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Editorial

A Decade of Green Bond Markets in Emerging Economies

Rajni Kant Rajhans 5-6

Articles

"Project Burnout": Proposing a New Definition for Burnout in the Project Management Context with the Purpose of https://erem.ktu.lt/index.php/erem

Published: 2023-04-11

Editorial

Articles

Environmental Research, Engineering and Management

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Media Ranking in Lithuania

SUBJECT AREA AND CATEGORY

Energy
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- Environmental Engineering
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PUBLISHER

Kaunas University of Technology

Kaunas University of Technology in Scimago Institutions Rankings

H-INDEX

8

PUBLICATION TYPE

Journals

ISSN

13921649, 20292139

COVERAGE

2015-2021

INFORMATION

Homepage

How to publish in this journal

erem@ktu.lt

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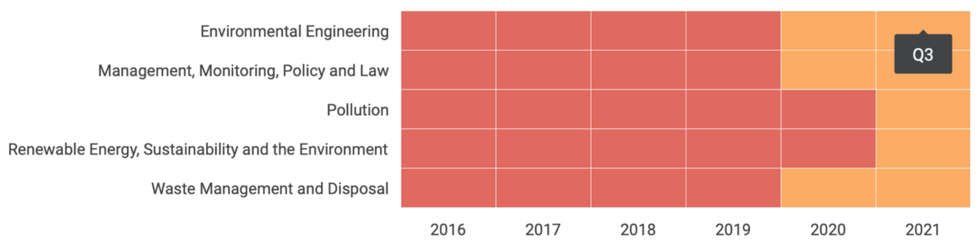

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2023 / Nr. 79 (1)

ISSN 1392-1649 (print)
ISSN 2029-2139 (online)

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ENVIRONMENTAL RESEARCH, ENGINEERING AND MANAGEMENT

Aplinkos tyrimai, inžinerija ir vadyba

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Environmental Research, Engineering and Management No. 79 (1)

The papers published in journal Environmental Research, Engineering and Management are abstracted by SCOPUS database (since 2016), EBSCO: Central & Eastern European Academic Source, EBSCO: Environment Complete, and EBSCO: Environment Index (since 2005), also Aerospace Database, Civil Engineering Abstracts, Metadex.

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CONTENT

EREM 79/1

Journal of Environmental Research, Engineering and Management
Vol. 79 / No. 1 / 2023
pp. 37–55
DOI 10.5755/j01.erem.79.1.32424

Received 2022/10 | Accepted after revision 2023/02

https://doi.org/10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

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The continuous growth of energy consumption leads to the increase of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). Carbon capture, utilization and storage (CCUS), which consists of carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), is a technology that aims to capture CO_2. Therefore, this study evaluates and provides an overview of CCUS in the period 2012–2022, by using a bibliometric analysis to obtain a complete perspective and reference on CCUS. The data search was carried out on January 20, 2022, by inputting the keyword “carbon capture utilization storage” into the Scopus database, and 296 documents were generated. Other software used included Open Refine, VOS viewer and Tableau to describe publication and citation trends, co-authorship, and co-occurrence. CCUS research trend increased by 2,766.6% from 2012 to 2022. The most productive country in investigating CCUS was China, and Zhang X. was the most prolific writer. The organization that published the highest number of research on the topic was the National Taiwan University. The publications and citations were dominated by the International Journal of Greenhouse Gas Control that was published by Elsevier Ltd., which also issues a number of significant publications and receives the highest number of citations.

Keywords: bibliometric analysis, carbon emission, carbon capture, carbon capture utilization, carbon capture storage.

