Carbon Dioxide Geological Utilization and Storage: A Bibliometric and Patent Analysis

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Abstract

Due to the increasing trend of global warming caused by man-made carbon dioxide emissions, people pay more and more attention to this problem. Anthropogenic carbon dioxide emissions have promoted the progress of global carbon use and storage (CUS) projects. Taking Incopat, Scopus and Web of Science databases as data sources, this study identified 1281 patents and 6435 research papers. Using bibliometric methods and knowledge maps, it quantitatively visualized the distribution of research institutions, cooperative research networks, keyword co-occurrence networks and research performance, and showed the current research pattern and future research direction of carbon dioxide geological utilization and storage technology. The results show that:(1) Carbon dioxide geological utilization and storage technology (CGUS) research hotspots mainly focus on CO2 enhanced oil exploitation technology (EOR), CO2 geological storage, CO2 enhanced natural gas, shale gas exploitation (EGR), Ocean storage, and other technologies; (2) Developed countries such as the United States and the United Kingdom have taken the lead in carrying out research on CGUS. China's follow-up research has become an absolute force in global technology research and development, with the highest number of patent applications and academic papers published. However, international cooperation should be further strengthened to improve research performance; (3) At present, the research on carbon dioxide utilization and storage technology is in a period of vigorous development. The research reputation is high, and the research fields show a trend of cross integration, mainly distributed in Environmental Science, geology, energy science and engineering. Finally, research directions of Carbon dioxide geological utilization and storage technology are proposed to provide a reference for future research.

Keywords: *Carbon dioxide utilization; geological storage; bibliometric; patent analysis; research fronts*

1. Introduction

In recent years, the global climate change caused by a large number of greenhouse gas emissions has attracted much attention. Carbon dioxide emission reduction technology, especially carbon dioxide geological storage technology, has attracted more and more attention because of its huge emission reduction potential [8]. However, due to the high cost and uncertainty of long-term geological storage, people are increasingly inclined to include the reuse of carbon dioxide [13]. Therefore, this paper mainly focuses on the analysis and utilization of CGUS technology. By analyzing the mutual penetration and promotion of the two technical fields of carbon dioxide utilization and storage, study the best carbon dioxide emission reduction methods to meet the needs of economy, safety, location-free and environment-friendly, and effectively alleviate the problem of global warming.

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Carbon dioxide geological utilization and storage technology (CGUS) refers to the process of injecting captured CO_2 into deep geological reservoirs through engineering and technical means, improving the recovery rate of valuable products and realizing the long-term isolation of CO_2 from the atmosphere [14]. According to the calculation of overseas research institutions, carbon utilization and storage theoretically has the potential to solve 62% of the global carbon dioxide emissions and has great development potential [12]. In recent years, the research on CO_2 geological utilization and storage technology mainly focuses on CO_2 injection and production optimization, well location optimization and leakage mitigation [9]. How to maximize CO_2 utilization and oil and gas reservoir recovery, maximize economic benefits and maximize buried stock is the direction and problem that still needs to be studied [7].

The existing literature can't fully reveal the development and application trend of carbon dioxide geological utilization and storage technology. Therefore, it is imperative to conduct in-depth and visual research with the help of bibliometric methods. Taking Incopat, Scopus and Web of Science databases as data sources, this paper uses patent analysis methods combined with bibliometrics and knowledge atlas to show the current research trend and future research direction of research institutions, cooperative research networks, keyword co-occurrence networks and research performance.

2. METHODS AND RESULTS

To examine the research landscape of global CO_2 geological utilization and storage, we use the search formula ("CO_2 sequence" or "carbon sequence") and ("geological utilization" or "enhanced oil recovery" or "enhanced geothermal systems" or "enhanced gas recovery" or "enhanced coal bed methane recovery"), and the search date is February 28, 2022. 1281 patent records and 6435 relevant paper records were retrieved to understand the current research status. The research hotspots and development trends were visualized through text clustering and VOSviewer.

