.

2 Research data and methods

2.1 Data source

At present, many scholars have conducted literature retrieval and measurement through the Web of Science platform(Gao et al., 2021; Wu et al., 2022; Gür, 2022). This paper uses the bibliometric method to systematically count the scientific literature in the engineering field of global CCUS technology research from 2000 to 2024 in the Science Citation Index Expanded (SCI-E) and Social Sciences Citation Index (SSCI) databases on the Web of Science platform. The retrieval formula: TS=("CCUS" or "carbon capture, utilization and storage" or "carbon capture and storage" or "carbon capture and sequestra*" or "carbon capture, utilization and sequestration" or "CO_2 capture, utilization and sequestration" or "CO_2 capture, utilization and storage" or "CCS" or "CO_2 capture and utilization" or "CO_2 capture and storage" or "CO_2 capture and sequestra*" or "carbon capture and utilization") is the retrieval condition for advanced retrieval. The search time is as of December 31, 2024.

2.2 Research methods

The document-based information mining and statistical method constructed in this study mainly includes the following four steps: literature extraction, literature screening, multi-tool bibliometric analysis and multi-mode result visualization, as shown in Fig. 2. The specific operation process is as follows:

(1) Data extraction and screening

Through the Science Citation Index Expanded (SCI-E) and Social Sciences Citation Index (SSCI) databases in the Web of Science platform and searching according to the search formulas described above, 8650 articles were initially retrieved. Subsequently, after manual screening, mainly through the title, abstract and literature type, the number of articles and reviews in the field of CCUS was finally determined to be 6753.

(2) Multi-tool bibliometric analysis

Visual analysis software such as VOSviewer, HistCite and Biblioshiny were used to analyze the annual number of papers, the distribution of major disciplines and journals, research countries, research institutions, research hotspots and future development trends.

The paper used the visual analysis software VOSviewer for co-occurrence analysis, analyzes the cooperative relationship between research countries, research institutions and research scholars, and explores the hot topics in this field. The VOSviewer software is used to draw the network diagram. The diameter of the circle represents the number of publications, and the width of the line represents the total strength of the association. Through this figure, we can clearly see the cooperation between various countries and institutions, as well as their respective research strength in this field.

In order to understand the main journals published in the field of CCUS, the local citation count (LCS) and total citation count (GCS) indicators in HistCite and Biblioshiny can be used. LCS represents the number of times that a paper entered into the HistCite and Biblioshiny databases was cited by other literatures, while GCS represents the number of times that a paper entered into the HistCite and Biblioshiny databases was cited by all literatures in the WOS database. The higher the LCS value, the greater the influence of its content in this field.

In order to reveal the dispersion law of literature, Biblioshiny software can be used to point out that in the field of CCUS, a few core journals collect most of the important research results and progress in this field. Based on Bradford 's Law, the core area can be divided, and the core journals can be selected and utilized more effectively through this law to avoid wasting time in a large number of documents. And use Biblioshiny software to establish a Sankey diagram to predict the future development trend of its CCUS field.

(3) Visualization of multi-mode results Through the use of few bibliometric analysis software, the research status and development trend of CCUS field are successfully visualized. The spatial and temporal distribution map of research hotspots was drawn, the cooperation of various countries and organizations was studied, and the future development prospects and directions were sorted out.

3 Results and analysis

3.1 Annual distribution and country distribution of CCUS

Through the statistics of the number of international literature published each year, we can clearly understand the research process in the field of carbon capture, utilization and storage (CCUS). From 2000 to 2024, the international research on CCUS has been increasing, and the number of relevant literatures has generally shown an increasing trend (Fig. 3). It can be seen that the field of CCUS is the focus of current engineering science research. As shown in Fig.3(a), based on the data of the trend of the top ten publications in the author 's country from 2000 to 2024, China, the United States, the United Kingdom, South Korea, Germany, Australia, Japan, Italy, Canada and India are in the leading position in CCUS research. The number of papers published by Chinese authors is the highest and the number of papers published in the past decade is the fastest growing, followed by the United States. Moreover, the number of papers published by Chinese authors in 2017 exceeded that of the

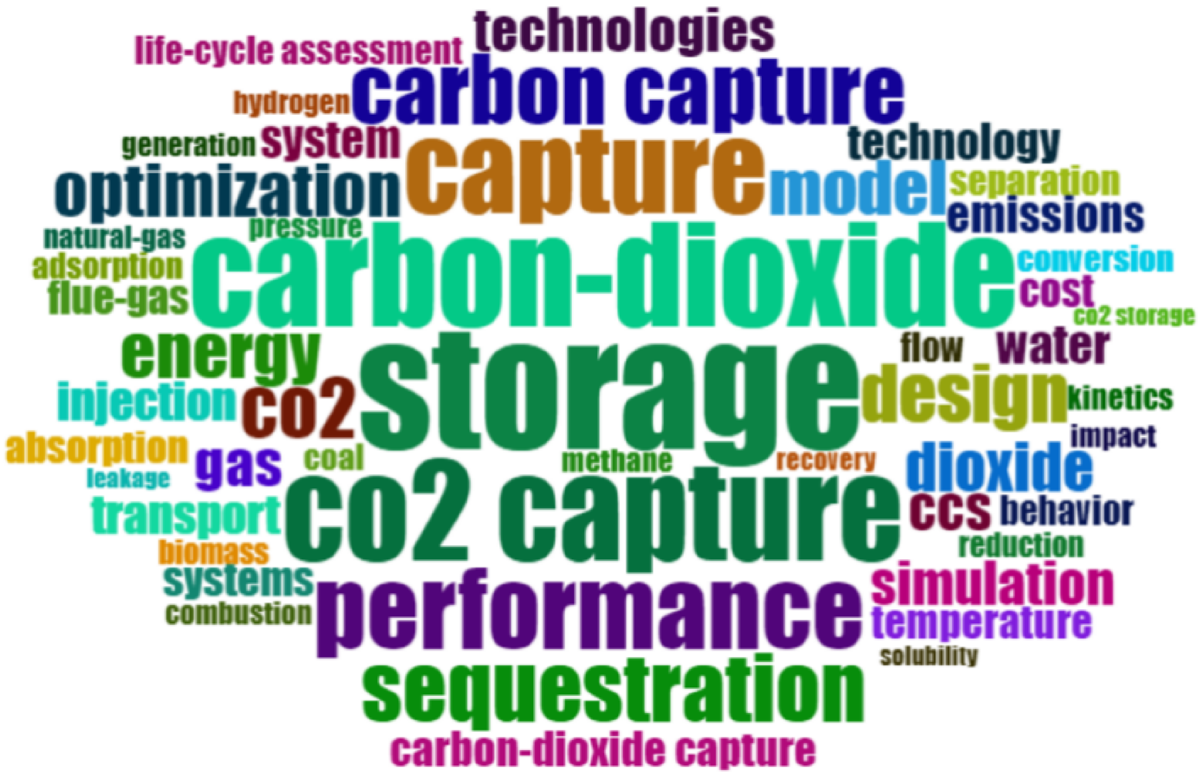

Fig. 1 Word cloud attention in CCUS technology field

United States for the first time, and far exceeded that of other countries at a high growth rate, even exceeding the sum of the second (United States) and third (United Kingdom) in 2024.