Introduction

The increase of greenhouse gas (GHG) emissions has become a global climate issue that profoundly raises the world's attention due to the impact of climate change. The Intergovernmental Panel on Climate Change (IPCC) launched a Special Report on Global Warming of 1.50 °C, which contains various impacts created on human health, food security and ecosystems. This impact can be anticipated through the attempt of limiting the temperature rise by 1.50 °C above the average temperature prior to industrial era. Total GHG emissions in 2018 reached 55.3 gigatons of CO_2 equivalent. Consequently, hydro-meteorological disasters may occur due to extreme weather that changes the length of dry and rainy season and increases the frequency and duration of droughts. Another impact of climate change is a rise in temperature and sea level (Nerem et al., 2018; Zhao et al., 2020). According to Stone et al. (2009), carbon dioxide emissions have increased by 40% since the period of the Industrial Revolution, and human activities might have greatly contributed to CO_2 release since that time. Carbon dioxide is capable of absorbing long-wave IR radiation (heat) being emitted by the earth which can make the greenhouse effect stronger, hence any increase in CO_2 emissions ultimately causes a rise in the earth's temperature.

The largest CO_2 emissions are generated from agricultural activities, energy production and energy use. Furthermore, trade, transportation, and the growing manufacturing industry add to CO_2 emissions as stated by Adom (2012), which exacerbates the ecological aspects of environment such as climate and climate change. Moreover, the tourism industry elevates carbon dioxide emissions; thereby it is important to raise the awareness of global warming and climate change into the practice of business as usual (Balogh and Jambor, 2017). In order to abate the global warming, reducing the levels of carbon dioxide (CO_2) emissions from exhaust gases produced by industrial activities has to be promptly undertaken since the levels of carbon dioxide (CO_2) emissions have continued to increase from year to year (Rinanti et al., 2014). Global warming has an impact on all living things and nature such as rising sea levels, climate anomalies and natural disasters (Fachrul et al., 2019; Rinanti et al., 2013).

By 2100, the level of atmospheric CO_2 emissions is estimated to reach around 800 ppm and the earth's surface temperature tends to rise by 4 °C (Wang and Oko, 2017). According to The Summary for Policymakers of the IPCC Working Group III report, Climate Change 2022: Mitigation of Climate Change, 195 countries in the world have agreed to limit GHG emissions. A conference held in Paris from 30 November to 12 December 2015 propagated the Paris Agreement to the United Nations Framework Convention on Climate Change. Furthermore, the treaty aims to mitigate the climate change towards a low-carbon, resilient and sustainable future and ensures that global temperature elevations keep well below 2 °C (Wang and Oko, 2017). Carbon capture, utilization and storage (CCUS) comprises carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), both of which aim to capture CO_2 that is being released into the air. The difference between these two technologies lies mainly in the fact that, in CCS, CO_2 emissions are captured and injected into underground storage areas, while in CCU, the CO_2 is converted into commercial products. Based on Zaemi and Rohmana (2021), CCUS's goal is to capture 85% of CO_2 that is released from power plants and industries and the resulting emissions are to be transported into 700 meters depth below sea level through pipes.

Based on IPCC (2022), CCS is the most feasible/accessible technology to reduce emissions from carbon-intensive industries and power generation; however, the mitigation costs tend to reach 138% without CCS technology. This technology is applied for the downstream phase of CCS pathways, by capturing carbon emissions to be stored and utilized for other production processes (Prayitno et al., 2021). Meanwhile, Reiner (2016) has found that CCS technology is employed for climate mitigation and expected to decrease the GHG emissions by 32% until 2050. This target can be justified by the research done by Akbar et al. (2021) that CCS technology captures 85–95% of the CO_2 produced by an industry. Besides of that CCS technology is also

able to reduce carbon emissions with an accuracy level of 95% when applied in a waste-to-energy plant.

The Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCC) has summoned all countries in the world to commit to implementing actions to keep average global temperature below 2 °C and to continue with efforts for suppressing the increase to 1.5 °C. Afterward, targets for each country's commitment were created, where the Paris Agreement set a target to reduce GHG emissions, which is called the Nationally Determined Contribution (NDC). The achievement of GHG emission reductions is verified to ensure that the calculation process complies with the principles that have been recognized as transparent, accurate, consistent, comprehensive, and comparable (TACCC) at the national and international level. This mechanism works through the improvement of scrutinizing and disclosure for lowering the GHG emissions level to encourage the countries for acquiring the climate incentive. The report of TACCC will be beneficial for stakeholders to set a number of measureable goals for climate change mitigation that includes the efforts for reducing emission, resilience enhancement and for allocating financial resources (Weikmans et al., 2019).

