

## Article

# Analysis of the Current Status and Hot Technologies of Carbon Dioxide Geological Storage

Feiran Wang <sup>2,4</sup>, Gongda Wang <sup>1,3,\*</sup>, Haiyan Wang <sup>1,3,\*</sup>, Huiyong Niu <sup>1,3</sup>, Yue Chen <sup>2</sup>, Xiaoxuan Li <sup>2</sup> and Guchen Niu <sup>2</sup> 

- <sup>1</sup> School of Civil and Resources Engineering, University of Science and Technology Beijing, Beijing 100083, China; niuhuiyong@163.com
- <sup>2</sup> School of Emergency Management and Safety Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China; wangfeiran2003@163.com (F.W.); 18883163779@163.com (Y.C.); 2010150504@student.cumtb.edu.cn (X.L.); nnniu188@163.com (G.N.)
- <sup>3</sup> State Key Laboratory of High-Efficient Mining and Safety of Metal Mines, University of Science and Technology Beijing, Ministry of Education, Beijing 100083, China
- <sup>4</sup> Yantai Laishan Gaoxin Vocational Training School, Yantai 264003, China
- \* Correspondence: wanggongda521@163.com (G.W.); whycumtb@163.com (H.W.)

**Abstract:** Carbon dioxide geological storage is one of the key measures to control and alleviate atmospheric carbon dioxide content. To better grasp the developmental dynamic and trend of carbon dioxide geological storage research over the world, promoting the research of CO<sub>2</sub> storage theory and technology, 5052 related studies published in the past 22 years were collected from the Web Of Science database. The annual published articles on carbon dioxide geological storage research, partnerships, research hotspots, and frontiers were analyzed by using the knowledge map method of article analysis. The results show that the articles on the carbon dioxide geological storage are increasing yearly. The United States, China, and the United Kingdom are the most active countries; meanwhile, Tianfu Xu and Xiaochun Li from China are experts with the most achievements in the field of carbon dioxide geological storage. Although the theoretical and research frameworks for geological storage of CO<sub>2</sub> are abundant, the field of enhanced gas formation recovery, shale gas extraction and subsurface storage, methane reservoirs, and methane adsorption are still challenging frontier science and technology topics.

**Keywords:** carbon dioxide geological storage; knowledge mapping; visual graph; CiteSpace



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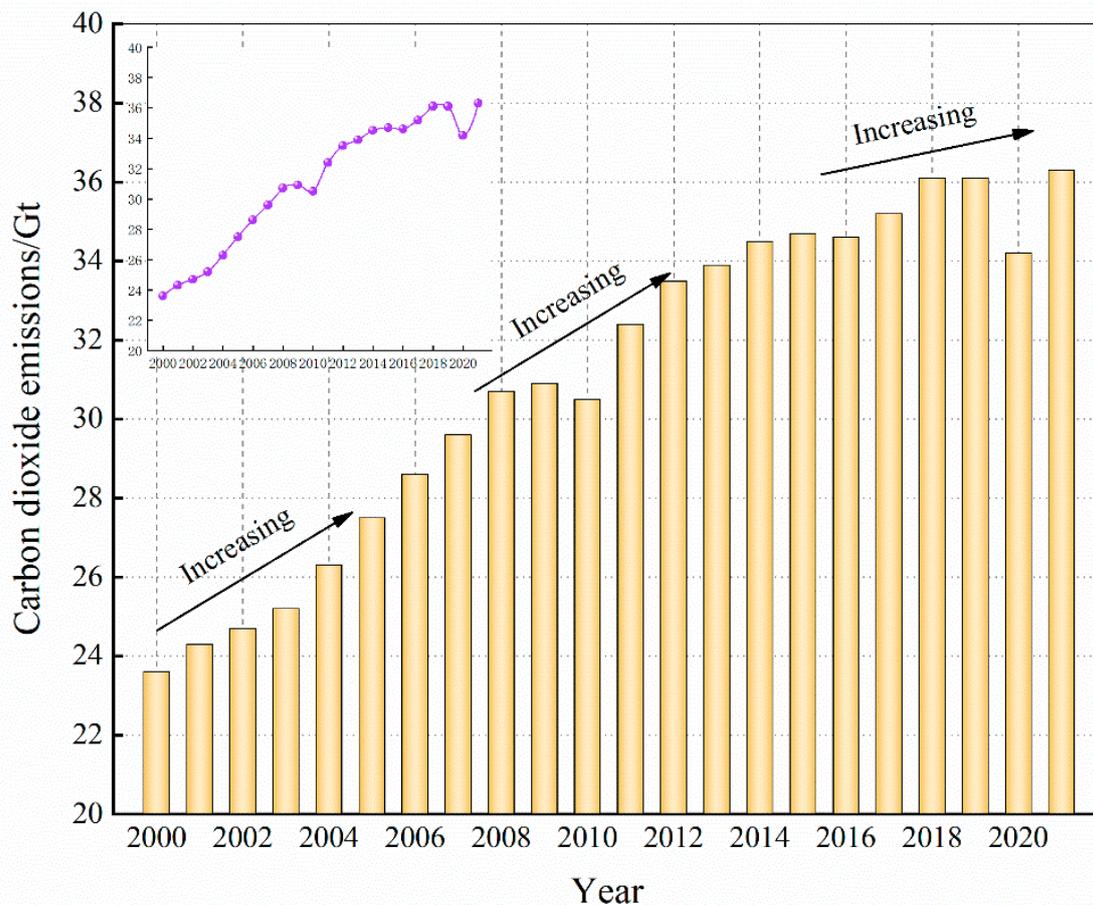
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## 1. Introduction

Global climate change has become a common challenge facing all mankind. The increasing temperature, rising sea level, frequent extreme weather, and climate events caused by climate change have become increasingly prominent issues and have evolved from scientific issues to global economic and political issues. The global average temperature has become about 1.1 °C higher than the pre-industrial level in the past few decades. Climate and environmental problems caused by global warming pose a major threat to the earth's organisms. However, it was not until the 1980s that the problem of global warming, which has its roots in the dramatic increase in atmospheric carbon dioxide emissions, became a widespread concern. In just the last two decades, global CO<sub>2</sub> emissions (see Figure 1) from energy combustion and industrial processes have risen from 23.6 Gt in 2000 to the highest level ever recorded in 2021, pushing emissions to 36.3 Gt [1–3]. Therefore, strong measures must be taken to control the emission of carbon dioxide into the atmosphere to slow down global warming. Under the goal of “coping with climate change and reducing carbon dioxide emissions”, carbon capture, utilization, and storage technology has become a current research hotspot as an important technical way to achieve the large-scale, low-carbon utilization of fossil energy.



**Figure 1.** CO<sub>2</sub> emissions in energy combustion and industrial processes from 2000 to 2021 [1].

CO<sub>2</sub> geological storage technology is used to store CO<sub>2</sub> originally discharged into the atmosphere in the storage geological body in the form of adsorption, free, water-soluble, and mineralized states [4]. It plays an important role in achieving deep CO<sub>2</sub> emission reduction, and this technology is considered to be the “ballast stone” for the fossil energy industry to achieve carbon neutrality. Global carbon dioxide geological utilization and storage technology is the most mature carbon dioxide oil flooding and deep salt water geological storage, and oil flooding projects have been safely put into commercial operation for nearly 50 years. As of the end of 2020, there are currently 26 commercial projects in operation around the world, with a total carbon dioxide capture scale of about 40 million tons/year, mainly including carbon dioxide flooding by oil companies and deep saltwater geological storage. In terms of deep saline reservoir media, as of the end of 2020, there are more than 12 geological storage projects proposed or under construction in the world, or geological storage projects with water displacement concepts, and they are gradually transitioning from small-scale demonstration to large-scale integration projects. In addition, many scholars have carried out research on the environmental risks of carbon dioxide geological storage, monitoring technology, and evaluation of storage sites, providing strong support for the construction of a scientific and sound geological support and safety assurance technology system, as well as carbon capture and storage planning and engineering deployment in the global energy industry. Li et al. [5], Oldenburg et al. [6], Shaw et al. [7], and Thibeau et al. [8] introduced the site selection standard of CO<sub>2</sub> geological storage sites and discussed the research progress of CO<sub>2</sub> geological storage technology; Zong et al. [9] compared and discussed the technical principles of marine storage, geological storage and ore carbonization. Zhao et al. [10] investigated the type of geological storage space and the amount of storage. Liu et al. [11] and Nedopekin et al. [12] conducted a risk assessment for CO<sub>2</sub> geological storage. Bouc et al. [13], Guo et al. [14], Mi et al. [15], and Maneintr

et al. [16] studied the evaluation potential of CO<sub>2</sub> geological storage. Li et al. [17] and Safaei-Farouji et al. [18] researched the technology of CO<sub>2</sub> storage in the underground saltwater layer. The Hydrogeological and Environmental Geological Survey Center of the China Geological Survey of the Ministry of Natural Resources has carried out the whole process research on the geological storage of carbon dioxide from basic theory, site exploration technology and method, completion technology, and perfusion test, safety, and environmental risk assessment, to the later environmental monitoring. Deng et al. [19] discusses the impact of CO<sub>2</sub> geological sequestration leakage on the atmosphere and underground environment as well as the impact on the global energy system. Zhu et al. [20] reviewed the research on key heat and mass transfer issues in the process of CO<sub>2</sub> geological storage and production of tight oil/shale gas/deep geothermal production in recent years by major international and domestic research teams and author research teams. Huang et al. [21] studied the carbonization corrosion of oil well cement caused by CO<sub>2</sub> in CO<sub>2</sub> geological storage. Martinez et al. [22] summarized the current research status of numerical simulation in the mechanical integrity analysis of the cap layer in the storage of the CO<sub>2</sub> saltwater layer. Wang et al. [23] used tNavigator numerical simulation software to study the leakage and migration characteristics of carbon dioxide in the cap layer and established a three-dimensional model. Li et al. [24] established a site uniform heat–water–force coupling model based on the TOUGH-FLAC3D coupling program. Considering the uniformity of pore permeability, the transport behavior of CO<sub>2</sub> in the formation, including the redistribution of effective stress and rock deformation, is analyzed, and a mechanical evaluation of the effectiveness of CO<sub>2</sub> storage at this particular site is provided. Zhang et al. [25] used a simulator connecting TOUGHREACT and FLAC3D to simulate the temperature–hydrologic–mechanical coupling process in geological storage. Although the research literature on CO<sub>2</sub> geological sequestration is extensive, the comprehensive overview and analysis of this field is relatively scarce. Using the powerful CiteSpace 5.8.R3 software tool, this study provides an in-depth visual exploration of the research results in the field of CO<sub>2</sub> geological storage, aiming to clearly delineate the core research focus, future trends, and interaction networks among the leading players in the field.. This not only contributes to a more comprehensive understanding of the knowledge structure and development of the field but also has strategic value and practical significance for promoting the transformation of carbon dioxide geological storage technology from theoretical research to practical application and promoting its industrialization process. By revealing potential research gaps and innovative directions, this study provides a valuable reference for relevant researchers, policymakers and industry practitioners to help achieve more efficient and safe carbon sequestration solutions.

With the rise of knowledge graph visualization technology, this series of problems can be effectively solved. At present, CiteSpace is the mainstream bibliometric drawing tool used, cited, and disseminated in scientific and technological papers, and it is widely used in the field of energy and environmental protection. Mao et al. [26] used CiteSpace to conduct a literature analysis on the research on energy conservation and emission reduction retrieved from the Web of Science core set database. Jiang et al. [27] used CiteSpace to map the knowledge of key research frontier issues of carbon capture utilization and storage (CCUS). Wang et al. [28] summarized carbon capture, utilization, and storage technologies in the carbon neutrality background based on CiteSpace. Qiu et al. [29] studied the carbon capture and storage (CCS) technology knowledge map by CiteSpace, which obtains the main emerging trends in the research field of CCS technology. It includes emerging technologies and processes, emerging materials, technical performance evaluation, and social and economic analysis. Zhong et al. [30] conducted an overview of the LCA (one of the main tools for evaluating carbon footprints) system through CiteSpace. Huang et al. [31] analyzed the global forest carbon sink research trend by CiteSpace. Shao et al. [32] adopted CiteSpace and VOSviewer to conduct coal pores visualization analysis and found that the structural quantity, internal development mechanism, and microchemical evolution of coal pores are the main research trends in this field. Liu et al. [33] used CiteSpace to summarize five

major transportation carbon emission accounting methods. Geng et al. [34] use CiteSpace to conduct an in-depth analysis of carbon neutrality research from multiple perspectives, reveal the current status and hot spots of carbon neutrality research, and predict future research trends. Li et al. [35] refined the research perspective of aviation carbon emissions, providing certain references for the research and development of carbon emissions. Zhang et al. [36] used CiteSpace to analyze relevant literature on carbon neutrality in the past ten years, providing references for energy transition goals, environmental sustainability, and urban development.