According to the data in Fig. 3(a), it is mainly divided into three stages: In the first stage (2000-2010), by comparing the top ten countries in the number of published papers, it is found that although the research in this field in the world started relatively late, and the increase in the number of papers in this decade is also relatively slow, with only 1324 papers published, on average, only 14 papers per year per country, indicating that each country in this stage is in the exploration period in the field of CCUS ; in the second stage (2010-2017), the number of papers issued by all countries in the world showed an increasing trend, especially in China, the United States and the United Kingdom, and the number of papers issued by the United States has been greater than that of China during the period 2010-2016. However, with the increase of China's attention to the environmental field, China's number of papers in the field of CCUS exceeded that of the United States in 2017; in the third stage (2018-2024), with the proposal of China's " carbon peak " and " carbon neutrality " targets in 2020, more attention has been paid to CCUS research in the engineering field, and the increase rate of papers in its related fields is faster, far faster than other countries in the world, indicating that China has made important achievements in this field.

Through the change trend of the world's total number of publications in the field of CCUS shown in Fig. 3(b), it can be seen that during the period from 2000 to 2024, the research and investment in the field of CCUS showed an increasing trend as a whole, and its growth trend was increasing. However, in 2009 and 2016, there was a slight downward trend. It may be because at the time of the financial crisis, in order to stimulate the economy, the research in the field of CCUS was relatively reduced, so the number of papers in related fields also showed a slight decrease.

3.2 Subject distribution and journal distribution of papers published in CCUS field

Through WOS retrieval and analysis, the top 10 disciplines in the field of CCUS were selected (Fig. 4). It was found that Engineering Chemical, Energy Fuels, Engineering Environmental, Green Sustainable Science Technology and Environmental Sciences had a large number of papers. They accounted for 27.86%, 19.44 %, 17.28 %, 12.1 % and 6.98 % of the total number of publications, respectively. In addition, the research field of CCUS also involves many disciplines such as Engineering Electrical Electronic, Chemistry Multidisciplinary, Physics Applied, Engineering Mechanical and Engineering Civil. It shows that the research of CCUS involves many disciplines and covers a wide range of contents. The research of interdisciplinary subjects also plays a very important role in promoting the innovation and development of this field.

The visualization software HistCite analysis results show that (Table 1), the top three journals with the highest number of publications are International Journal of Greenhouse Gas Control (1205 articles), Applied Energy (426 articles) and Journal of Cleaner Production (380 articles). The journals with relatively high Local Citation Score (LCS) and Global Citation Score (GCS) are International Journal of Greenhouse Gas Control, Applied Energy, Environmental Science& Technology, etc.,