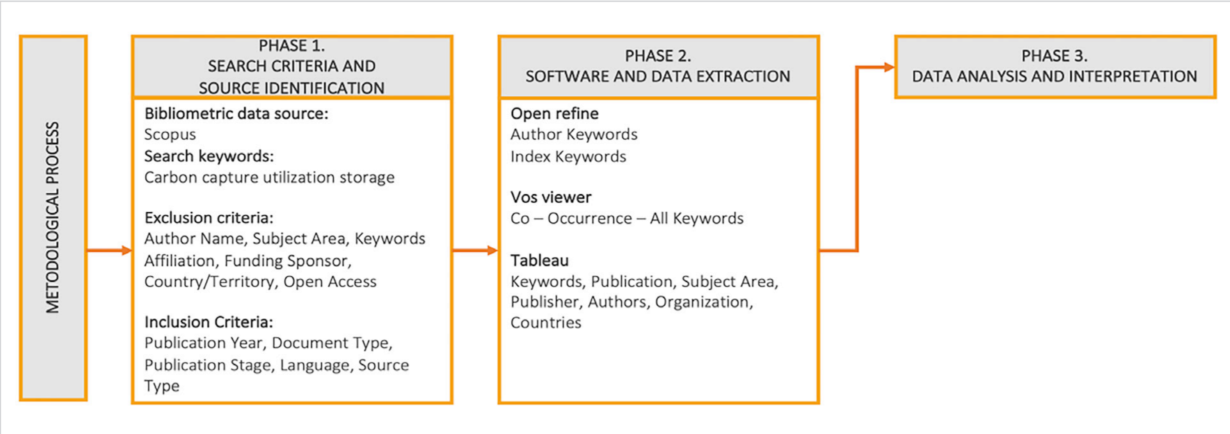
However, the technology of CCUS has not been widely applied, although data and references collection on the technology is largely available. Moreover, the implementation cost of CCUS varies greatly in the fields of electricity and industry (Adisaputro and Saputra, 2017). According to Zaemi and Rohmana (2021), the challenges of developing CCUS are to determine the location of infrastructure and the environment to be used as CO_2 storage areas plus the high required costs. Owing to the significant topic of the IPCC Agenda 2030 on greenhouse gases, CCUS remains to be an interesting global issue to be investigated as a climate change mitigation technology although many studies of greenhouse gases have been extensively conducted. In addition, a number of research works have investigated the application of CCUS technology in some countries, such as the United States (Alphen et al., 2010), China (Jiang and Ashworth, 2020), ASEAN countries (Kimura et al., 2020) and the United Kingdom (Gough et al., 2020). This review, therefore, offers the trend of research development in the field of CCUS to show the acceleration of technology used to apply the CCUS methods for industrialization in some countries within the year of 2012–2022.

The significant objective of this research is to evaluate the growing trend of investigation on CCUS from 2012–2022, as well as to determine the distribution and productivity of research by authors, organizations, and countries, plus the distribution of research work on subject areas and publishers through the following research questions namely: (1) How do the CCUS technologies provide a solution for reducing the carbon emission of industries around the world?; (2) What are the CCUS technologies that most frequently applied for the industry within 2012–2022?; (3) Who are the most prolific authors followed by the most productive countries and organizations?; (4) What are the potential areas of interest in the research development of CCUS technologies? Therefore, the bibliometric analysis which aims to find the research gaps for further exploration on the topic of carbon capture, utilization and storage, was conducted by using the Scopus database. This article divides its systematics of writing into the following parts, namely the introduction, methods, results and discussion, conclusion and references list.

Methods

According to Chen et al. (2015), Singh and Borthakur (2018), a bibliometric analysis is an effective method of analyzing research progress and quantitative trends in publications on a particular topic, by providing an overview of literature contribution both nationally and internationally (Zhang et al., 2020; Zyoud et al., 2022). Sweileh (2022) explains that any bibliometric study uses a statistic approach to identify growth patterns and development of publications as well as collaborative patterns among authors, institutions, and countries. Moreover, bibliometrics identify the research gaps through analyzing the research niche offered by the publication database, which is useful to provide the basis for conducting further research (Singh and Borthakur, 2018; Zhang et al., 2020). The method is divided into three phases, namely data mining, extraction and analysis, as presented in *Fig. 1*.