Through the above analysis, a large number of scholars have carried out theoretical analysis, numerical simulation, and field test research on the environmental risks, monitoring technology, and storage field of carbon dioxide geological storage, but the following problems have also been exposed: (1) the research content of carbon dioxide geological storage is extensive and diverse, and the research hotspots are also in continuous evolution; (2) while there are numerous literature reviews on CCUS and CCS technologies, there is a scarcity of literature reviews specifically focusing on carbon sequestration within CCUS or CCS; (3) there is a wealth of research on carbon sequestration-related technologies, but there is hardly any literature specifically delving into the topic of carbon sequestration itself; (4) some existing literature reviews on carbon sequestration technology do exist, but this article fills a gap by providing a unique analytical perspective that other articles lack.

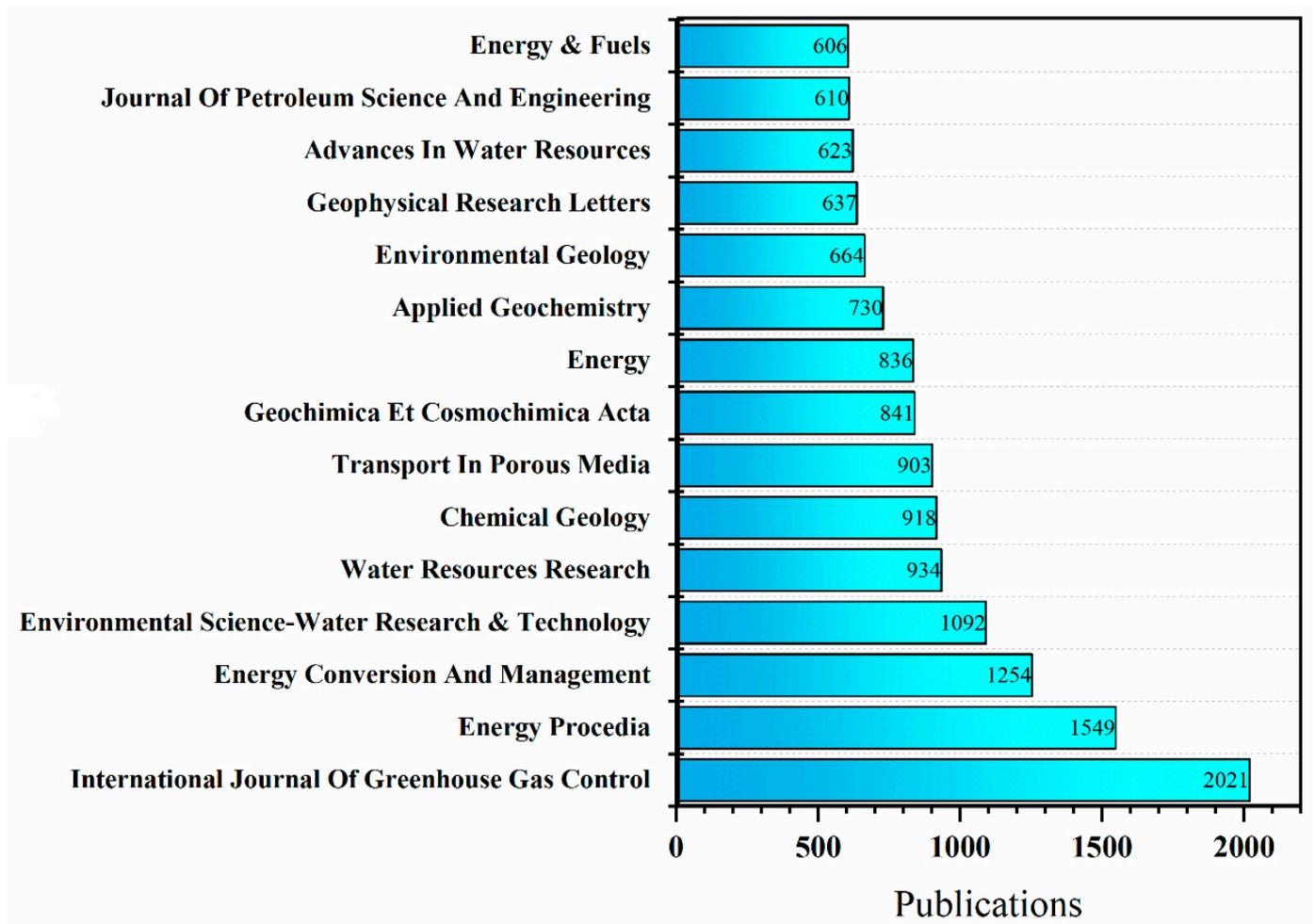
In order to accurately control the research results and research direction in this field, this paper uses the core database of Web of Science as the data source, carries out statistical analysis and data mining on the research literature of carbon dioxide geological storage from 2000 to 2021, and divides it into three parts for special research. The first part provides the analysis of the temporal characteristics of article output; the second part deeply studies the distribution characteristics and research subjects of the literature in the dataset, including the output of authors, institutions, and countries as well as cooperative relations; the third part focuses on the hot frontier shown in the database, tracks these contents, and draws the knowledge map. This paper reveals the track, characteristics and laws of carbon dioxide geological storage research in order to provide a reference and information for the knowledge framework, dynamic change, and development trends within the carbon dioxide geological storage field.

## 2. Data and Method

### 2.1. Data Sources

The research data in this paper come from the Web of Science database, which covers the global natural sciences, engineering and technology, social sciences, arts, and humanities; includes a variety of authoritative and high-impact academic journals in the world; and is the most well-known and widely used database in the world. Across a total of 1036 of the major disciplines in the field of CO<sub>2</sub> geological storage, the citation frequency of the top 15 journals are shown in Figure 2, covering the subject areas of mining, energy, environmental protection, industry, etc. Therefore, the research results of CO<sub>2</sub> geological storage collected by the Web of Science database are very representative, standardized, and authoritative. In this paper, research results on CO<sub>2</sub> geological storage were found in the Web of Science database for the period from 2000 to 2021. During the search, we looked at the definition of CO<sub>2</sub> geological sequestration on Wikipedia, as well as interpretations of the term in different subject areas, plus international translations of CCUS and CCS. In this paper, the high-frequency research term “carbon dioxide geological storage or CO<sub>2</sub> geological storage” was determined. In order to ensure the comprehensiveness and rigor of the dataset in this paper, and to strengthen the objectivity and persuasion of the conclusions of this paper, we read a large number of studies in the literature for verification. Then, using “carbon dioxide geological storage or CO<sub>2</sub> geological storage or carbon dioxide geological sequestration or CO<sub>2</sub> geological sequestration” as the search term, a total of 6061 articles were retrieved. After a preliminary screening, some irrelevant literature, such as editorial materials, conference abstracts, early acquisitions, book chapters, corrections,

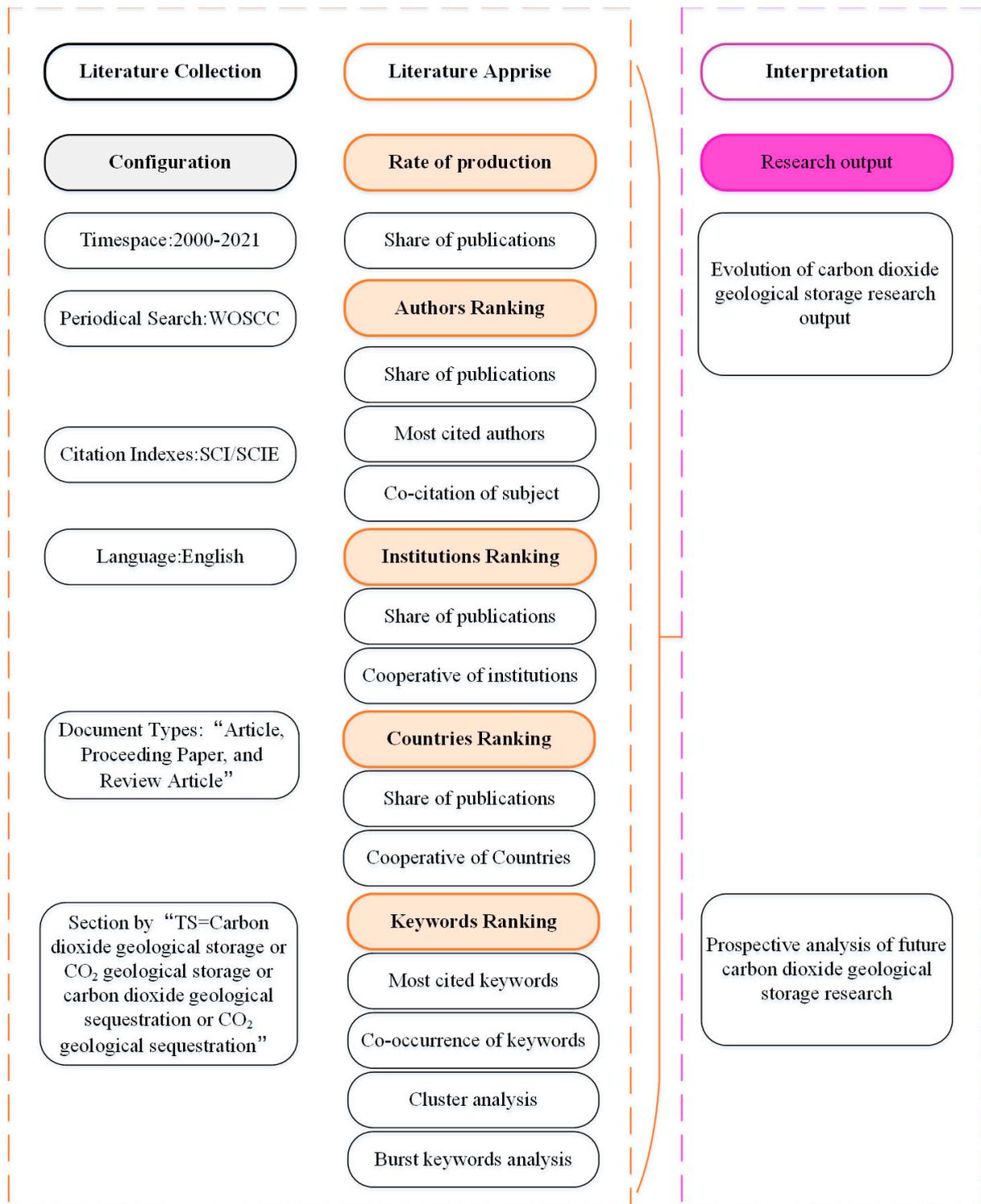
letters, etc., were eliminated, which only briefly mentioned relevant words in the abstract or introduction or reference. Therefore, we set the document types to articles, proceedings, and review articles. After manual screening, the downloaded literature was imported into CiteSpace, and 5052 retrieved studies were selected by software automatic filtering. The retrieval method is shown in Figure 3.



**Figure 2.** Citation frequency of major journals in the field of CO<sub>2</sub> geological storage.

## 2.2. Analysis Method

In this work, knowledge graph visualization analysis of CO<sub>2</sub> geological storage was performed using CiteSpace (version 5.8.R3), which is a scientific literature data mining and visualization analysis software developed by Prof. Chaomei Chen's team based on Java language [37]. The analysis process is based on bibliometrics and analyzed by mathematical and statistical methods through cooperative network topology, keyword co-occurrence analysis, and emergent keyword detection. Utilizing the time and space of research on authors, institutions, countries, and hot frontiers, the distribution information of research results in the field, quantitative relationships and the changing pattern of research trends can be obtained.



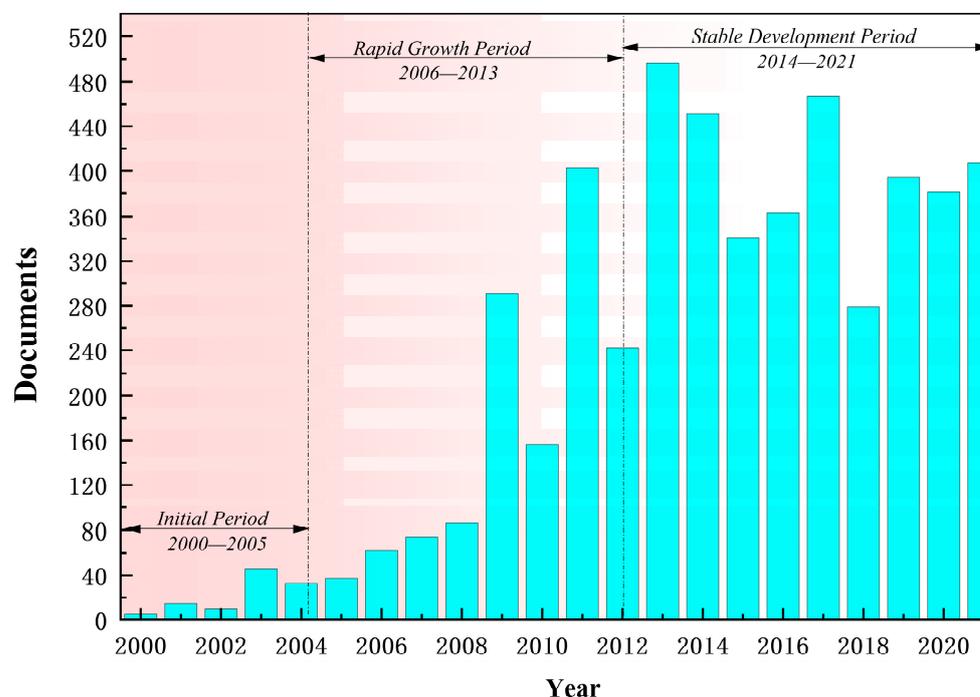
**Figure 3.** Data acquisition methods.