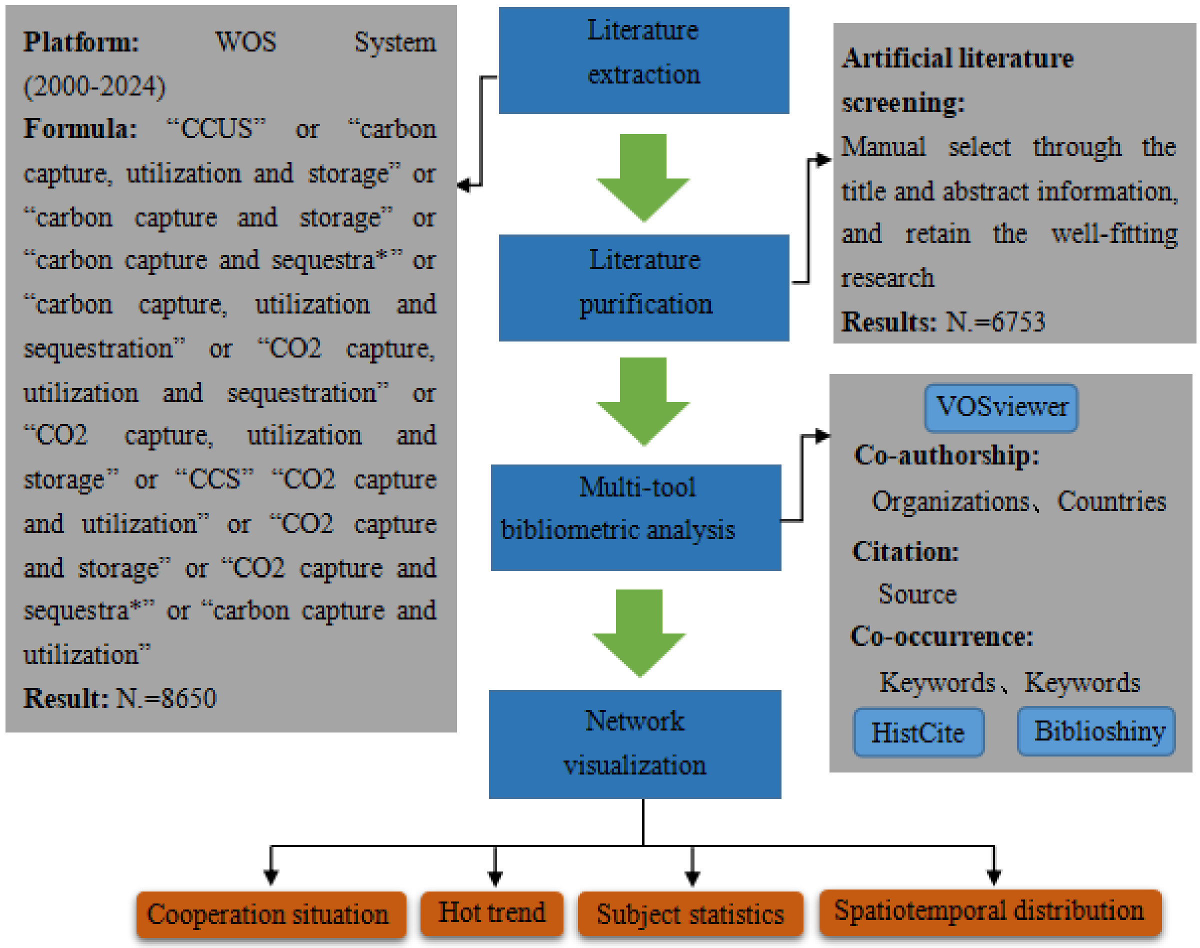

Fig. 2 Research framework

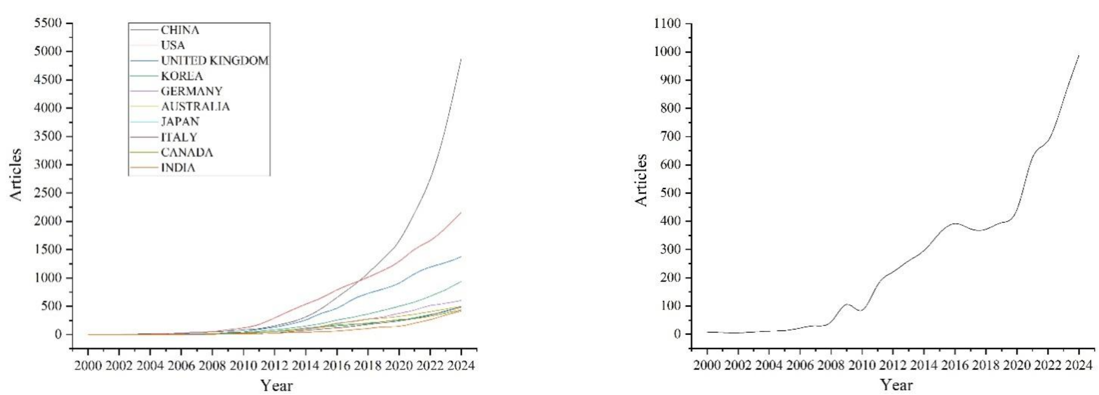

Fig. 3 Annual distribution and national distribution of papers in CCUS field (a: the change trend of the top ten papers in the author 's country from 2000 to 2024; b: trends in the number of publications worldwide from 2000 to 2024)

and most of them belong to the field of environmental science and energy conversion. Among them, the journal with the highest impact factor is Chemical Engineering Journal, with an impact factor of 13.2(2020-2024) in the past five years. The number of publications in the CCUS field is only 154, with LCS and GCS of 950 and 9762, respectively. However, the average LCS and GCS are the highest values, 6.2 times/article and 63.4 times/article, respectively, indicating that the journal is an international and interdisciplinary journal. It not only involves the fields of chemical industry, environment and sustainable energy development, but also has great influence in the field of CCUS. As shown in Figure 5, the core areas of journals in this field are divided by Bradford 's Law, which are International Journal of Greenhouse Gas Control, Applied Energy, Journal of Cleaner Production, Fuel and Chemical Engineering Journal, with a total number of 2465 papers. It shows that the five journals in the core area account for 36.5 % of the total number of journals (571). Therefore, if future scholars want to understand

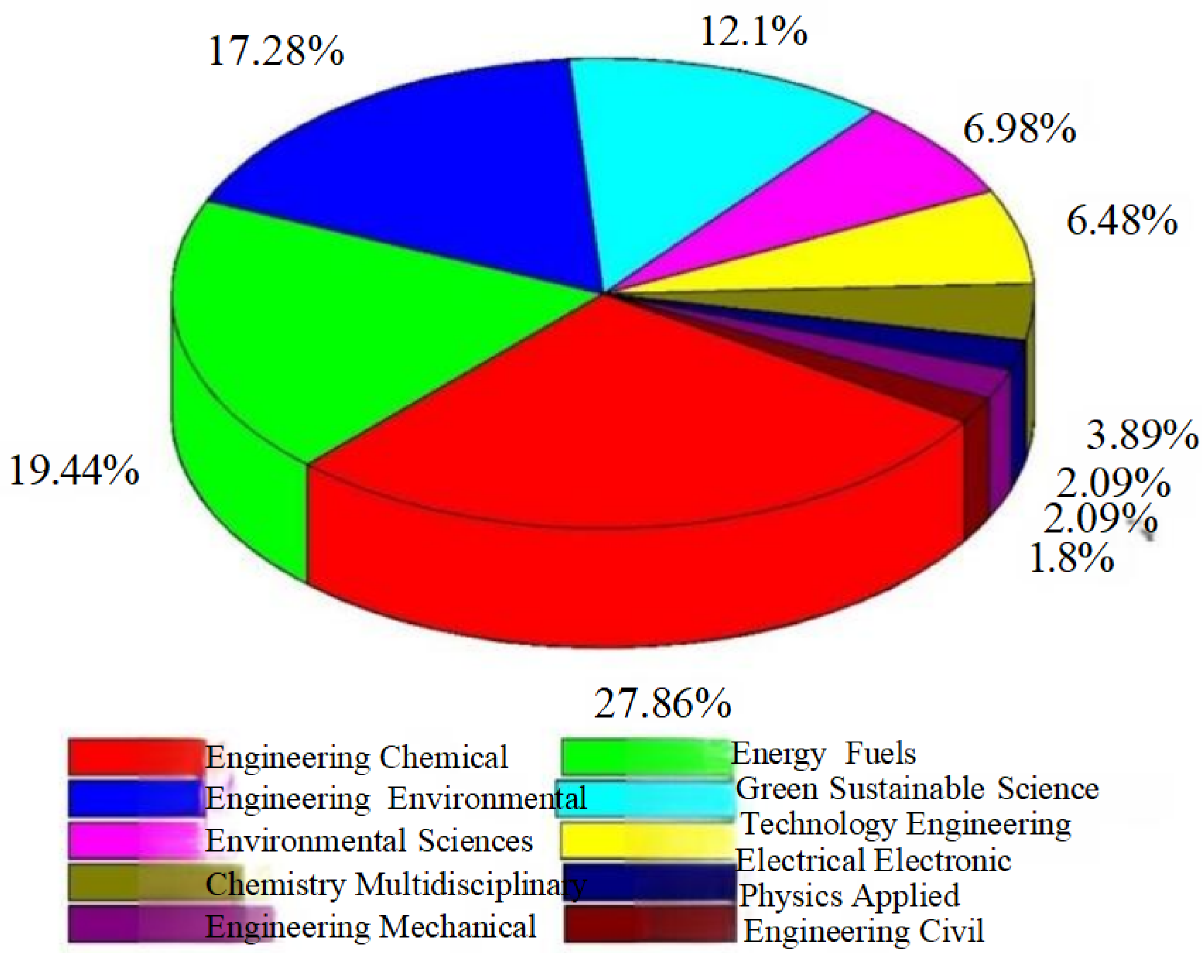

Fig. 4 The top ten disciplines of CCUS in the field of engineering from 2000 to 2024