3. RESULTS AND DESCUSSION

3.1. Global research hotspots in CGUS

Patent research on CO_2 geological utilization and storage technology has focused on CO_2 enhanced oil exploitation technology (EOR), CO_2 geological storage, CO_2 enhanced natural gas, shale gas exploitation (EGR), CO_2 displacement coalbed methane (ECBM), CO_2 enhanced geothermal system (EGS), CO_2 uranium ore leaching and production increase (EUL) and Ocean storage (Figure. 1).

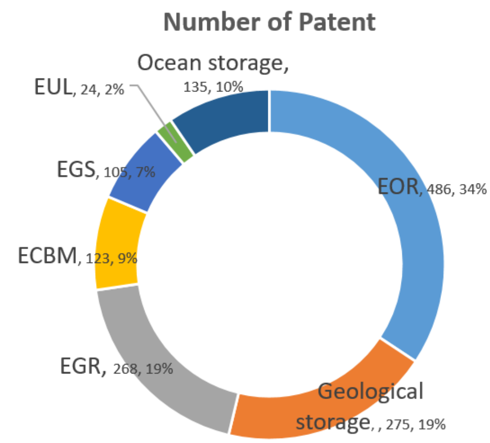

Figure 1 CGUS patent technology area

The word cloud in Figure 2 was extracted using SciVal's Elsevier Fingerprint Engine. This technique uses text mining and natural language processing techniques to extract important keywords from the titles, abstracts, and author keywords of publications in the domain. Each keyword is assigned a relevance between 0 and 1, where the most frequent keywords are assigned as 1. The results are ranked in order of significance. Literature research is basically consistent with the technical focus of the patent application.

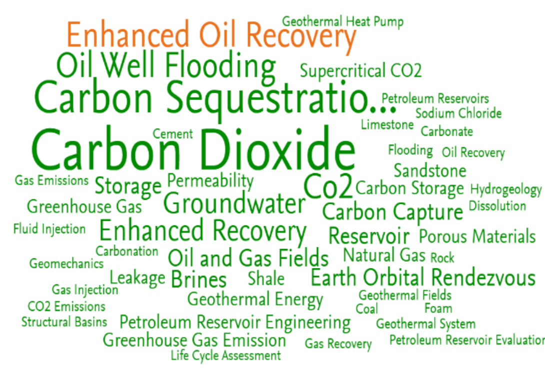

Figure 2 Word cloud of CGUS publications

We further mapped a keywords network visualization graph (Figure 3) based on WOS data in recent ten years, from which the evolutionary timeline of research hotspots in this field can be observed. Carbon dioxide enhanced oil exploitation, enhanced natural gas exploitation, enhanced geothermal system and geological storage technology have become research hotspots in recent ten years, with high technical activity.