### 3. Results and Analysis

#### 3.1. Annual Publications

The article output reflects the research results and knowledge active degree for a certain discipline. It is reasonable to judge the social and academic circles' importance regarding the research in this field through the time series distribution and cumulative output of the article. The number of research results on CO<sub>2</sub> geological storage is shown in Figure 4. In general, the research on CO<sub>2</sub> geological storage can be roughly divided

into three stages. The percentage of articles issued in the three periods are 2.89%, 35.84%, and 61.27%, respectively, and the number of studies in the literature shows an obvious increasing trend.



**Figure 4.** Temporal distribution of documents from 2000 to 2021.

- (1) Initial stage (2000–2005). The number of published articles increased from 5 in 2000 to 37 in 2005, and the annual average of published articles worldwide was less than 18. At that time, the international community only had the United Nations Framework Convention on Climate Change (UNFCCC), which came into force in 1994 and established the ultimate goal of addressing climate change and the basic principles of international cooperation in addressing climate change, and the Kyoto Agreement, promulgated in December 1997, which limited greenhouse gas emissions in the form of laws and regulations. Developed countries began to take on the obligation to reduce carbon emissions in 2005, while developing countries began to take on the obligation to reduce emissions in 2012. It can be seen that the reason for the lack of research results at this stage may be that countries do not pay enough attention to climate change. The corresponding capital investment, technology development, promotion and application, policies and regulations, institutional settings, and information dissemination have become the factors limiting countries' adaptation to climate change as well as the barriers restricting research on environmental protection.
- (2) Rapid growth stage (2006–2013). The annual published articles in this stage show an increasing trend, rising from 62 in 2006 to 497 in 2013. The annual average number of published articles is 199 with an increase rate 11.7 times than that of the initial stage. The increase in research results shows that countries all over the world pay attention to the environmental consequences caused by carbon emissions, and the direct reason is the carbon emission policies issued by countries all over the world. For example, the European Union [38,39] began to implement the new energy policy in 2007. On June 4, The Outline of The National Medium-Long Term Science Technology Development Plan (2006–2020) issued by China [40] lists the "development of efficient, clean and near-zero CO<sub>2</sub> emission fossil energy development and utilization technologies" as the key research content in the advanced energy field. The Bali Action Plan, formulated in 2007, adheres to addressing climate change under the framework of

sustainable development and puts forward specific targets, ways, and measures for emission reduction. The UK [41,42] introduced laws and regulations related to carbon capture and storage technologies in 2008. The US [43] adopted Clean Energy and Security, which is an incentive system for developing carbon capture and storage technologies. In December 2009, the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) proposed a follow-up target requiring developed countries to reduce their emissions by 40% by 2020 compared with the 1990 base year and to achieve zero emissions (at least a 95% reduction) by 2050. The 2015 Paris Agreement sets out arrangements for global action on climate change after 2020 with the long-term goal of keeping the global average temperature rise below 2 degrees Celsius over pre-industrial times and striving to limit the temperature rise to 1.5 degrees Celsius. Australia [44,45] also established special organizations and financial support to develop carbon storage technologies. Within these framework constraints, many countries around the world are developing various carbon reduction regulations to achieve their own goals. In the context of countries actively responding to protect the environment, research results have shown significant growth.

- (3) Stable development phase (2014–2021). The growth rate of annual publications in this phase has slowed down, but the number of articles is more stable. This may be because the laws and regulations related to CO<sub>2</sub> geological storage, emission reduction, and climate may be more mature, the research incentives in this field are better, and the research results of CO<sub>2</sub> geological storage have been implemented to a certain extent. However, under different geographical conditions and resource endowments, there are differences in the path of energy-clean transformation in different countries, so the number of articles has decreased slightly compared with previous years, but the overall trend remains stable.

### 3.2. Co-Authorship Network

#### 3.2.1. Co-Authorship of Author Analysis

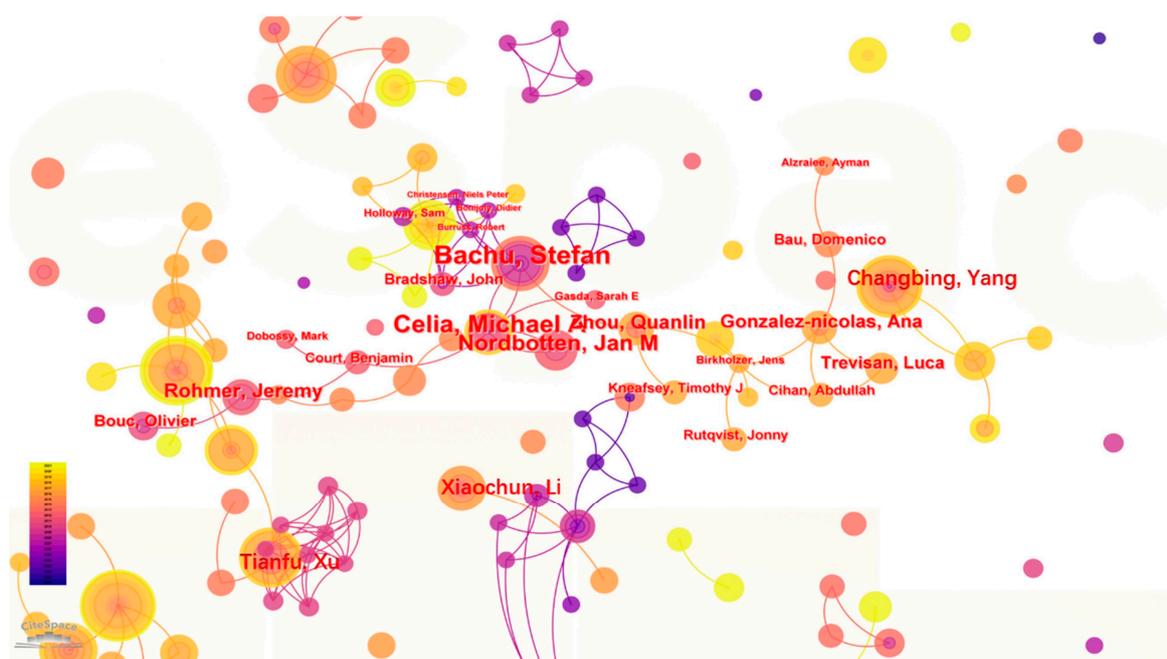
To determine the main authors involved in the study of CO<sub>2</sub> geological storage and their cooperation relationships, the author cooperation maps of “Nodes (representing different authors) = 906” as “Links (representing cooperation between two authors) = 1093” were obtained through software processing, as shown in Figure 5. According to Price’s Law [46] proposed by Derek Price, the specific formula is

$$M = 0.794 \times \sqrt{N_{\max}} \quad (1)$$

where  $M$  represents the minimum number of documents issued by core authors in a certain field, and  $N_{\max}$  represents the maximum number of publications in the field. The minimum number of core author publications in the international research field of CO<sub>2</sub> geological storage calculated by this formula is 6.

According to statistics, 49 authors published at least six articles among 906 authors, accounting for 5.41%. In terms of the number of publications issued, Tianfu Xu has the largest number, 45, and he is an important authority figure in this field. Tianfu Xu, a professor at Jilin University, has made a series of important achievements in the theoretical and simulation research on the coupling of underground multiphase fluid movement and geochemical migration and proposed a new conceptual model that comprehensively reflects geothermal conduction as well as geological, geochemical, and hydrodynamic conditions. A computer program has been independently developed to simulate the coupling process and mechanism of underground multiphase fluid movement and geochemical migration, which has been applied to the geological disposal of CO<sub>2</sub> and nuclear waste, the transport of pollutants, the exploitation and utilization of geothermal energy, etc., and has been increasingly used in petroleum applications. Xiaochun Li is a researcher, doctoral supervisor, and leader of the CO<sub>2</sub> geological storage discipline group at the Hubei Key Laboratory of

Environmental Geotechnical Engineering, Wuhan Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. He focuses on complex or new rock engineering such as high steep slopes, large-depth underground engineering, and CO<sub>2</sub> geological storage. Prof. Xiaochun Li has long been engaged in the research of rock reactions and the auto-flow-mechanics coupling process. Qi Li also from the Hubei Key Laboratory of Environmental Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, is mainly engaged in research on energy, environment, and water resources related to energy and waste underground storage, especially in acid gas reinjection (sulfur carbon combined geological storage) and carbon dioxide (CO<sub>2</sub>) geological utilization and storage (CCUS). His main research fields include elastic wave velocity imaging and the acoustic emission localization of acid gas core displacement, optical fiber monitoring technology and analysis methods for the sedimentary rock seepage process, numerical description and process simulation of chemical-mechanical coupling, site selection of energy and waste underground storage sites, environmental geological risk, and assessment of carbon dioxide/methane/hydrogen sulfide leakage, utilizing the China CCUS Technology Surgical roadmap and ISO-TC265 cross problem. Table 1 shows the top 15 highly productive authors with more than six publications. The data show that these authors are important scholars in this field and have laid a good research foundation. However, all of the authors' centrality indexes are in the minimal range of 0.00 to 0.01, and the majority have a centrality index of 0. This shows that most of the results of the current research are not highly influential.



**Figure 5.** Author collaboration map. (a) The darker the color, the earlier the vintage.

From the analysis of the tightness and sparsity of node distribution, nodes in the graph are scattered. Among the key high-yield authors, Bachu and Celia are distributed in the center of the graph, and their centrality ranks first among the high-yield authors. Bachu, Celia, Bonijoly, Didier, Christensen, Niels Peter, Bradshaw, Burruss, Quanlin, and Zhou had relatively close academic cooperation, with a close distribution of nodes and thick connections, indicating that the international cooperation network had taken shape, while the domestic teams led by Tianfu, Xu, Xiaochun, Li, Changbing, and Yang were scattered in the lower left and lower right corners of the graph, respectively. They still lack scientific influence among high-yield authors. Although the cooperation teams of Tianfu and Xu are more closely related, the node size shows that their cooperation teams are not the high-yield core authors in this field, which will affect the team's scientific research ability and the number of published papers as well as also limit their cooperation with

international high-yield authors. Regarding author cooperation, authors should develop outwardly and inwardly, expand outwardly to form a broader network of cooperative relations, strengthen core cooperation inwardly, and form a closer network of cooperative relations from two aspects, so as to have more development opportunities and broader space for development in the international community.

**Table 1.** Statistics of core authors in the field of carbon dioxide geological storage.

| Serial Number | Publications | Centrality | Author                |
|---------------|--------------|------------|-----------------------|
| 1             | 45           | 0          | Tianfu, Xu            |
| 2             | 36           | 0          | Xiaochun, Li          |
| 3             | 34           | 0          | Qi, Li                |
| 4             | 30           | 0          | Yongchen, Song        |
| 5             | 29           | 0          | Ziqiu, Xue            |
| 6             | 23           | 0          | Kempka, Thomas        |
| 7             | 23           | 0.01       | Bachu, Stefan         |
| 8             | 21           | 0          | Iglauer, Stefan       |
| 9             | 20           | 0          | Lanlan, Jiang         |
| 10            | 18           | 0.01       | Celia, Michael A      |
| 11            | 16           | 0          | Niemi, Auli           |
| 12            | 16           | 0          | Yu, Liu               |
| 13            | 14           | 0          | Bryant, Steven L      |
| 14            | 14           | 0          | Bachu, S              |
| 15            | 13           | 0          | Shariatipour, Seyed M |

### 3.2.2. Co-Authorship of Institutions Analysis

Institutions are the disciplinary research resources and professional concentration that have a certain academic influence on the discipline [47]. According to the formula (1), the M value in this study is 16.25, so the minimum number of publications by the core institution is 17. Therefore, it can be concluded that among the 508 global institutions covered in the collected literature, 103 are high-yield institutions, accounting for 20.48% of the total. Table 2 shows the top 20 high-yield institutions with more than 10 publications. Figure 6 shows the published statistics of the top 20 high-productivity organizations in the past 10 years.