Fig. 1. *Study method diagram*



Search criteria and source identification

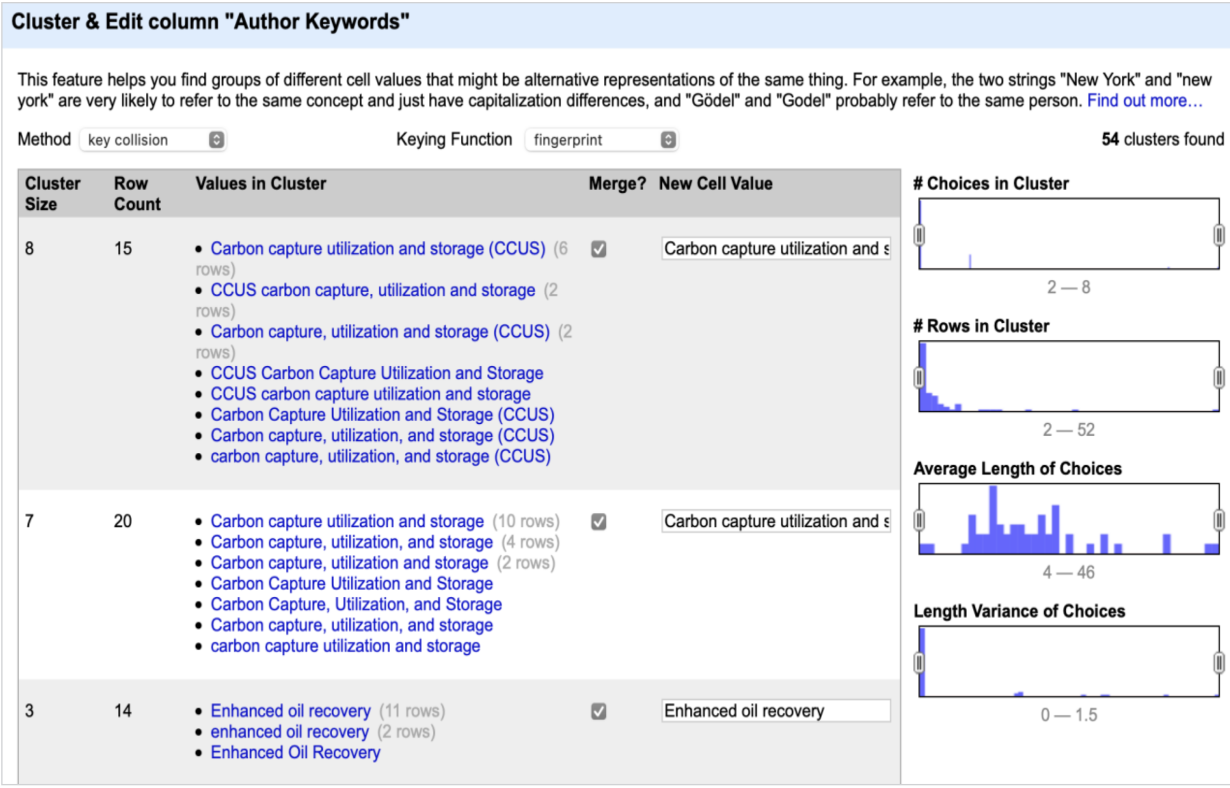
In phase I, data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into Scopus database. Owing to the nature of Scopus as the world's leading literature database published by Elsevier and known to have the highest number of citations (Herawati et al., 2022; Borthakur and Govind, 2017), the Scopus database fits into the expected outcomes of this study. Then, filtering was done with the year of publication, document type, publication stage, language, and source type to obtain more significant results. The data were mined from 2012 to 2022 by limiting the type of article document, final publication stage, journal source type and the English language used. After filtering, 296 available documents were generated and the search results were exported in the CSV format with citation information, bibliographical information, abstract, and keywords. Files exported from the Scopus database were fed into the Open Refine software to reduce inconsistent and repetitive keywords in the mined data.