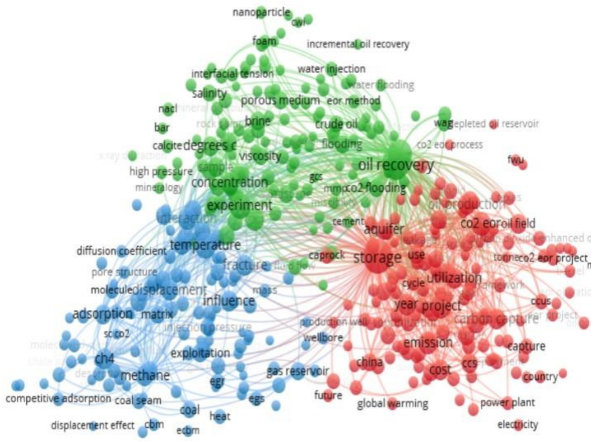

Figure 3 Keywords network visualization of CGUS

Carbon dioxide geological utilization and storage technology first received attention in enhanced oil exploitation. Depleted oil reservoirs have high potential for CO_2 storage, in the 1990s, at least 71 projects in the world used carbon dioxide to drive oil, and further exploitation can be realized by injecting carbon dioxide to replace and dissolve the remaining oil, the remaining oil in the oilfield can be recovered by up to 40%. When oil prices are below $20 a barrel, about half of the flooded oil fields in the United States can be developed profitably by injecting carbon dioxide [blunt, m, 1993] At present, the main research of this technology mainly focuses on the coupling optimization of enhanced oil recovery and carbon dioxide storage capacity. The dynamic simulation of two important processes is carried out at the same time, and the weighted objective function is used for optimization, such as the CO_2 distribution map in the reservoir and the setting of oil wells [10]. In 2019， Dong, XH and Liu, HQ et al. shows that offshore heavy oilfields will be the future exploitation focus, the multicomponent thermal fluids injection process in offshore and the thermal-CO_2 and thermal-chemical (surfactant and foam) processes in onshore heavy oil reservoirs are some of the opportunities identified for the next decade, cost optimization will be the top priority for all the oil companies in the world [4].

Exhausted conventional and unconventional gas reservoirs have large pore space after natural gas exploitation and decompression. In addition, they can store hydrocarbons in sealed reservoirs with impermeable caprocks for many years, providing a safer option than saline or other geological traps. In 2016, Gao, H introduced the latest progress of tight gas sandstone pore structure characterization, permeability measurement technology and tight gas enhanced production technology, and proposed that CO_2 injection into tight gas reservoir is an important technology, which has great potential in improving CH_4 recovery and storing CO_2 into depleted tight gas reservoir [6].

Enhanced geothermal system (EGS) was proposed as a new concept of in 2000, which is, using carbon dioxide instead of water as heat transfer and diversion, Current research was focused on identification of CO_2 behavior within the reservoir during and after injection, namely injection-induced seismicity, potential leakage pathways, and long-term containment complexities associated with CO_2-brine-rock interaction [1].

CO_2 geological sequestration is the most widely used sequestration technology. In this process, CO_2 is stored in geological underground structures such as saline aquifers, depleted oil and gas reservoirs and unmineable coal beds [5] [11] [15] [16]. In 2019, Ajayi, t, Gomes, JS et al. introduced the physical processes involved in geological storage technology, modeling procedures and simulators used, capacity estimation, measurement, monitoring and verification technology, risks and challenges involved, and field/pilot projects. Bachu,S put forward the concept of carbon dioxide storage efficiency in 2015 and discussed several kinds of influencing factors of storage efficiency, which can be used for local scale CO_2 storage estimation [2] [3].

3.2. Status of global academic outputs

Field-Weighted Citation Impact (FWCI, from Scopus) is a metric validated by several studies that can be used to analyze the robustness and research performance of research subjects. When FWCI = 1, it means that publications in the field are cited as the average of similar publications worldwide. FWCI above 1.00 indicates an above-average research performance. As shown in table 1, the overall FWCI of CGUS research is 1.42, indicating that the citation performance of publications in this field is 42% above the global average. Researches showed the research results increased steadily after 2016, from 1456 papers and 4367 authors in year 2016 to 1899 papers and 6456 authors in year 2021, it shows that the geological utilization and storage technology of carbon dioxide has received continuous attention. It is worth noting that FWCI in 2021 is only 1.33, the lowest in recent six years. Due to the short publication time and less citations, FWCI maybe cannot completely objectively reflect the value of publications.

Table 1 Global Overview of Academic Performance

	2016	2017	2018	2019	2020	2021
Publications	1456	1823	1522	1872	1783	1899
FWCI	1.43	1.42	1.44	1.45	1.47	1.33
Authors	4367	5428	5924	6364	6140	6456

According to the Incopat patent data in recent ten years (Figure 4), we have drawn the CGUS patent application trend chart, from which we can see that the global patent application trend is similar to that of China, showing a continuous upward trend. It is worth noting that with Canada's official withdrawal from the “Kyoto Protocol” in 2012, the negative reaction of the United

States and the firm opposition of Russia, Japan and other countries to the second phase of the commitment period of the protocol, global technology research and development began to decline significantly in the following two years. After the "Paris Agreement" was reached in 2015, technology research and development returned to the right track. During this period, Chinese patents sudden rise thanks to policy support, the number of patent applications rose steadily, reaching a peak of 83 in 2021, exceeding 80% of the total global patents in that year, becoming an absolute force driving global technology research and development.