**Table 2.** Statistics of core institutions in the field of carbon dioxide geological storage.

| Serial Number | Publications | Centrality | Institution                | Country   |
|---------------|--------------|------------|----------------------------|-----------|
| 1             | 419          | 0.29       | Univ Texas Austin          | America   |
| 2             | 208          | 0          | Chinese Acad Sci           | China     |
| 3             | 201          | 0.22       | Univ Calif Berkeley        | America   |
| 4             | 170          | 0.06       | Univ Edinburgh             | Britain   |
| 5             | 169          | 0.49       | China Univ Min & Technol   | China     |
| 6             | 169          | 0.46       | British Geol Survey        | Britain   |
| 7             | 149          | 0.13       | Univ Calgary               | Canada    |
| 8             | 142          | 0.46       | Jilin Univ                 | China     |
| 9             | 128          | 0.31       | Univ Bergen                | Norway    |
| 10            | 126          | 0.1        | China Univ Geosci          | China     |
| 11            | 125          | 0.23       | Pacific NW Natl Lab        | America   |
| 12            | 124          | 0.09       | Heriot Watt Univ           | Britain   |
| 13            | 124          | 0.11       | Curtin Univ                | Singapore |
| 14            | 124          | 0.05       | Univ Cambridge             | America   |
| 15            | 104          | 0.05       | China Univ Petr            | China     |
| 16            | 103          | 0.05       | Stanford Univ              | America   |
| 17            | 99           | 0.02       | Princeton Univ             | America   |
| 18            | 99           | 0.17       | China Univ Petr East China | China     |
| 19            | 97           | 0          | Lawrence Berkeley Natl Lab | America   |
| 20            | 96           | 0          | Uppsala Univ               | Sweden    |

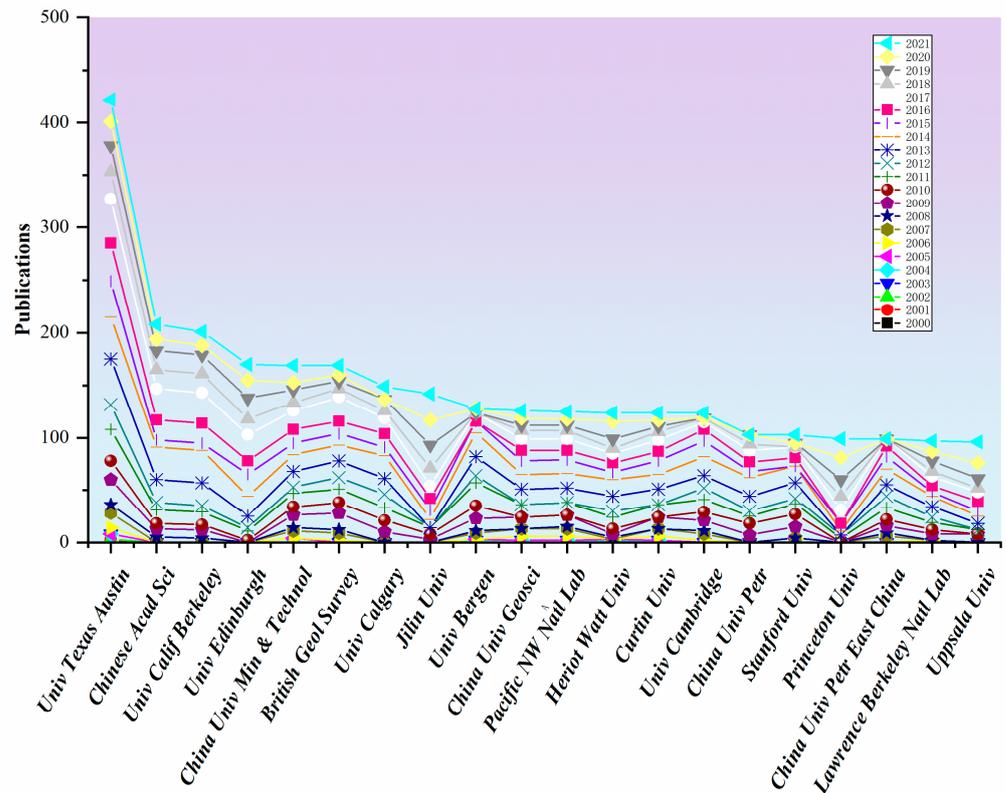


Figure 6. Statistics of top 5 core institutions.

As shown in Figure 7, universities and their affiliated scientific research institutions are the main research positions in the field of carbon dioxide geological storage. At the level of institutional cooperation, the 508 institutions obtained have 1540 linkage relationships, and the number of linkages between nodes can measure the affinity of institutions.

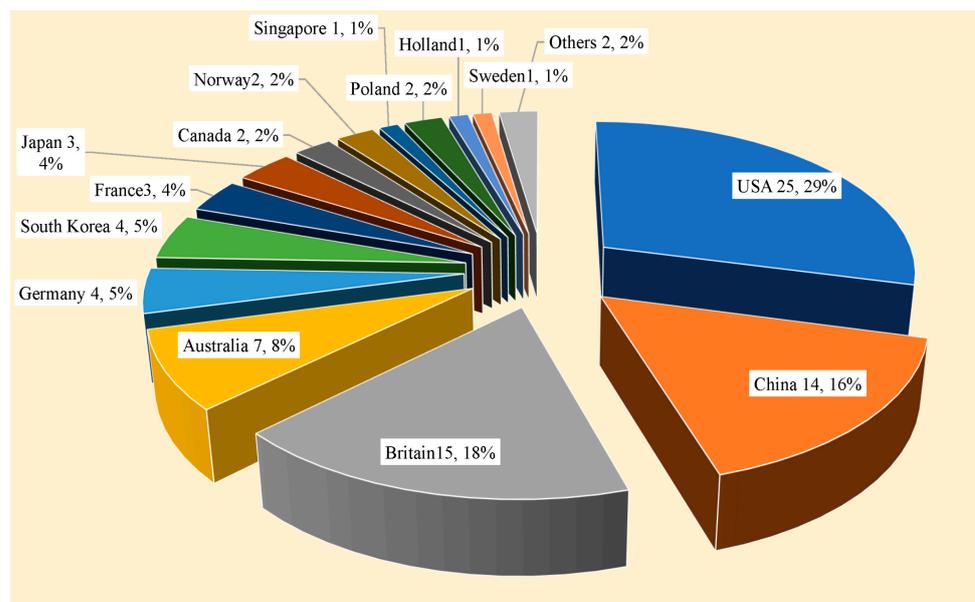


Figure 7. Cooperation map of institutions. (a) The more links there are, the more frequent the inter-institutional partnerships are. (b) The thicker the line, the closer the cooperation between the institutions. (c) The darker the color, the earlier the vintage.

Institutions such as the China University of Mining and Technology, Tsinghua University, the University of Edinburgh, the University of California at Berkeley, and Stanford University are major research centers, and they have close collaborative relationships with many other institutions. These large nodes indicate a relatively high level of research activity in the field and also imply a high level of influence in the field. The University of Texas at Austin has collaborations with eight institutions including Intelligent Opt Syst Inc, Georgia Institute of Technology, Texas A&M University, and Seoul National University [48–52]. The Chinese Academy of Sciences has frequent collaborations with the University of Chinese Academy of Sciences and Ibaraki University [53–55]. UC Berkeley works closely with Reykjavik Energy, Yveland University and CSIRO Petroleum [56–59]. By looking at the color of the nodes, you can see that certain institutions show different levels of activity at different times. For example, some institutions are more active in the early stages and less active in the later stages, and vice versa. This may reflect shifts in research priorities or changes in the allocation of resources. In addition, as the research progresses, new models of cooperation may emerge, and old models of cooperation may change. There are several typical clusters of institutional collaborations, which are analyzed in depth to reveal successful experiences, problems faced, and contributions to the field as a whole. For example, the cooperation between several Chinese universities and the China National Petroleum Corporation and China Petroleum and Chemical Corporation shows the close collaboration between industry and academia, which is crucial for the research and development and practical application of new technologies.

As can be seen in Figure 7, the high-producing institutions are also the central nodes of the collaborative network of high-quality papers. From the perspective of cooperation relationships, the formation of a cooperative institutional network is generally dominated by different colleges or institutions within the same university or different universities in the same city, and the cooperation of transnational, inter-regional and inter-disciplinary institutions is relatively rare. Thus, it seems that the collaboration among research members in the field of CO<sub>2</sub> geological storage is not strong, but there are collaborative teams with internal members mainly from the same institution. There is less collaborative research across institutions, and cooperation and cross-citation among authors are weak. The reasons for the confining cooperation are often various factors such as the research field, research orientation, working mode, and geographical location. This also indicates that although international research in the field of CO<sub>2</sub> geological storage has achieved a certain development, space in knowledge integration and joint in-depth exploration still exists for further cooperation among research institutions.

In Figure 7, it is worth noting that the high-yield institute mechanism includes 25 American institutions such as the University of Texas at Austin, University of California at Berkeley, Pacific NW National Lab, University of Cambridge, Stanford University, Lawrence Berkeley National Lab, Princeton University, etc. There are 15 British institutions such as the University of Edinburgh, British Geological Survey, Heriot Watt University, University of London Imperial Coll Science Technology & Med, etc. There are also 14 Chinese institutions such as the Chinese Academy of Sciences, China University of Mining & Technology, Jilin University, China University of Petroleum, etc. It is found that high-yielding institutions in the United States, the United Kingdom, and China account for 63%. It indicates that these three countries take the lead in the research of CO<sub>2</sub> geological storage in the world. The specific geographical distribution of each institution is shown in Figure 8.



**Figure 8.** Analysis of regional distribution proportion of institutions.

### 3.2.3. Co-Authorship of Countries Analysis

According to Formula (1), among 87 countries, countries with more than 30 papers are defined as high-yield countries. In terms of the article number published by national authors, the USA and China rank first and second with 1367 and 922, respectively. Figure 9 shows the number of articles they have published over the past two decades. These research achievements and attention in the carbon dioxide geological storage field far exceed those of other countries. In this area, they have important and outstanding scholars and researchers, which has laid a good foundation for the developments in this area. It is followed by England (587), Australia (406), France (465), Germany (367), Canada (341), Norway (269), Japan (266), Scotland (233), the Netherlands (183), Spain (165), etc. They also play an important role in the carbon dioxide geological storage. Denmark (0.75), Norway (0.57), Romania (0.46), Italy (0.42), Brazil (0.40), and Malaysia (0.40) have centrality index values greater than 0.4. It shows that these countries have a great influence on this research field and form an influential bridge role. From a geographical point of view, the core countries are mostly the United States, China and northern Europe. These countries tend to be good models of economic, scientific, and cultural power, and its impact will also radiate to neighboring countries as carbon storage research output increases.

Figures 10 and 11 show the map of national cooperation. It can be seen from the maps and data that the cooperation among countries in the field of CO<sub>2</sub> geological storage can be divided into two parts. The first part is represented by the United States. The characteristic is a large number of cooperative countries and rough relations, but most of them are single-line cooperation without forming a complete cooperation network. It is reflected in the cooperation between the United States and Australia, Turkey, Iceland and South Korea. The second part is represented by Germany, France and Canada. The center cooperation is relatively close, but the edge is still dominated by linear cooperation, which lacks a complete cooperation network. The few cooperative publications between the two parts indicates that cooperation between countries is not close and the cooperative network is still in its infancy. Therefore, the stable cooperation relationship should be strengthened in the central part, while the linear cooperation in the edge should be closer to the center in order to strengthen the cooperation between nodes and form a closer cooperative relationship. More direct cooperation should be established between centers to strengthen marginal cooperation. Only in this way can countries cooperate more closely in the carbon dioxide geological storage field. Thus, there are more development opportunities and a broader space for development.