Tab. 1 Top ten journals in CCUS field from 2000 to 2024

Journal title	Number of publications (article)	LCS	Average LCS	GCS	Average GCS	The average impact factor in 2020-2024
International Journal of Greenhouse Gas Control	1205	6535	5.4	37000	30.7	4.3
Applied Energy	426	2598	6.1	24966	58.6	10.4
Journal of Cleaner Production	380	791	2.1	12959	24.1	10.2
Fuel	233	352	1.5	7442	31.9	6.5
Chemical Engineering Journal	221	265	1.2	6984	31.6	13.2
Journal of CO_2 Utilization	197	363	1.8	8363	42.5	7.4
Energy & Fuels	170	360	2.1	3881	22.8	4.5
Greenhouse Gases-Science and Technology	165	351	2.1	2400	14.5	2.7
Environmental Science & Technology	154	950	6.2	9762	63.4	11.6
IEEE Transactions on Applied Superconductivity	146	24	0.2	1443	9.9	1.5

the important research directions in CCUS-related fields, they only need to search the core area journals to avoid wasting time in searching a large number of documents.

3.3 The characteristics of cooperation space among countries, institutions and authors

Based on the visual network analysis of VOSviewer software (Fig. 6), cooperation between countries is one of the important

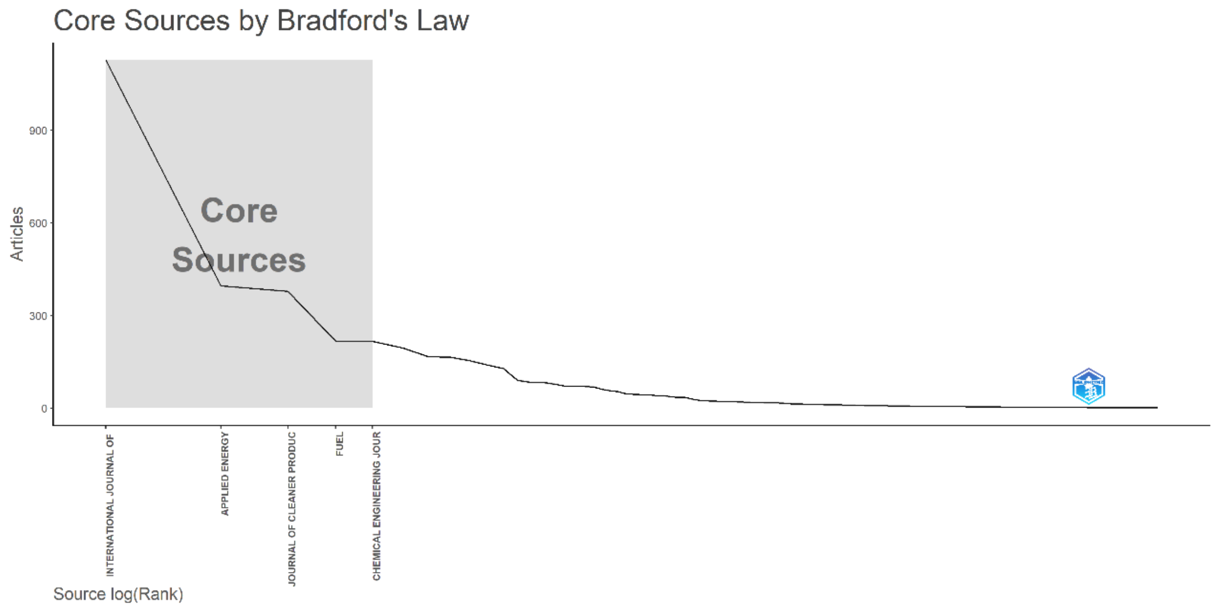

Fig. 5 The core area shown by Bradford 's Law

ways to achieve innovative research and improve scientific research capabilities. The results of Total link strength (TLS) show that China (911), the United States (789), the United Kingdom (766), South Korea (466) and Germany (353) are the top 5 countries respectively, which have strong influence and cooperate more with other countries. Among them, China has the most frequent cooperative research in the field of CCUS with the United States, Germany, South Korea and Australia.

The results of the cooperative network analysis of the publishing institutions (Figure 7) show that the Chinese Academy of Sciences is closely related to cooperation with other institutions. In the ranking of total link strength parameters (TLS), the Chinese Academy of Sciences (314) ranked first, followed by United States Department of Energy (DOE) (125), University of Texas at Austin (85), Beijing Institute of Technology (78), University College London (71). In terms of the number of published papers, the Chinese Academy of Sciences (231) is the institution with the highest number of published papers. United States Department of Energy (DOE) (203), University of Texas at Austin (85), Beijing Institute of Technology (49), and University College London (46) are institutions second only to the Chinese Academy of Sciences. Specifically, the Chinese Academy of Sciences has close cooperation with China University of Petroleum, Southwest Petroleum University, Tsinghua University, University of Edinburgh, University of Texas at Austin and other institutions, mainly for domestic cooperation. The University of Texas at Austin mainly has close cooperation with international academic research institutions such as the University of Edinburgh, the Chinese Academy of Sciences, China University of Petroleum, and Delft University of Technology. Therefore, international cooperation in the field of CCUS is still very frequent.

From the perspective of the author 's cooperative relationship and the number of publications (Figure 8), Zhang Xian from Adm Ctr Chinas Agenda 21 ACCA21, Mac Dowell Niall from Imperial College London, and Li Yong from China University of Mining & Technology, Junghwan Kim of Kangwon National University are the high-yield research scholar of CCUS in the field of engineering research, with more than 15 papers published. The results of total link strength (TLS) show that Zhang Xian (26), Mac Dowell Niall (21), Li Yong (16) and Junghwan Kim (11) are closely related to the cooperation of other authors.