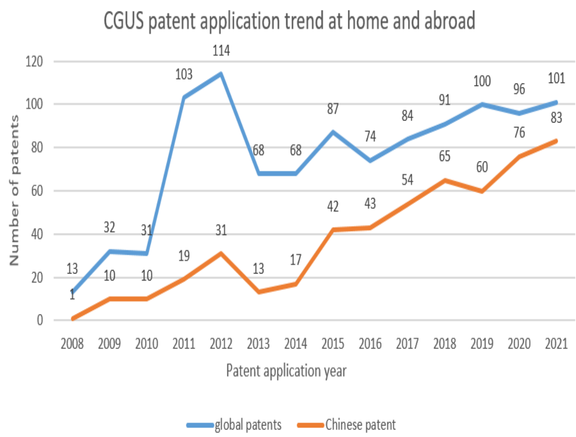

Figure 4 CGUS patent application trend at home and abroad

3.3. *Impact of international collaboration on research performance*

International collaborations, which account for 20.8% of global research, have an FWCI of 3.1, compared to 1.63 for only national publications and 2.02 for only institutional collaboration publications. The FWCI for single authors is the lowest at 1.32 (Table 2). In terms of the citation rate of papers, the average number of citations of articles on international cooperation is 4.14, followed by the papers published by only institutional, with an average number of citations of 2.49, and the average number of citations of articles published by only national is the lowest, with is 1.05. There is no doubt that international collaborations can significantly boost research performance.

Table 2 Global Collaboration and Academic Performance

Collaboration	Share	Publications	Citation	FWCI
International	20.8%	1338	5545	3.1
Only national	25.5%	1640	1714	1.63
Only institutional	26.2%	1686	4197	2.02
Single authorship	3.6%	231	562	1.32

Patents involve technical secrets that are exchanged for technical protection through disclosure. For the sake of the applicant's own interests, there is usually no application for international cooperation. However, we can learn from valuable invalid patents (exceeding the legal protection period) to avoid repeated research, and improve research efficiency

3.4. *Global CGUS country distribution and collaboration network*

In analyzing the overall landscape of CGUS research (Table 3), China has 2678 publications, while the FWCI of only 1.62, The rate of international cooperation is also relatively low (40.9%). The U.S. has 3439 publications, the FWCI is 1.75, The Australia has 688 publications, yet the FWCI is 2.23, the best of all, it may be benefiting from large sedimentary basin in the offshore area, which has good geological conditions for carbon dioxide storage and huge storage capacity. Italy, France and Japan have similar FWCI and publications. Although China is a latecomer in CGUS research, it is making the most rapid progress and has the highest volume of publications, and the quality of publications and international cooperation need to be improved.

Table 3 Ranking of Countries in CGUS Data

Country	Publications	Citations	FWCI	International Collaboration
US	3439	57879	1.75	43.1
China	2678	53314	1.62	40.9
UK	1155	24088	1.69	62.1
Germany	1003	15901	1.44	56.5
Australia	688	18064	2.23	71.9
Canada	657	10509	1.55	64.4
Italy	615	11229	1.69	59.5
France	512	10472	1.81	73.8
Japan	452	7484	1.74	51.3
India	438	6167	1.50	36.3

As mentioned above, international collaboration can significantly improve research performance. So the analysis of international research collaboration networks becomes imperative. As shown in Figure 5, the U.S., the U.K., Australia, Germany and China are at the center of global research collaboration. In terms of research cooperation distances, all countries are relatively distant from each other. China has the most collaboration with the U.S., the U.K., and Japan, among which the collaboration between China and the U.S. has proven effective.