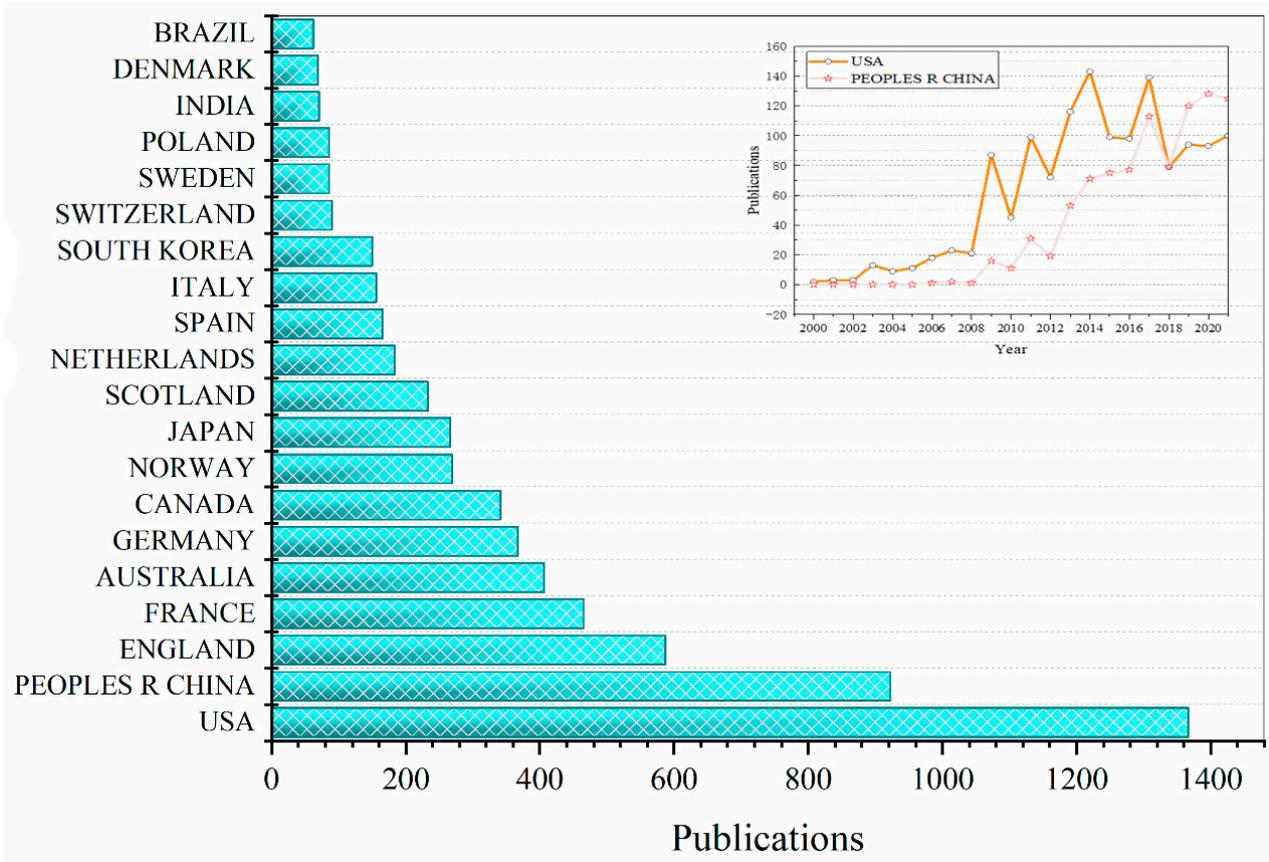


Figure 9. Publication volume analysis of high-yield countries.

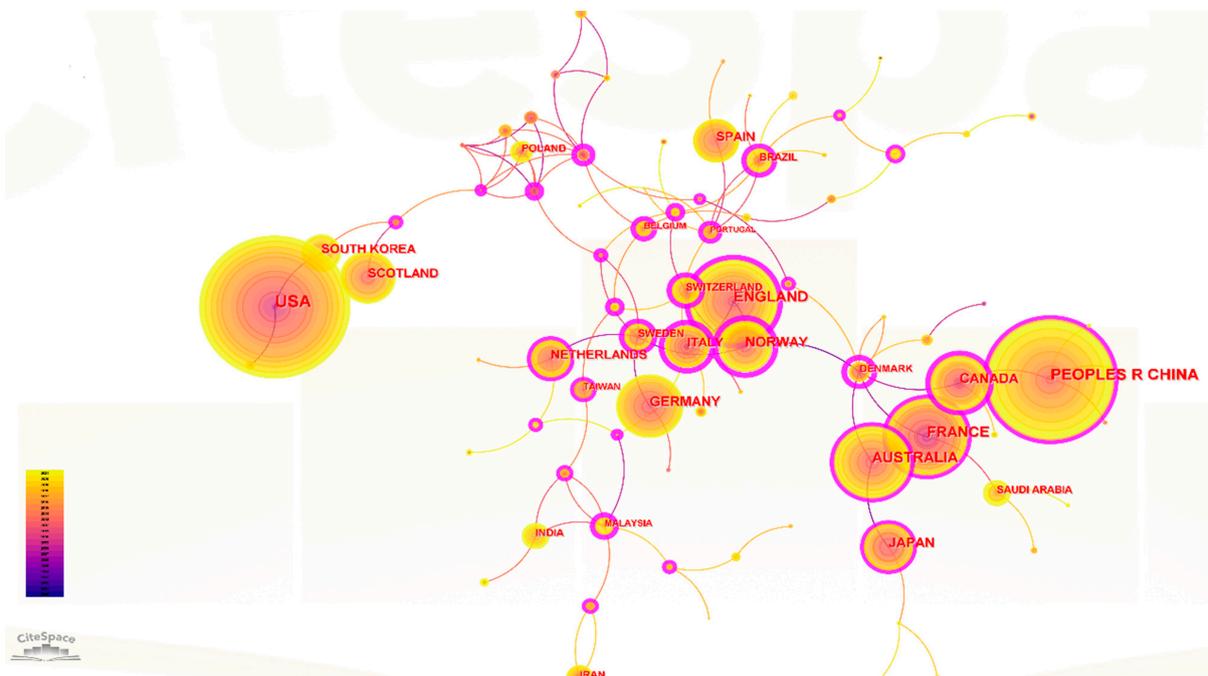
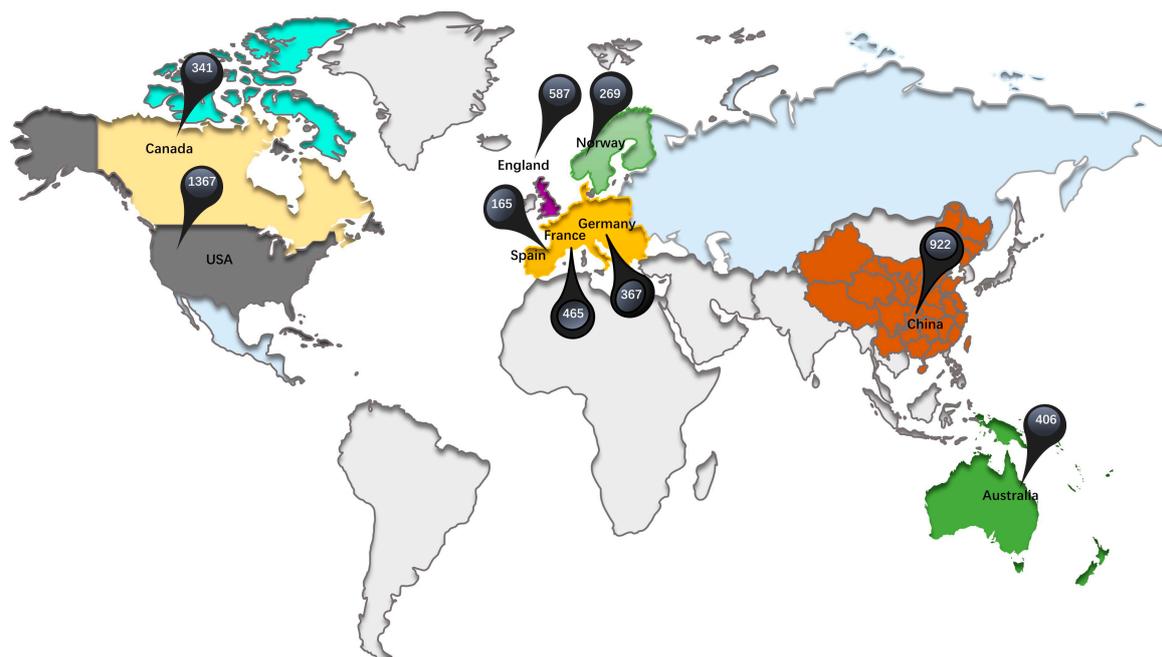


Figure 10. National cooperation map. (a) The more lines that are connected, the more frequent the cooperative relations between countries. (b) The thicker the line, the closer the cooperation between countries. (c) The darker the color, the earlier the vintage.



**Figure 11.** Geospatial visualization map. (Note: This image is a simplified version of the world map and simply shows the location of countries.)

With the passage of time, the international cooperation pattern has shown a dynamic development trend, and countries continue to expand their diplomatic tentacles on the basis of their existing cooperation frameworks and include new partners. This process has not only deepened the closeness of old alliances but also led to the creation of new ones, thus weaving a more complex and geographical network of international cooperation. Countries no longer adhere to the traditional bilateral or limited multilateral cooperation mode but rather actively explore trans-regional and cross-cultural multidimensional cooperation paths, aiming at jointly addressing global challenges and sharing the fruits of scientific and technological innovation and economic development. The establishment of these new partnerships marks a more solid step by the international community in pursuing the Sustainable Development Goals and lays the foundation for building a more balanced and inclusive global governance system.

### 3.3. Co-Occurrence Network of Keywords

Keywords are the most representative field terms chosen by the author for the completed scholarship and reflect the focus of the research results. Keyword frequency analysis is the statistical data given by the authors on the frequency of occurrence of the same keyword. The higher the frequency of the words, the more the research field pays attention to the keywords. The co-occurrence analysis of keywords is a statistical analysis of the frequency of occurrence of author keywords in pairs. The more frequently a keyword pair appears, the higher the original similarity of the two keywords. A clustering algorithm is used in CiteSpace to further normalize the co-occurrence intensity. The analysis of word frequency and keyword co-occurrence in academic papers can objectively and accurately reflect the distribution structure of hot topics and themes in the research field. The co-occurrence network of keywords obtained using CiteSpace for the CO<sub>2</sub> geological storage study is shown in Figure 12.

In Figure 12, “CO<sub>2</sub>”, “storage”, “storage”, “injection”, “simulation”, “geological storage”, “reservoir”, and “leakage” appear more frequently in the field of CO<sub>2</sub> geological storage. The high-frequency keywords reflect that the primary and most important risk factor for CO<sub>2</sub> geological storage is leakage, and most simulation and monitoring studies conducted during the development, implementation, and monitoring phases of CO<sub>2</sub> storage



main clusters, as shown in Figure 13. The clustering module value (Modularity,  $Q > 0.3$ ) and the average silhouette degree (Weighted Mean Silhouette,  $S > 0.7$ ) reflect the clarity of the keyword clustering boundary and the clustering scale, respectively. In the map, Modularity  $Q = 0.8302$ , Weighted Mean Silhouette  $S = 0.9409$ , indicating that all 10 clusters passed the clustering test, and the clustering structure was significant. The CO<sub>2</sub> storage potential of the sequestering geologic body is influenced by its scale, sealing property, burial depth, porosity, permeability, temperature, pressure, ground stress, hydrology and other geological conditions, as well as technical, economic, and policy measures, which is highly consistent with the current clustering results.

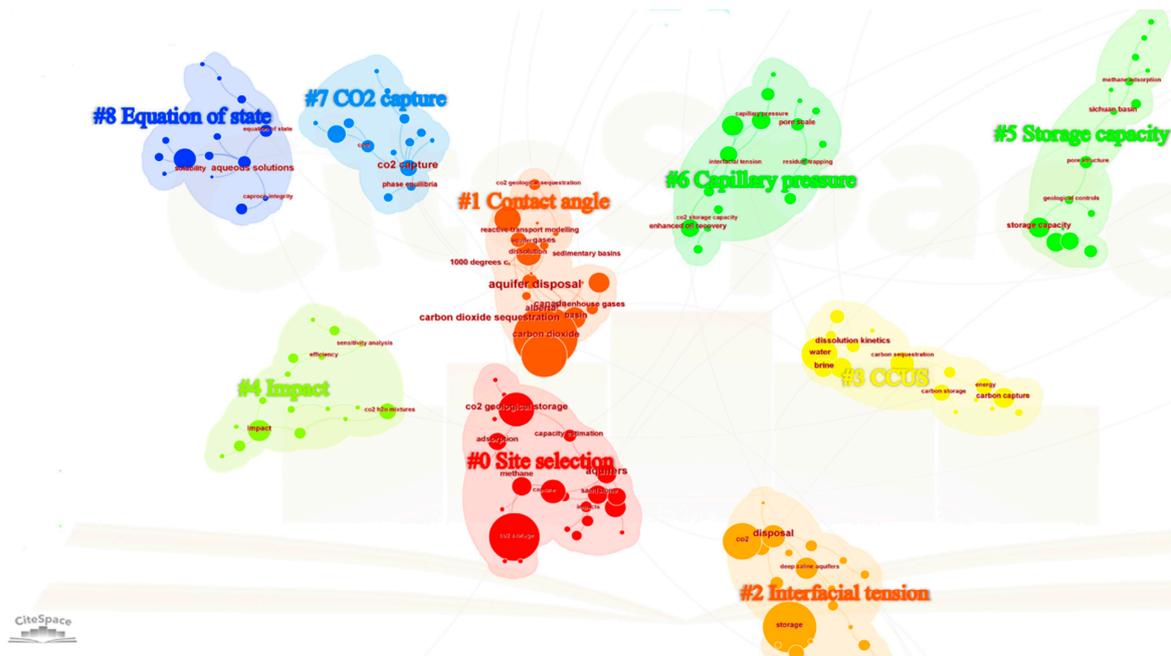


Figure 13. Keyword clustering analysis.