3.4 Research hotspots in the field of CCUS

The frequency of keywords is closely related to the attention of the research topic. As shown in Fig. 9, it can be seen from the keyword network distribution map that it is mainly divided into two directions: CO_2 capture (blue clustering) and Storage (red clustering), indicating that scholars mainly focus on these two directions. The main research directions related to CO_2 capture (blue clustering) are performance, energy, carbon capture and technologies, etc., aiming to show the capture performance of energy and the research and development of technology. The main research directions related to storage (red clustering) are carbon-dioxode, capture, sequestration, simulation, model and pressure, etc., aiming to study the numerical simulation of storage performance. There is no practical engineering research on on-site carbon dioxide storage.

3.5 Analysis of fund project funding As shown in Figure 10, the article analyzes the number and proportion of papers funded by various funds. Among them, the National Natural Science Foundation of China has the largest number of funded papers, with 1,257 papers, accounting for 17.238%; the second is UK Research Innovation, with 336 papers, accounting for 4.608%; the third is the European Union, with 297 papers, accounting for 4.073%; followed by the United States Department of Energy, Engineering Physical Sciences Research Council, Fundamental Research Funds for the Central Universities, National Key Research and Development Program of China, Natural Environment Research Council, National Research Foundation

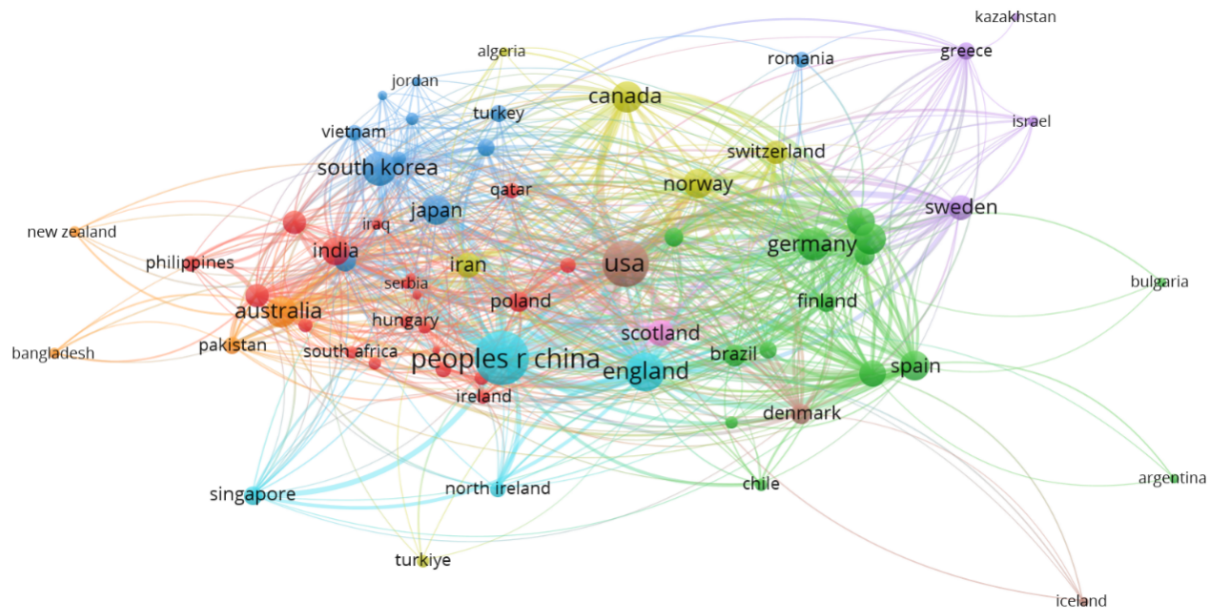

Fig. 6 Cooperation among major countries in CCUS engineering field

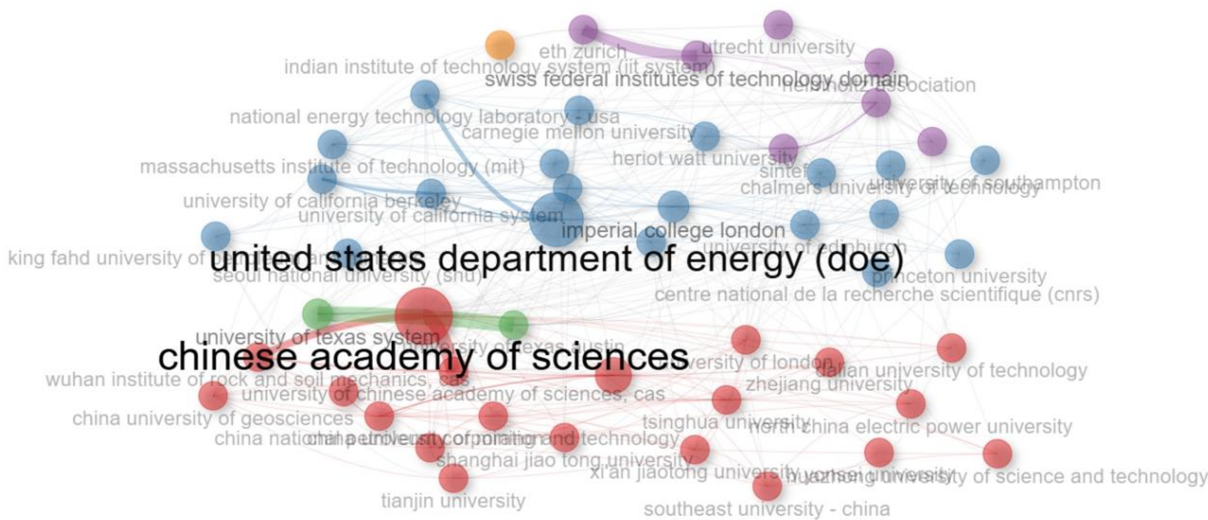

Fig. 7 Cooperative research relationship diagram between main publishing institutions in CCUS engineering field

of Korea and National Science Foundation, with 283, 237, 213, 178, 134, 133 and 132 papers respectively, accounting for 3.881%, 3.25%, 2.921%, 2.441%, 1.838%, 1.824% and 1.81% respectively. The National Natural Science Foundation of China, Fundamental Research Funds for the Central Universities and National Key Research and Development Program of China all come from China, which shows China's high attention to CCUS research.

3.5 The development trend of CCUS research

Through Biblioshiny, the spatial sequence of keywords in CCUS research papers is analyzed to illustrate the research hotspots in a specific period. The blue line in Figure 11 is the heat bar, which represents the duration of the word frequency. The position and size of the blue circle represent the strongest time point and intensity of the word frequency outbreak, and it can be seen from the heat bar that there is no word frequency heat in 2000-2006. According to the size of the term frequency in Fig. 10, the keyword burst index from 2007 to 2024 is divided into three time periods (2007-2014, 2015-2022 and 2023-2024) to describe the development trend of CCUS research.