Software and data extraction

The data obtained from the Scopus database was further extracted and processed by using Open Refine, Vos Viewer and Tableau Public software. The data were fed into Open Refine to reduce several keywords with different spellings but same meaning and to establish the keywords in an exact writing format for avoidance of repetition. Open Refine is able to clean the data from one format to another, overcomes inconsistencies in data sets and divides data into more detailed parts, in an automatic or manual attempt (NIH, 2022).

Fig. 2 shows repeated keywords, namely "Carbon Capture Utilization and Storage (CCUS)", "CCUS carbon capture, utilization and storage", "Carbon capture, utilization and storage (CCUS)", "CCUS Carbon Capture Utilization and Storage", "CCUS Carbon Capture Utilization and Storage", "Carbon Capture Utilization and Storage (CCUS)", "Carbon capture, utilization and Storage (CCUS)" and "carbon capture, utilization, and storage (CCUS)". Some of these have the same meaning but different spellings, hence they are reduced to one format of the keyword, i.e., "Carbon Capture Utilization and Storage (CCUS)". The reduced keywords generated through Open Refine were then fed into the VOS Viewer software, which presents and visualizes specific information about bibliometric chart maps for easier analysis of the relationships or networks about a research topic (Athar et al., 2019). Open Refine enables the author to select the preferred data set, thus the results contained a list of useful data that removes redundant keywords. It means that carbon capture utilization and storage (CCUS) has been tested as the natural result of removing data with redundant keywords. In addition, CCUS is the representative value of other related values (Bergamschi, 2019), to generate a more extensive subject field such as Carbon Capture and Carbon Storage, Carbon Capture Strategies and Carbon Storage Sustainable.

Fig. 2. *Extract data using Open Refine*



The software provides data visualization based on co-authorship, co-occurrence, citation, bibliometric coupling, and co-citation. In this study, co-occurrence of all keywords (author and index keywords) as well as co-authorship (authors) based on network and overlay visualization were used particularly. In co-occurrence analysis, all keywords were chosen as the selected unit with a full counting method. Based on the 296 documents from Scopus, 3,298 keywords were obtained. Once the minimum number of occurrences was set at eight, 78 thresholds were generated, indicating that 78 keywords were repeated eight times in the 3,298 keywords.

Even though the keywords were tidied up in Open Refine, some redundant keywords still appeared that had the same meaning as CO_2 and carbon dioxide. These were employed as a writing format using Thesaurus note, which were then imported into VOS Viewer. In co-authorship analysis, the applied unit analysis referred to authors with the full counting method. The total number of authors in the 296 Scopus-generated documents was 1,011. After setting the minimum number of an author's documents at three, the threshold obtained was 76 authors. Tableau software was used to simplify complex data in the form of interactive graphic visualizations, for easy analysis and understanding (Akhtar et al., 2020). Akhtar et al. (2017) and Murray (2013) stated that Tableau is the most powerful and flexible analytical platform for providing data information and managing their rows into various visualization types.

Data analysis and interpretation

296 research publications were processed by using Open Refine, VOS Viewer and Tableau software regarding publication and citation trends; co-authorship and co-occurrence were analyzed and interpreted, then comparative analysis was conducted within the aforementioned research publications.

The method should consist of research design, subject characteristics, data collection process and data analysis. If necessary, it should raise ethical issues

particularly when dealing with human participants. Appropriate statistical methods should be used, although the biological mechanism should be emphasized. The statistical model, classes, blocks, and experimental units must be designated. Consultation with a statistician is recommended to prevent any incorrect or inadequate statistical methods.

Results and Discussion

Global distribution of publication and citation trend (2012–2022)

One of the objectives mentioned in this article is the determination of global research distribution in 2012–2022. The trends of publications and citations in those years are presented in *Fig. 3*. The total number of publications obtained from Scopus regarding "Carbon Capture Utilization and Storage" was 296. This figure increases significantly from 3 publications in 2012 to 83 publications in 2021. The number of publications and citations in 2021 are inversely related. In 2022, the total number of published documents and citations seemed to decrease because the data were collected in January, hence they did not represent 2022 as a whole. From 2012 to 2015, the increase of published documents and citations was directly proportional, but in 2016, the number of citations increased. The highest citations occurred in 2016; however, the number decreased by 72% after 2016.