In Figure 13, Cluster 1 (red) is the #0 site, and the red cluster is focused on “storage”, “geologic media”, “and climate change”, which show that the siting studies of CO<sub>2</sub> geological storage are mainly focused on stratigraphic media and climate [67–70]. The quality factor of the formation media is influenced by the structural characteristics, porosity, permeability and saturation of the formation at the time of fracturing. Therefore, the estimate of this value can be used to predict the extent and effectiveness of fracturing. The study of stratigraphic media is closely related to CO<sub>2</sub> geological storage, as the decay of stratigraphic media mass coefficients has yielded important results in detecting CO<sub>2</sub> storage.

In Figure 13, Cluster 2 (orange) is the #1 contact angle, and the orange cluster is centered around “pressure”, “kinetics”, “silicon surface”, and “multiphase flow rotation”. Among the high-frequency keywords, “stress” appears with high centeredness, indicating that safety and long-term storage are of particular concern as the carbon storage project proceeds. In addition, the issue of how to monitor the subsurface migration and leakage of CO<sub>2</sub> is very important for the effectiveness of CO<sub>2</sub> storage [71–73]. Another high-frequency keyword that appears is “kinetics”, indicating that the reaction kinetics of hydromagnesite based on CO<sub>2</sub> storage is gradually attracting attention to CO<sub>2</sub> mineral storage with circulating ammonium chloride solution as an intermediate. The new process systematically studied the kinetics of the fluid–solid two-phase reaction of hydromagnesite in ammonium chloride solution. It is committed to solving two major problems that have been affecting the development of CO<sub>2</sub> mineral storage, which are the slow mineral dissolution rate and difficult recovery of dissolved media [74,75].

In Figure 13, Cluster 3 (yellow) is the #2 interfacial tension, swelling around “capillary pressure”, “temperature conditions”, “free energy” and “molecular dynamics simula-

tions” [76–78]. The term comes about because the injection and subsequent stages of CO<sub>2</sub> involve many physical processes, and capture in CO<sub>2</sub> aquifers benefits from three physical processes: buoyancy, viscous, and capillary forces. Among them, temperature condition is a high-frequency keyword for high centeredness, indicating that the research on the effect of interfacial tension on CO<sub>2</sub> geological sealing is mainly focused on temperature conditions and other aspects. For example, when studying the effect of CO<sub>2</sub>, the study of filler in the physical and chemical properties of natural spring water in the Wudalianchi area has a significant effect on the water quality indicators of natural spring water, which can increase the surface tension of carbonated water [79].

### 3.4. Frontal Analysis

By using the mutation detection technology and algorithm provided by CiteSpace 5.8.R3 software, the mutation words with high-frequency change rates are detected from a large number of subject words by studying the time distribution of word frequency, and the frontier field and trend of CO<sub>2</sub> geological storage research are determined. The specific parameters are  $\alpha_1/\alpha_0 = 2$ ,  $\alpha_i/\alpha_{i-1} = 2$ . A specific value is assigned to the key parameter  $\gamma$  in the mutation word analysis, that is,  $\gamma = 0.7$ , and the state and minimum duration are set as 2 and 4, respectively, as shown in Figure 14. In the figure, Keywords stands for highlighted keywords; Year stands for the event that the keyword appears; Strength stands for the prominence intensity of the keyword, the higher the intensity, the greater the influence; and Begin and End represent the start and end time of the keyword prominence, respectively.

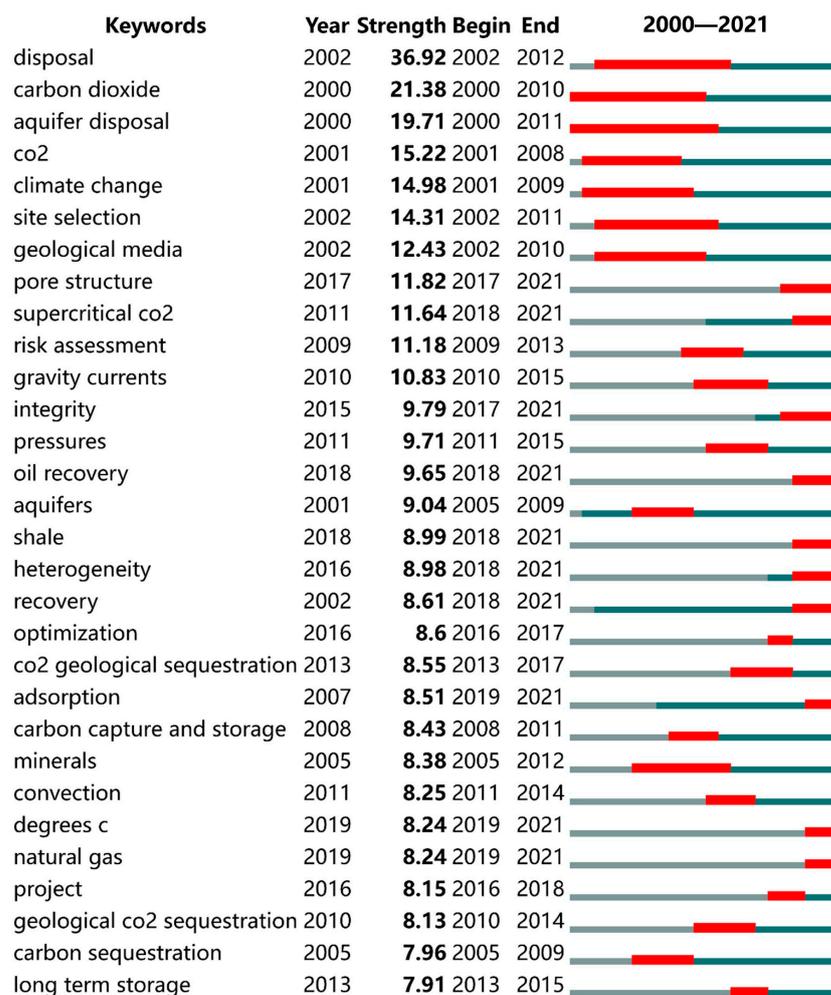


Figure 14. Top 30 keywords with the strongest citation bursts.

The top 30 highlighted words are shown in Figure 14, and the highest highlighted word are “disposal, carbon dioxide and aquifer disposal”, which indicate that the injection of CO<sub>2</sub> into the brackish water layer has been a hot research issue in the field of CO<sub>2</sub> geological storage. This direction focuses on the study of CO<sub>2</sub> transport in the subsurface brackish water layer, the analysis and evaluation of the geological conditions of the subsurface brackish water layer, and the estimation of CO<sub>2</sub> storage capacity. For example, Yamamoto et al. [80] developed a two-dimensional reactive transport model for long-term CO<sub>2</sub> geological storage, Bachu et al. [81] studied the injection of deep saline aquifers and storage in salt caverns, and Damen et al. [82] assessed the risk posed by subsurface CO<sub>2</sub> storage (CO<sub>2</sub> and CH<sub>4</sub> leakage, seismicity, ground motion, and brine displacement).

In terms of emergence time, research in the field of CO<sub>2</sub> geological storage has seen a large number of emergent terms between 2000 and 2012. Examples include “aquifer disposal”, “site selection”, “climate change”, “geologic media”, “aqueous solutions”, “carbon capture and storage”, “risk assessment”, etc. [83–90]. This period is an important time for CO<sub>2</sub> geological storage research. Global scholars have dedicated their research to focus on climate, environment, geology, carbon dioxide, and coal mining. The objects, contents, and directions of research are diverse, and the number of articles is increasing, particularly from 2012 to 2016, featuring research on sedimentary basins, pure water, rates, convection, geological storage, freshwater resources, ocean acidification, and potential impacts. This indicates that the research objects and research directions have changed, mainly focusing on waters, oceans, and gas convection, and the research forms have become more diversified. After 2016, scholars conducted more and more perfect research on the content, methods, and objects of CO<sub>2</sub> geological storage, based on which “supercritical CO<sub>2</sub>”, “pore structure”, “oil recovery”, “shale”, and “methane” will be the frontier buzzwords for future research. The research hotspots surrounding the above keywords include the influence of the CO<sub>2</sub>–rock–water interaction on the safety of CO<sub>2</sub> storage, the combined storage of CO<sub>2</sub> and enhanced oil recovery, the adsorption/desorption of CO<sub>2</sub> after entering the coal seam, the expansion/contraction of coal, and the change in permeability.

#### 4. Conclusions

CO<sub>2</sub> geological storage is one of the technologies to effectively mitigate global carbon emissions. It is of great significance to master the research hotspots and development trends in this field for the sustainable development of the energy and environment industry. The paper provides valuable information to experts and scholars studying CO<sub>2</sub> geological storage, helping researchers reduce the time spent developing research questions for empirical articles, conducting bibliometric analyses, or conducting content analyses for systematic literature reviews. On the other hand, it helps to seek the latest information on the storage potential, risk assessment, and geological conditions of the storage geological body (size, sealing, burial depth, porosity, permeability, temperature, pressure, ground stress, hydrology, etc.) and other current research and future trends in the field of carbon dioxide geological storage.

- (1) Based on the analysis of the research results of carbon dioxide geological storage in the past 20 years (2000–2021), the published papers are divided into three periods: the initial period (2000–2005), the rapid growth period (2006–2013), and the stable development period (2014–2021). Overall, the number of articles on CO<sub>2</sub> geological sequestration published by countries around the world is on the rise.
- (2) Countries with the richest research achievements are the United States, China, and the United Kingdom through the analysis of research subjects (authors, institutions, and countries). It mainly concentrates on the University of Texas at Austin, Chinese Academy of Sciences, University of Edinburgh, and other institutions. They form cooperative networks with Stefan Bachu and Michael A Celia as the center and radiating to the outside. The contact between authors is limited by region, economy, culture, and other aspects. Moreover, there is little cooperation between eastern and

western countries. Most of the cooperation is between the core institutions in some major scientific research countries.

- (3) Through the analysis of hot research keywords and research frontiers, we found that the research fields of CO<sub>2</sub> geological storage mainly focus on climate, environment, geology, and coal mining, and the research contents mainly focus on rock siting, deep brine CO<sub>2</sub> injection, geological storage temperature, porous media, etc., and the research objects mainly focus on waters, oceans and gas convection. Strengthening shale gas recovery and underground storage, pore structure, methane reservoir and methane adsorption will be the future research directions.

CO<sub>2</sub> geological storage will become an indispensable technical direction for China to achieve carbon de-peaking after 2030 and carbon neutrality by 2060, which can achieve emission reductions under the premise of avoiding excessive adjustment of the energy structure and ensuring energy security, and realize the smooth transition of China's energy structure from fossil energy to renewable energy. However, relative to China's CO<sub>2</sub> emissions and emission reduction needs, the emission reduction contribution of CO<sub>2</sub> geological storage is still very low, and a lot of work needs to be further carried out. In terms of CO<sub>2</sub> geological storage potential assessment, there are four prospective research directions. (1) Further verify the CO<sub>2</sub> storage potential of deep unrecoverable coal seams and deep saltwater layers. Through more detailed geological investigation work, the favorable traps in geological bodies are identified, the target area and target layer of CO<sub>2</sub> storage are defined, and the potential of CO<sub>2</sub> geological storage in China is updated to serve large-scale demonstration projects. (2) Follow up research on depleted oil and gas reservoirs and CO<sub>2</sub> storage potential in shallow sea. The CO<sub>2</sub> storage of oil and gas reservoirs has changed from the goal of increasing oil and gas production to the goal of CO<sub>2</sub> emission reduction. The CO<sub>2</sub> storage potential assessment of sedimentary basins on the continental shelf has been improved, and the CO<sub>2</sub> storage potential assessment and suitability evaluation of marine water bodies have been carried out. (3) Clarify the suitability evaluation system and index selection for CO<sub>2</sub> geological storage. At present, the evaluation indexes of CO<sub>2</sub> geological storage suitability are obtained through the analytic hierarchy process. To better serve the CO<sub>2</sub> geological storage demonstration project, it is necessary to further modify the evaluation system and indexes of CO<sub>2</sub> geological storage suitability in order to obtain more accurate actual storage and matching storage. (4) Improve the calculation method of CO<sub>2</sub> geological storage. For example, in terms of CO<sub>2</sub> geological storage in the deep salt water layer, this can include how to transition the ideal pure NaCl solution assumption to the actual CO<sub>2</sub>-mixed salt system in the calculation method. In terms of CO<sub>2</sub> geological storage in deep unrecoverable coal seams, this can include how to improve the adsorption model to accurately predict the adsorption storage of supercritical CO<sub>2</sub>.