The burst frequencies of Integrated Gasification Combined Cycle (IGCC), Carbon Dioxide Capture and Storage (CCS), Coal Gasification and Oxyfuel were relatively strong from 2007 to 2014. And the prominence time of Carbon Dioxide Capture and Storage and Integrated Gasification Combined Cycle is relatively long. Oxyfuel technology can completely burn fuel into carbon dioxide and water, and at the same time capture, concentrate and store carbon dioxide to prevent carbon dioxide from being directly released into the atmosphere and causing pollution. Carbon Dioxide Capture and Storage is the process of separating carbon dioxide from atmospheric, industrial or

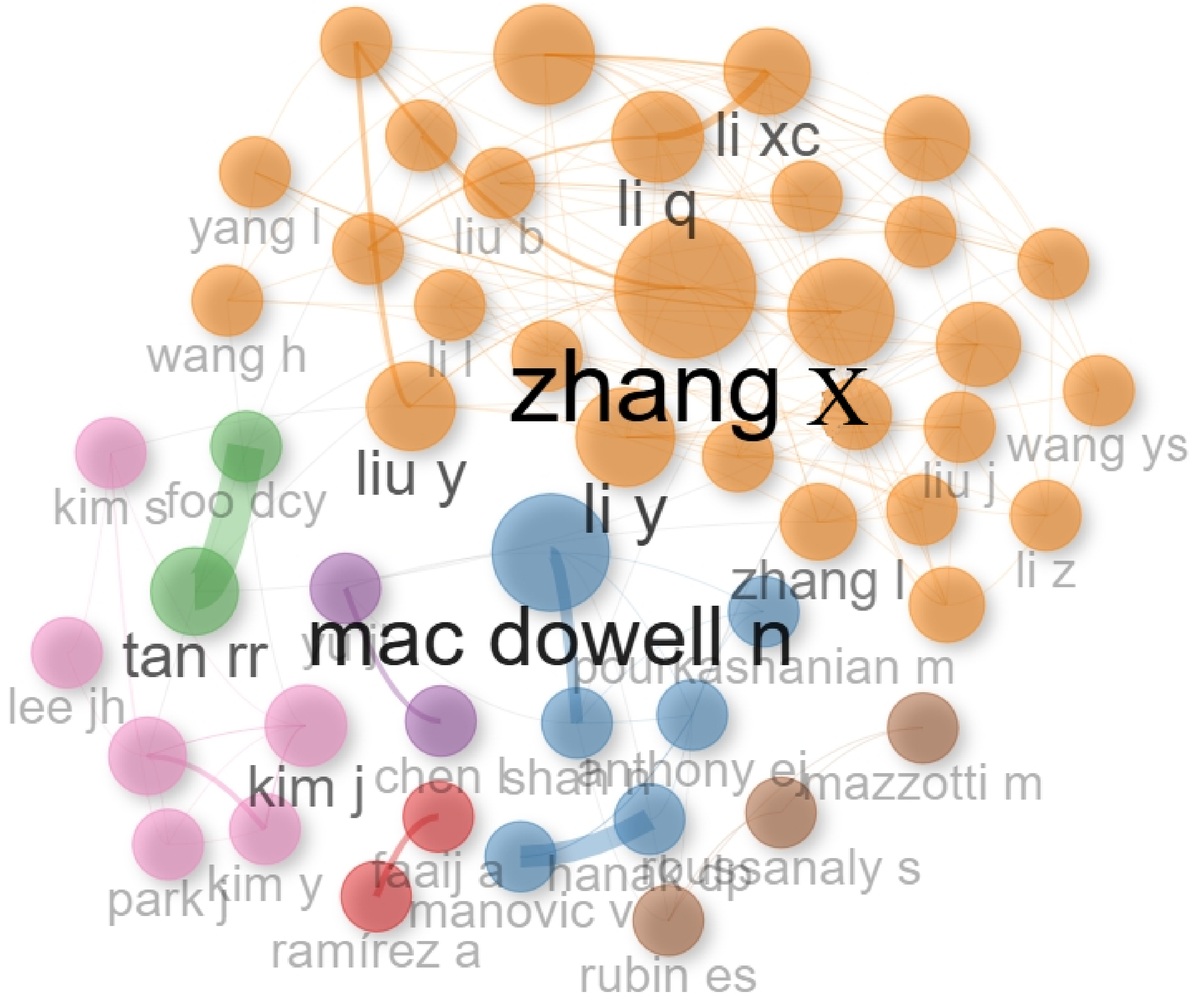

Fig. 8 The cooperative research relationship among the main authors in the field of CCUS

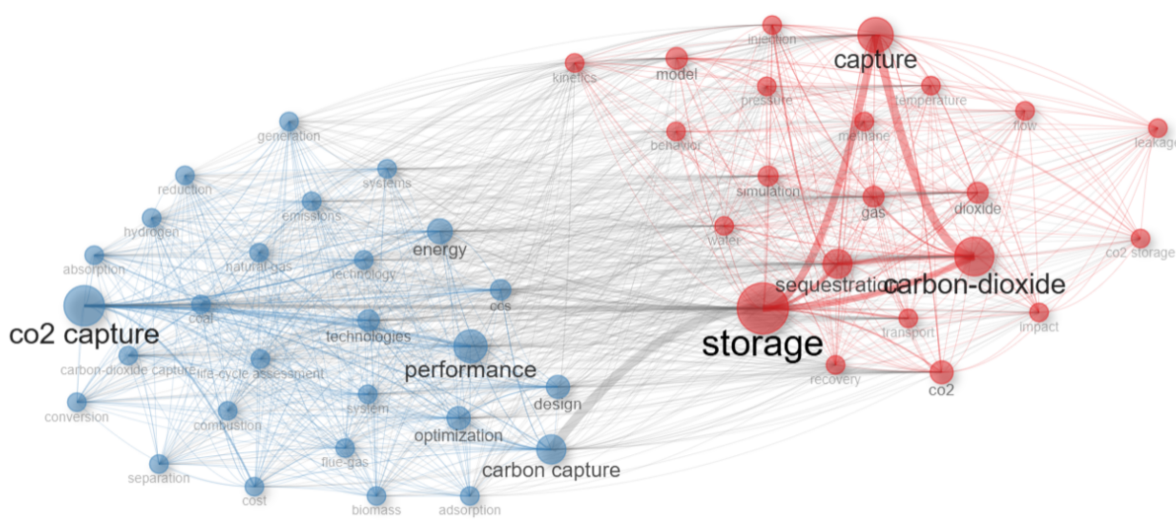

Fig. 9 Keyword co-occurrence network in CCUS field papers

energy-related emission sources and storing it in geological reservoirs, isolating it from the atmosphere for a long time. IGCC technology can capture and process coal before combustion through coal gasification process, so as to achieve near zero emission of carbon dioxide. However, the construction and operation cost of IGCC technology is high, which is the main