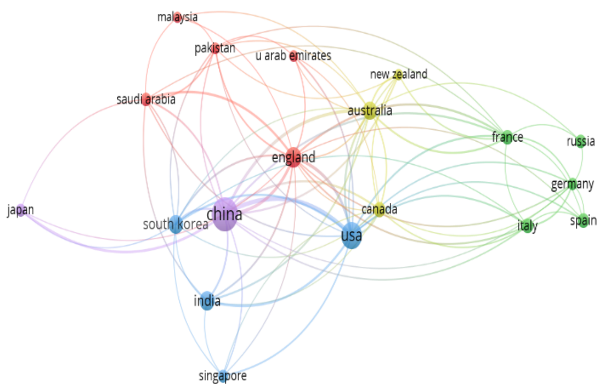

Figure 5 Global collaboration network in CGUS

3.5. Analysis of global publication journals and patent sources

Most of the academic publications on CGUS data are published in journals and conference minutes related to environmental science, geology, energy science, etc. among them, the International Journal of Greenhouse Gas Control has the largest publication volume, with 618 relevant documents, but FWCI is only 0.96. Other major sources of publications include Energy Procedia (363 papers, FWCI = 0.88), Journal of Petroleum Science and Engineering (239,1.45), Science of the Total Environment (188, 1.75), and Journal of Cleaner Production (182, 2.00). Sources with great academic impact but fewer publications include Advanced Materials (28 papers, FWCI = 11.10), SPE Reservoir Evaluation and Engineering (28, 9.76) and Energy and Environmental Science (24, 6.66).

Through the analysis of global patent sources (Figure 6), It can be seen that the main application countries of CGUs patents are China and the United States. In terms of patent applications, the United States has an absolute advantage in strengthening oil exploitation technology and geological storage, and the number of patent applications is far ahead. China has an advantage in strengthening oil exploitation, displacing coalbed methane, and strengthening the exploitation of natural gas and shale gas, with a large number of patents. The UK has advantages in marine carbon dioxide storage technology. Saudi Arabia and Canada as oil producing countries, have more patent applications in strengthening oil exploitation technology. In addition, Japan's patent technology layout is relatively balanced, and all technology branches have corresponding patent layout.

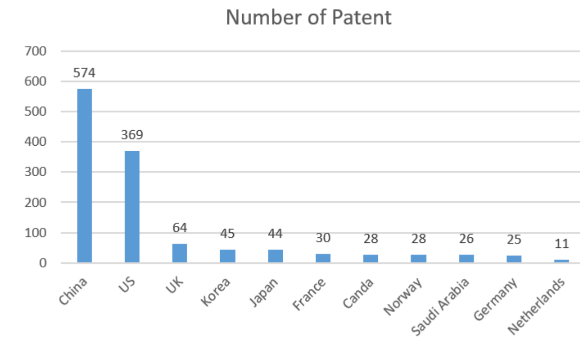

Figure 6 Global patent sources

4. Conclusion

The combination of carbon dioxide geological utilization and storage technology can improve the utilization rate of carbon dioxide and maximize economic benefits, which has great prospects. This technology has the characteristics of long storage time (at least hundreds of years) and minimal impact on the environment. In this paper, we apply various bibliometric and scientific mapping methods to analyze the research performance of CO_2 geological utilization and storage technology, and reveal its knowledge structure, academic prospect and future research direction. We believe that China has become an absolute force driving global technology research, but the quality of research needs to be improved. Development the global scientific community should further strengthen international cooperation to improve research performance, in particular, China, the United States, UK, Australia, South Korea, Japan, Germany and other countries should establish close cooperation networks. At present, the main hot technical fields focus on CO_2 enhanced oil exploitation, CO_2 enhanced natural gas, shale gas exploitation, CO_2 geological storage and marine storage, CO_2 displacement of coalbed methane and others. Further efforts in these research directions are very important to promote the early realization of Carbon Neutrality and Carbon Peak in the world.

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