At present, the main bottleneck of CO<sub>2</sub> geological storage is the high cost and the low economic feasibility. Therefore, reducing the cost of CO<sub>2</sub> treatment and conversion is the key to the large-scale application of CO<sub>2</sub> geological storage in the world in the future. In addition, the improvement and development of carbon emissions trading can help CCUS projects reach economic feasibility. For investors, the CCUS market has a definite and huge potential for development. CCUS projects and related companies in this market with high technical maturity and good economic viability will become a sought-after investment target for investors.

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## References

- INTERNATIONAL ENERGY AGENCY. Global Energy Review: CO<sub>2</sub> Emissions in 2021. Available online: <https://www.iea.org/reports/global-energy-review-CO2-emissions-in-2021-2> (accessed on 1 March 2022).
- Lau, H.C.; Tsai, S.C. Global decarbonization: Current status and what it will take to achieve net zero by 2050. *Energies* **2023**, *16*, 7800. [[CrossRef](#)]
- Zhou, W.; Pan, L.; Mao, X. Optimization and comparative analysis of different CCUS systems in china: The case of shanxi province. *Sustainability* **2023**, *15*, 13455. [[CrossRef](#)]
- Dang, H.; Guan, B.; Chen, J.; Ma, Z.; Chen, Y.; Zhang, J.; Guo, Z.; Chen, L.; Hu, J.; Yi, C.; et al. Research on carbon dioxide capture materials used for carbon dioxide capture, utilization, and storage technology: A review. *Environ. Sci. Pollut. R.* **2024**, *31*, 33259–33302. [[CrossRef](#)] [[PubMed](#)]
- Li, P.; Zhou, D.; Zhang, C.; Chen, G. Assessment of the effective CO<sub>2</sub> storage capacity in the Beibuwan Basin, offshore of southwestern P.R. China. *Int. J. Greenh. Gas Control* **2015**, *37*, 325–339. [[CrossRef](#)]
- Oldenburg, C.M. Screening and ranking framework for geologic CO<sub>2</sub> storage site selection on the basis of health, safety, and environmental risk. *Environ. Geol.* **2008**, *54*, 1687–1694. [[CrossRef](#)]
- Shaw, J.; Bachu, S. Screening, Evaluation, and Ranking of Oil Reservoirs Suitable for CO<sub>2</sub>-Flood EOR and Carbon Dioxide Storage. *J. Can. Petrol. Technol.* **2002**, *41*, 51–61. [[CrossRef](#)]
- Thibeau, S.; Mucha, V. Have we overestimated saline aquifer CO<sub>2</sub> storage capacities? *Oil Gas Sci. Technol.–Rev. D'ifp Energ. Nouv.* **2011**, *66*, 81–92. [[CrossRef](#)]
- Zong, J.; Sun, L.; Bao, W. Research of present status and development suggestions regarding the carbon capture, utilization and storage. IOP conference series. *Earth Environ. Sci.* **2020**, *510*, 42001.
- Zhao, J.; Zheng, J.; Ren, L.; Lin, R.; Zhou, B. A review on geological storage of marine carbon dioxide: Challenges and prospects. *Mar. Petrol. Geol.* **2024**, *163*, 106757. [[CrossRef](#)]
- Liu, H.J.; Were, P.; Li, Q.; Gou, Y.; Hou, Z. Worldwide status of CCUS technologies and their development and challenges in china. *Geofluids* **2017**, *2017*, 1–25. [[CrossRef](#)]
- Nedopekin, F.; Shestavin, N.; Yurchenko, V. Environmental safety in the implementation of carbon dioxide geological storage technologies in the Donbass. *E3S Web. Conf.* **2019**, *126*, 74. [[CrossRef](#)]
- Bouc, O.; Bellenfant, G.; Dubois, D.; Guyonnet, D.; Rohmer, J.; Wertz, F.; Gastine, M.; Jacquemet, N.; Vong, C.Q.; Grataloup, S.; et al. Safety criteria for CO<sub>2</sub> geological storage: Determination workflow and application in the context of the Paris Basin. *Energy Procedia* **2011**, *4*, 4020–4027. [[CrossRef](#)]
- Guo, J.; Wen, D.; Zhang, S.; Xu, T.; Li, X.; Diao, Y.; Jia, X. Potential and suitability evaluation of CO<sub>2</sub> geological storage in major sedimentary basins of china, and the demonstration project in ordos basin. *Acta Geol. Sin.-Engl. Ed.* **2015**, *89*, 1319–1332.
- Mi, Z.; Wang, F.; Yang, Y.; Wang, F.; Hu, T.; Tian, H. Evaluation of the potentiality and suitability for CO<sub>2</sub> geological storage in the Junggar Basin, northwestern China. *Int. J. Greenh. Gas Control* **2018**, *78*, 62–72. [[CrossRef](#)]
- Maneeintr, K.; Rawangphai, M.; Sasaki, K. Evaluation for offshore carbon dioxide geological storage potential in the gulf of thailand. *Energy Procedia* **2017**, *142*, 3486–3491. [[CrossRef](#)]
- Li, Y.; Ranjith, P.G.; Perera, M.S.A.; Yu, Q. Residual water formation during the CO<sub>2</sub> storage process in deep saline aquifers and factors influencing it: A review. *J. CO<sub>2</sub> Util.* **2017**, *20*, 253–262. [[CrossRef](#)]
- Safaei-Farouji, M.; Thanh, H.V.; Dai, Z.; Mehbodniya, A.; Rahimi, M.; Ashraf, U.; Radwan, A.E. Exploring the power of machine learning to predict carbon dioxide trapping efficiency in saline aquifers for carbon geological storage project. *J. Clean. Prod.* **2022**, *372*, 133778. [[CrossRef](#)]
- Deng, H.; Bielicki, J.M.; Oppenheimer, M.; Fitts, J.P.; Peters, C.A. Leakage risks of geologic CO<sub>2</sub> storage and the impacts on the global energy system and climate change mitigation. *Clim. Chang.* **2017**, *144*, 151–163. [[CrossRef](#)]
- Zhu, C.-F.; Guo, W.; Wang, Y.-P.; Li, Y.-J.; Gong, H.-J.; Xu, L.; Dong, M.-Z. Experimental study of enhanced oil recovery by CO<sub>2</sub> huff-n-puff in shales and tight sandstones with fractures. *Petrol. Sci.* **2020**, *18*, 852–869. [[CrossRef](#)]
- Huang, S.; Wang, L.; Li, Z.; Su, D.; Luo, Q. Machine learning-based prediction model for CO<sub>2</sub>-induced corrosion on oil well cement under high-pressure and high-temperature condition. *Constr. Build. Mater.* **2024**, *414*, 134999. [[CrossRef](#)]
- Le Gallo, Y.; Martinez, F.A. Influence of a Sub-Seismic blind faults on the safety assessment of CO<sub>2</sub> geological storage in deep saline aquifer. *Energy Procedia* **2017**, *114*, 3393–3405. [[CrossRef](#)]
- Wang, X.; Liao, X.; Dong, P.; Tang, K.; Zhao, X.; Guo, C. Influence of Heterogeneous Caprock on the Safety of Carbon Sequestration and Carbon Displacement. *Processes* **2022**, *10*, 1415. [[CrossRef](#)]
- Li, C.; Hao, S.; Zhang, S.; Jiang, Y.; Yi, Z. Simulation Study on the Mechanical Effect of CO<sub>2</sub> Geological Storage in Ordos Demonstration Area. *Water* **2024**, *16*, 144. [[CrossRef](#)]
- Zhang, Y.; Hao, S.; Yu, Z.; Li, X.; Xu, T. Land Uplift Induced by Injection: A Feasible Method to Evaluate the Security of CO<sub>2</sub> Capture and Sequestration Projects. *Environ. Earth Sci.* **2018**, *77*, 513. [[CrossRef](#)]

26. Mao, L.; Zhu, Y.; Ju, C.; Bao, F.; Xu, C. Visualization and bibliometric analysis of carbon neutrality research for global health. *Front. Public Health* **2022**, *10*, 896161. [[CrossRef](#)] [[PubMed](#)]
27. Jiang, K.; Ashworth, P. The development of Carbon Capture Utilization and Storage (CCUS) research in China: A bibliometric perspective. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110521. [[CrossRef](#)]
28. Wang, D.; Huangfu, Y.; Dong, Z.; Dong, Y. Research hotspots and evolution trends of carbon neutrality—Visual analysis of bibliometrics based on CiteSpace. *Sustainability* **2022**, *14*, 1078. [[CrossRef](#)]
29. Qiu, H.; Liu, L. A Study on the Evolution of Carbon Capture and Storage Technology Based on Knowledge Mapping. *Energies* **2018**, *11*, 1103. [[CrossRef](#)]
30. Zhong, S.; Chen, R.; Song, F.; Xu, Y. Knowledge mapping of carbon footprint research in a LCA perspective: A visual analysis using CiteSpace. *Processes* **2019**, *7*, 818. [[CrossRef](#)]
31. Huang, L.; Zhou, M.; Lv, J.; Chen, K. Trends in global research in forest carbon sequestration: A bibliometric analysis. *J. Clean. Prod.* **2020**, *252*, 119908. [[CrossRef](#)]
32. Shao, Z.; Tan, B.; Guo, Y.; Li, T.; Li, X.; Fang, X.; Wang, F.; Zhang, Q.; Wang, H. Visualization and analysis of mapping knowledge domains for coal pores studies. *Fuel* **2022**, *320*, 123761. [[CrossRef](#)]
33. Liu, Z.; Qiu, Z. A systematic review of transportation carbon emissions based on CiteSpace. *Environ. Sci. Pollut. Res. Int.* **2023**, *30*, 54362–54384. [[CrossRef](#)] [[PubMed](#)]
34. Geng, Y.; Zhu, R.; Maimaituexun, M. Bibliometric review of carbon neutrality with CiteSpace: Evolution, trends, and framework. *Environ. Sci. Pollut. Res.* **2022**, *29*, 76668–76686. [[CrossRef](#)] [[PubMed](#)]
35. Li, X.; Tang, J.; Li, W.; Si, Q.; Guo, X.; Niu, L. A bibliometric analysis and visualization of aviation carbon emissions studies. *Sustainability* **2023**, *15*, 4644. [[CrossRef](#)]
36. Zhang, Q.; Xiao, Y.; Liu, Y.; Deng, T.; Li, Z.; Li, R. Visualizing the intellectual structure and evolution of carbon neutrality research: A bibliometric analysis. *Environ. Sci. Pollut. Res.* **2023**, *30*, 75838–75862. [[CrossRef](#)] [[PubMed](#)]
37. Chen, C.M. Visualizing and exploring scientific literature with CiteSpace. In Proceedings of the Chiir'18: Proceedings of the 2018 Conference on Human Information Interaction & Retrieval, New Brunswick, NJ, USA, 11–15 March 2018; pp. 369–370. [[CrossRef](#)]
38. Niedertscheider, M.; Haas, W.; Görg, C. Austrian Climate Policies and GHG-Emissions Since 1990: What is the role of climate policy integration? *Environ. Sci. Policy* **2018**, *81*, 10–17. [[CrossRef](#)]
39. Dixon, T.; Zakkour, P.; Chapman, J. Trials and tribulations of getting CCS in an ETS. Principles for CCS in an ETS from UK work for the EU ETS. *Energy Procedia* **2009**, *1*, 4443–4450. [[CrossRef](#)]
40. Zhang, L.; Sun, N.; Wang, M.; Wu, T.; Wei, W.; Pang, C.H. The integration of hydrogenation and carbon capture utilisation and storage technology: A potential low-carbon approach to chemical synthesis in China. *Int. J. Energ. Res.* **2021**, *45*, 19789–19818. [[CrossRef](#)]
41. Averchenkova, A.; Fankhauser, S.; Finnegan, J.J. The impact of strategic climate legislation: Evidence from expert interviews on the UK Climate Change Act. *Clim. Policy* **2021**, *21*, 251–263. [[CrossRef](#)]
42. Espa, I.; Marín Durán, G. Renewable energy subsidies and WTO law: Time to rethink the case for reform beyond Canada-Renewable Energy/Fit program. *J. Int. Econ. Law.* **2018**, *21*, 621–653. [[CrossRef](#)]
43. Torvanger, A. Governance of bioenergy with carbon capture and storage (BECCS): Accounting, rewarding, and the Paris agreement. *Clim. Policy* **2019**, *19*, 329–341. [[CrossRef](#)]
44. Cook, P.J. CCS Research Development and Deployment in a Clean Energy Future: Lessons from Australia over the Past Two Decades. *Engineering* **2017**, *3*, 477–484. [[CrossRef](#)]
45. Li, Q.; Chen, Z.A.; Zhang, J.T.; Liu, L.C.; Li, X.C.; Jia, L. Positioning and revision of CCUS technology development in China. *Int. J. Greenh. Gas Control* **2016**, *46*, 282–293. [[CrossRef](#)]
46. Hu, A.M.; Chen, H.F. Data visualization analysis of knowledge graph application. In Proceedings of the 2021 2nd International Conference on Artificial Intelligence and Information Systems (Icaais '21), Chongqing, China, 28–30 May 2021. [[CrossRef](#)]
47. Ding, X.; Yang, Z. Knowledge mapping of platform research: A visual analysis using VOSviewer and CiteSpace. *Electron. Commer. Res.* **2022**, *22*, 787–809. [[CrossRef](#)]
48. Núñez-López, V.; Gil-Egui, R.; Hosseini, S. Environmental and operational performance of CO<sub>2</sub>-EOR as a CCUS technology: A cranfield example with dynamic LCA considerations. *Energies* **2019**, *12*, 448. [[CrossRef](#)]
49. Cahill, A.G.; Jakobsen, R. Geochemical modeling of a sustained shallow aquifer CO<sub>2</sub> leakage field study and implications for leakage and site monitoring. *Int. J. Greenh. Gas Control* **2015**, *37*, 127–141. [[CrossRef](#)]
50. Yong, K.; Shen, X.D.; Cui, S.; Fan, M.H. Supercritical drying: A promising technique on synthesis of sorbent for CO<sub>2</sub> capture. *Int. J. Global Warm.* **2017**, *12*, 228–241.
51. Hasan, M.M.F.; First, E.L.; Boukouvala, F.; Floudas, C.A. A multi-scale framework for CO<sub>2</sub> capture, utilization, and sequestration: CCUS and CCU. *Comput. Chem. Eng.* **2015**, *81*, 2–21. [[CrossRef](#)]
52. Kim, M.; Na, J.; Park, S.; Park, J.; Han, C. Modeling and validation of a pilot-scale aqueous mineral carbonation reactor for carbon capture using computational fluid dynamics. *Chem. Eng. Sci.* **2018**, *17*, 301–312. [[CrossRef](#)]
53. Li, Q.; Shi, H.; Yang, D.; Wei, X. Modeling the key factors that could influence the diffusion of CO<sub>2</sub> from a wellbore blowout in the Ordos Basin, China. *Environ. Sci. Pollut. Res.* **2017**, *24*, 3727–3738. [[CrossRef](#)] [[PubMed](#)]
54. Dong, J.; Feng, X.; Hao, X.; Kuang, W. The environmental degradation behavior of FeNiMnCr high entropy alloy in high temperature hydrogenated water. *Scripta Mater.* **2021**, *204*, 114127. [[CrossRef](#)]