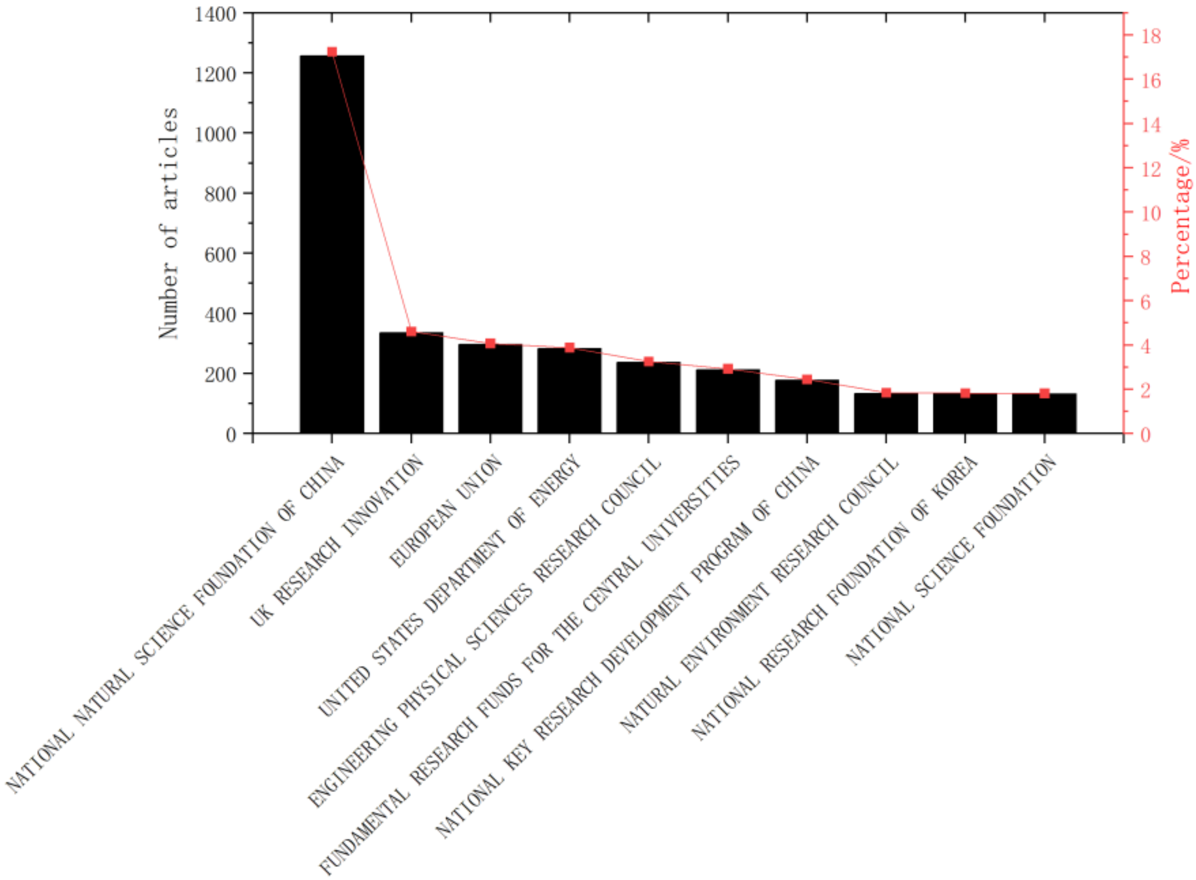

Fig. 10 The number and proportion of funding for each fund project

challenge in practical application.

From 2015 to 2022, keywords such as Carbon capture and storage and CO_2 capture have a strong frequency of emergence, with a frequency of 501 and 416, respectively, and a relatively long time of emergence, both of which are 7 years, indicating that these two directions have a vital role and objective value of sustainable research. And in 2021, CCUS keywords appear again, showing a strong frequency of emergence in 2023, and its emergence time continues until 2024, indicating that CCUS technology is the trend of future research.

From 2023 to 2024, it can be seen that the three keywords of Energy transition, Integrated CO_2 capture and utilization, and Molecular dynamics will be the future research hotspots and trends. Energy transition is the research direction of the combination of carbon storage and geological energy storage, that is, the use of formation pores or goafs as reservoirs, carbon dioxide as energy conversion medium, in the trough of electricity through the compressor to use excess electricity to compress carbon dioxide stored in the corresponding reservoir, in the peak of electricity will be high pressure carbon dioxide release into electricity, in order to achieve the purpose of energy conversion. Molecular dynamics is used to study the effects of environmental and structural factors on important parameters such as CO_2 adsorption, diffusion, interfacial tension, and contact angle. These parameters are essential for understanding the migration and sequestration behavior of CO_2 in geological reservoirs.

Energy transformation promotes global policies to accelerate the process of carbon neutrality. Countries guide the research and development of low-carbon technologies through carbon pricing and industrial subsidies, and drive the industrial system to transform to renewable energy and energy efficiency optimization. The breakthrough of integrated CO_2 capture and utilization (ICCU) technology significantly reduces the cost of carbon management. Combined with molecular dynamics simulation, the atomic-level analysis of adsorption materials and catalytic reaction mechanisms accelerates the development of new carbon conversion catalysts. In the industrial field, by coupling ICCU and green hydrogen production, CO_2 can be used to prepare synthetic fuels/chemicals, forming a ’ negative carbon industrial chain ’. Policy support, innovation of computing tools and engineering collaboration are driving carbon neutralization technology from laboratory to large-scale application.