Research on carbon capture, utilization and storage (CCUS) has been issued from several journals and publishers including Elsevier Ltd., MDPI AG, Frontiers Media S.A., Italian Association of Chemical Engineering – AIDIC, and Blackwell Publisher Ltd, which are the top 5. Elsevier Ltd. has the highest number of publications and 1,322 citations of 97 documents, as well as journals reaching 28. Furthermore, its top 5 journals with the number of publications and citations respectively are Journal of 1) Greenhouse Gas Control (36.76%; 24.93%), 2) Cleaner Production (17.65%; 7.01%), 3) Applied Energy (17.65%; 38.40%), 4) Energy (16.18%; 13.28%), and 5) CO_2 Utilization (11.76%; 16.38%). Based on the results, 138 journals published articles on carbon capture, utilization and storage with up to 3,947 received citations.

Co-authorship analysis

This co-authorship analysis indicates the relationship between authors, countries and organizations, represented in a network diagram containing nodes and lines classified in different clusters. The clusters of nodes and lines are being distinguished by colors, while the size of nodes shows the weight and repetition of keywords. In addition, the distance from one node to another illustrates the strength of their relationship, and farther link between nodes means both keywords have less research (Khosroabadi et al., 2021).

Authors

The authors who conducted research on CCUS were 62, while their productivity is depicted in *Fig. 5* with the highest number of publications and citations. Zhang X is the most prolific writer in terms of the number of

Fig. 3. *Annual publication and citation spread (2012–2022)*

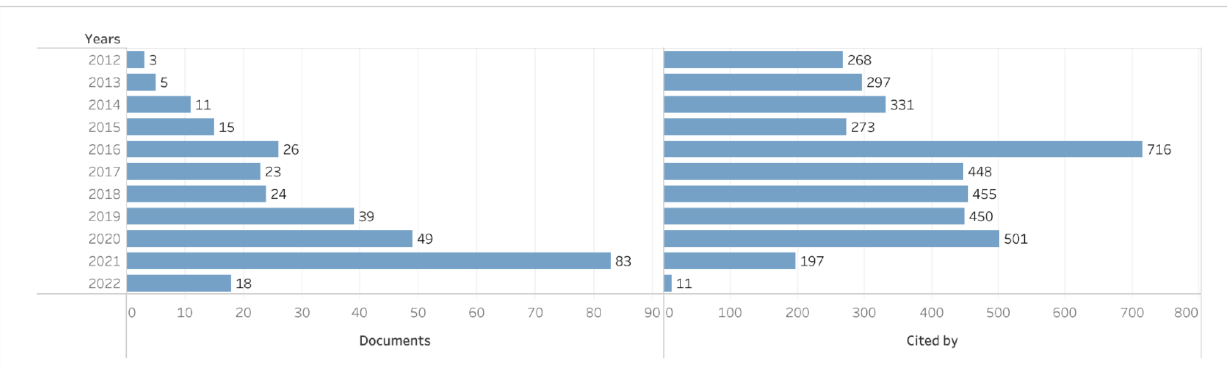


Fig. 4. *Distribution of publications and citations by journal: (a) publication and (b) citation*