55. Song, C.; Liu, Q.; Qi, Y.; Chen, G.; Song, Y.; Kansha, Y.; Kitamura, Y. Absorption-microalgae hybrid CO<sub>2</sub> capture and biotransformation strategy—A review. *Int. J. Greenh. Gas Control* **2019**, *88*, 109–117. [[CrossRef](#)]
56. Burton, E. Effects of California's climate policy in facilitating CCUS. *Energy Procedia* **2014**, *63*, 6959–6972. [[CrossRef](#)]
57. Miranda-Barbosa, E.; Sigfússon, B.; Carlsson, J.; Tzimas, E. Advantages from Combining CCS with Geothermal Energy. *Energy Procedia* **2017**, *114*, 6666–6676. [[CrossRef](#)]
58. Duran, C.J.; Seydoux-Guillaume, A.-M.; Bingen, B.; Gouy, S.; de Parseval, P.; Ingrin, J.; Guillaume, D. Fluid-mediated alteration of (Y,REE,U,Th)-(Nb,Ta,Ti) oxide minerals in granitic pegmatite from the Evje-Iveland district, southern Norway. *Miner. Petrol.* **2016**, *110*, 581–599. [[CrossRef](#)]
59. Trimm, D.L.; Liu, I.O.Y.; Cant, N.W. The effect of carbon monoxide on the oligomerization of acetylene in hydrogen over a Ni/SiO<sub>2</sub> catalyst. *J. Mol. Catal. A: Chem.* **2009**, *307*, 13–20. [[CrossRef](#)]
60. Jiang, X. A review of physical modelling and numerical simulation of long-term geological storage of CO<sub>2</sub>. *Appl. Energ.* **2011**, *88*, 3557–3566. [[CrossRef](#)]
61. Payton, R.L.; Sun, Y.; Chiarella, D.; Kingdon, A. Pore scale numerical modelling of geological carbon storage through mineral trapping using true pore geometries. *Transp. Porous Med.* **2022**, *141*, 667–693. [[CrossRef](#)]
62. Fatah, A.; Ben Mahmud, H.; Bennour, Z.; Gholami, R.; Hossain, M. The impact of supercritical CO<sub>2</sub> on the pore structure and storage capacity of shales. *J. Nat. Gas. Sci. Eng.* **2022**, *98*, 104394. [[CrossRef](#)]
63. Li, R.; Jiang, P.; He, D.; Chen, X.; Xu, R. Experimental Investigation on the Behavior of Supercritical CO<sub>2</sub> during Reservoir Depressurization. *Environ. Sci. Technol.* **2017**, *51*, 8869–8876. [[CrossRef](#)] [[PubMed](#)]
64. Bachu, S. Sequestration of CO<sub>2</sub> in geological media in response to climate change: Road map for site selection using the transform of the geological space into the CO<sub>2</sub> phase space. *Energ. Convers. Manag.* **2002**, *43*, 87–102. [[CrossRef](#)]
65. Grataloup, S.; Bonijoly, D.; Brosse, E.; Dreux, R.; Garcia, D.; Hasanov, V.; Lescanne, M.; Renoux, P.; Thoraval, A. A site selection methodology for CO<sub>2</sub> underground storage in deep saline aquifers: Case of the Paris Basin. *Energy Procedia* **2009**, *1*, 2929–2936. [[CrossRef](#)]
66. Hsu, C.; Chen, L.; Hu, A.H.; Chang, Y. Site selection for carbon dioxide geological storage using analytic network process. *Sep. Purif. Technol.* **2012**, *94*, 146–153. [[CrossRef](#)]
67. Nocito, F.; Dibenedetto, A. Atmospheric CO<sub>2</sub> mitigation technologies: Carbon capture utilization and storage. *Curr. Opin. Green Sustain. Chem.* **2020**, *21*, 34–43. [[CrossRef](#)]
68. Labus, K.; Tarkowski, R.; Wdowin, M. Modeling gas–rock–water interactions in carbon dioxide storage capacity assessment: A case study of Jurassic sandstones in Poland. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 2493–2502. [[CrossRef](#)]
69. He, D.; Jiang, P.; Lun, Z.; Liu, X.; Xu, R. Pore scale CFD simulation of supercritical carbon dioxide drainage process in porous media saturated with water. *Energy Sources Part A Recovery Util. Environ. Eff.* **2019**, *41*, 1791–1799.
70. Santori, G.; Charalambous, C.; Ferrari, M.; Brandani, S. Adsorption artificial tree for atmospheric carbon dioxide capture, purification and compression. *Energy* **2018**, *162*, 1158–1168. [[CrossRef](#)]
71. Li, Y.; Pang, Z. Capacity and suitability assessment of deep saline aquifers for CO<sub>2</sub> sequestration in the Bohai Bay Basin, East China. *Environ. Earth Sci.* **2016**, *75*, 1. [[CrossRef](#)]
72. Donda, F.; Volpi, V.; Persoglia, S.; Parushev, D. CO<sub>2</sub> storage potential of deep saline aquifers: The case of Italy. *Int. J. Greenh. Gas Control* **2011**, *5*, 327–335. [[CrossRef](#)]
73. Frailey, S.M. Methods for estimating CO<sub>2</sub> storage in saline reservoirs. *Energy Procedia* **2009**, *1*, 2769–2776. [[CrossRef](#)]
74. Harrison, A.L.; Power, I.M.; Dipple, G.M. Accelerated carbonation of brucite in mine tailings for carbon sequestration. *Environ. Sci. Technol.* **2013**, *47*, 126–134. [[CrossRef](#)] [[PubMed](#)]
75. Giammar, D.E.; Bruant, R.G.; Peters, C.A. Forsterite dissolution and magnesite precipitation at conditions relevant for deep saline aquifer storage and sequestration of carbon dioxide. *Chem. Geol.* **2005**, *217*, 257–276. [[CrossRef](#)]
76. Zhong, J.; Jiang, X. A study of using cosmic-ray muon radiography to detect CO<sub>2</sub> leakage from a primary storage into geological formations. *Environ. Earth Sci.* **2016**, *75*, 1–13. [[CrossRef](#)]
77. Zhang, Z.H.; Huisingh, D. Carbon dioxide storage schemes: Technology, assessment and deployment. *J. Clean. Prod.* **2017**, *142*, 1055–1064. [[CrossRef](#)]
78. Chevalier, S.; Faisal, T.F.; Bernabe, Y.; Juanes, R.; Sassi, M. Numerical sensitivity analysis of density driven CO<sub>2</sub> convection with respect to different modeling and boundary conditions. *Heat. Mass. Transfer* **2015**, *51*, 941–952. [[CrossRef](#)]
79. Zou, J.; Yang, Y.; Jia, S.; Gao, C.; Song, Z. The sources and biogeochemical cycling of carbon in the Wudalianchi UNESCO Geopark volcanic system in Northeast China. *Environ. Sci. Pollut. Res.* **2019**, *26*, 2918–2928. [[CrossRef](#)] [[PubMed](#)]
80. Yamamoto, H.; Nanai, S.; Zhang, K.; Audigane, P.; Chiaberge, C.; Ogata, R.; Nishikawa, N.; Hirokawa, Y.; Shingu, S.; Nakajima, K. High-performance supercomputing as a risk evaluation tool for geologic carbon dioxide storage. *Energy Procedia* **2013**, *37*, 3997–4005. [[CrossRef](#)]
81. Bachu, S. Sequestration of CO<sub>2</sub> in geological media: Criteria and approach for site selection in response to climate change. *Energ. Convers. Manag.* **2000**, *41*, 953–970. [[CrossRef](#)]
82. Damen, K.; Faaij, A.; Turkenburg, W. Health, safety and environmental risks of underground CO<sub>2</sub> storage—overview of mechanisms and current knowledge. *Clim. Change* **2006**, *74*, 289–318. [[CrossRef](#)]
83. Amshoff, P.; Weger, T.; Ostertag-Henning, C. Dissolution kinetics of CO<sub>2</sub> and CO<sub>2</sub>-SO<sub>2</sub> mixtures in water and brine at geological storage conditions of 16 MPa and 333 K. *Int. J. Greenh Gas Control* **2018**, *79*, 173–180. [[CrossRef](#)]

84. Pratama, E.; Ismail, M.S.; Ridha, S. Identification of coal seams suitability for carbon dioxide sequestration with enhanced coalbed methane recovery: A case study in South Sumatera Basin, Indonesia. *Clean. Technol. Environ.* **2018**, *20*, 581–587. [[CrossRef](#)]
85. Chen, Q.; Ding, W.; Sun, H.; Peng, T.; Ma, G. Indirect mineral carbonation of phosphogypsum for CO<sub>2</sub> sequestration. *Energy* **2020**, *206*, 118148. [[CrossRef](#)]
86. Davarazar, M.; JahanianFard, D.; Sheikhejad, Y.; Nemati, B.; Mostafaie, A.; Zandi, S.; Khalaj, M.; Kamali, M.; Aminabhavi, T.M. Underground carbon dioxide sequestration for climate change mitigation—A scientometric study. *J. CO<sub>2</sub> Util.* **2019**, *33*, 179–188. [[CrossRef](#)]
87. Aydiner, K. Carbon-dioxide storage in geological media. *J. Powder Metall. Min.* **2015**, *4*, e135. [[CrossRef](#)]
88. Hammad, H.M.; Nauman, H.M.F.; Abbas, F.; Ahmad, A.; Bakhat, H.F.; Saeed, S.; Shah, G.M.; Ahmad, A.; Cerdà, A. Carbon sequestration potential and soil characteristics of various land use systems in arid region. *J. Environ. Manag.* **2020**, *264*, 110254. [[CrossRef](#)] [[PubMed](#)]
89. Wang, J.; Han, G.; Wang, Z.; Yun, J.; Wang, Z.; Li, Z.; Lv, S.; Qin, J. Plant-Soil carbon storage in dynamic succession of ecological restoration in national grassland natural park. *Sustainability* **2023**, *15*, 15837. [[CrossRef](#)]
90. Desai, J.; Sreekesava, K.S.; Dharek, M.S.; Sunagar, P.; Ganesh, C.R. Carbon dioxide sequestration by mineral carbonation using alkaline rich material. *IOP Conf. Series. Mater. Sci. Eng.* **2020**, *814*, 12035. [[CrossRef](#)]

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