4 Economic and environmental impact analysis of CCUS

The core goal of carbon capture, utilization and storage (CCUS) technology system is to reduce atmospheric carbon dioxide concentration through human intervention, but its whole life cycle implementation process is accompanied by significant energy and material resource consumption, which may lead to secondary environmental risks such as ecosystem disturbance and public health security. The current academic research shows a clear imbalance : although breakthroughs have been made in

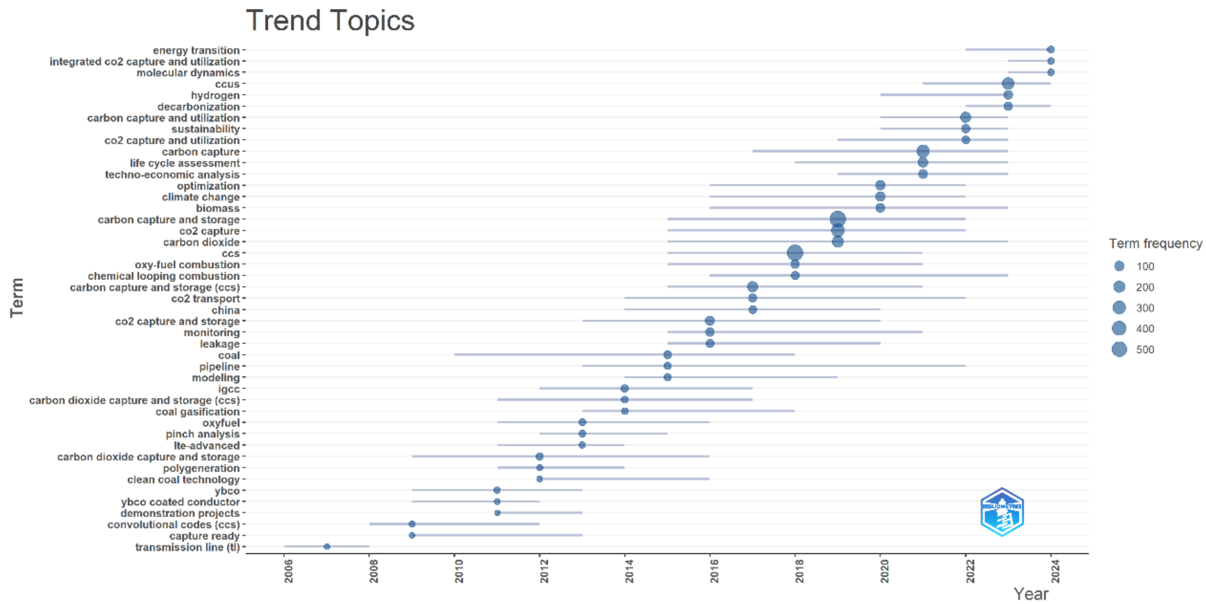

Fig. 11 Trend topics

basic technology research and development, the systematic environmental impact assessment system for CCUS projects has not yet been perfected. Specifically, the environmental effects of the technology chain are mainly reflected in two dimensions : firstly, the additional energy consumption of the capture and transport links leads to the increase of associated pollution emissions ; secondly, multi-link carbon leakage risks such as geological storage facilities and high-pressure pipe network systems pose a potential threat to ecological security and public health (Davoodi et al., 2023; Wang et al., 2023).

Domestic and foreign academic circles generally identify carbon capture, utilization and storage (CCUS) technology as a key emission reduction path. However, there is still a significant gap between the current technology deployment process and the expected goal. In the context of China, economic bottleneck has become the core factor restricting the large-scale commercial application of CCUS technology. By systematically combing the CCUS technical and economic research system, this paper aims to construct a theoretical analysis framework and provide theoretical support for subsequent research (Nath et al., 2024; Hanson et al., 2024). The existing literature research shows that the research in this field mainly focuses on three core areas: First, construct a full life cycle cost assessment model covering the whole process of capture, transportation, storage and utilization ; secondly, based on the carbon neutrality target constraint, the cost-benefit comparative analysis of CCUS technology and emission reduction paths such as renewable energy substitution and carbon market mechanism is carried out. Third, explore the impact mechanism of fiscal and tax subsidy mechanism, industrial policy tools and public-private cooperation model on the economic feasibility of the project. Relevant research provides multi-dimensional theoretical support for optimizing the technical economy of CCUS, but there are still research gaps in the dynamic cost evolution mechanism and policy synergy effect.

5 Conclusions

With the increasingly prominent problems of global climate change and environmental pollution, carbon neutrality has become a global initiative that has attracted much attention. As the main factor of global warming, the good management and utilization of carbon dioxide is of great significance for achieving the goal of carbon neutrality. In the field of CCUS research, China, the United States, the United Kingdom, South Korea and Germany are the top five countries with the largest number of papers published. Among them, although China's research on CCUS technology started late compared to the United States, it developed very rapidly and published far more than other countries. The main academic journals published in this research field are Engineering Chemical, Energy Fuels, Engineering Environmental, Green Sustainable Science Technology, Environmental Sciences. Journals with high citation frequency include International Journal of Greenhouse Gas Control, Applied Energy, Environmental Science & Technology, etc. The research institutions in this field mainly include the Chinese Academy of Sciences, Tsinghua University, University of Texas at Austin, Beijing Institute of Technology, University College London and so on.

The keyword co-occurrence network shows that the related research on CCUS mainly focuses on the two directions of CO_2 capture and storage, mainly to explore the energy capture performance and technology research and development and storage performance numerical simulation research, has not carried out a large number of carbon dioxide geological storage engineering practical research. In the future, the development trend of CCUS technology mainly focuses on three main directions : Energy transition, Integrated CO_2 capture and utilization, and Molecular dynamics. It mainly explores the integration of carbon storage and geological energy storage, and combines storage and energy storage to promote better energy recycling and sustainable development in the field of Energy transition.

And the use of Molecular dynamics theory can provide more sufficient theoretical support and technical reference for the potential and safety of carbon dioxide storage in the future. At the same time, the economic feasibility of CCUS technology may also continue to become the focus of scholar research.

In the future, CCUS technology research and policy directions need to focus on key research gaps. Although there are many achievements in the performance exploration of CO_2 capture and storage technology, the engineering practice research, especially the practical application of CO_2 geological storage engineering, is still insufficient. In terms of future development, it is necessary to strengthen the research on the combination of carbon storage and geological energy storage in energy transformation, and increase the exploration of the application of molecular dynamics theory in carbon dioxide storage potential and safety assessment, so as to provide more solid theoretical support for technological development. At the same time, for the economic feasibility of CCUS technology, it is necessary to further study, formulate reasonable policies, encourage technology application and promotion, promote CCUS technology to better help achieve carbon neutrality goals, and promote sustainable energy development.

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Conflict of interest

The authors declare no competing interest.

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