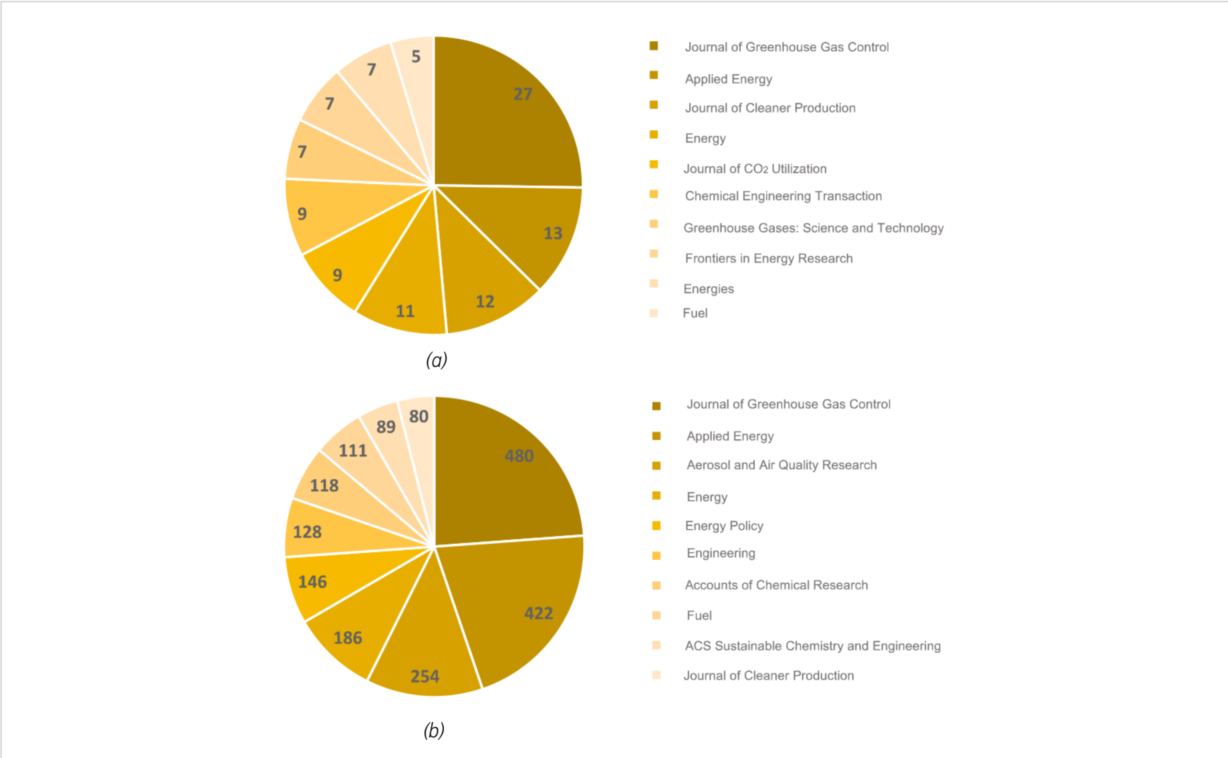
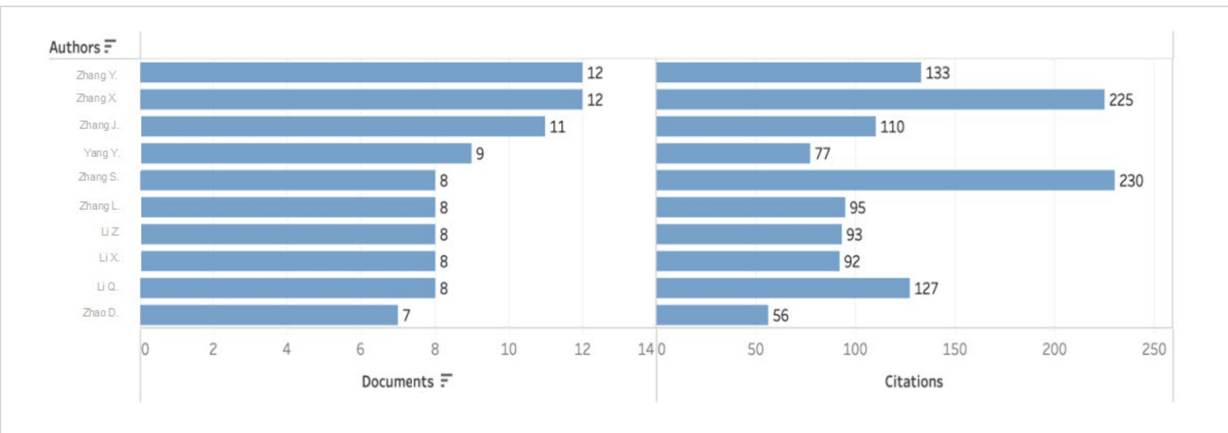
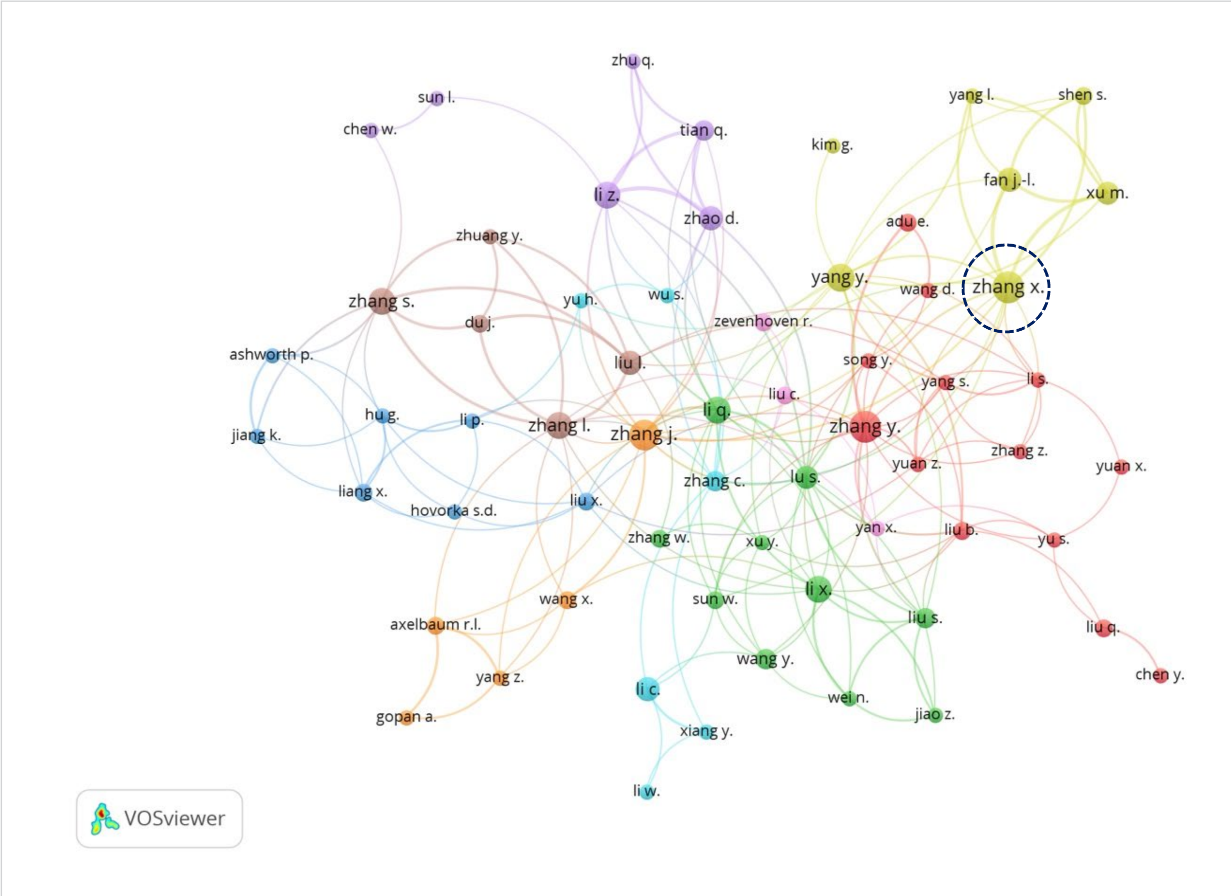


Fig. 5. *Author productivity in terms of publications and citations*



publications issued during 2012–2022, namely 12 documents that received 225 citations. These were lesser compared to Zhang S who reached 230 citations with a total of 8 documents published. The authors' relationship to one another is presented in *Fig. 6*, and in total, they are divided into 9 clusters distinguished by the nodes' color. Zhang X has the highest total link strength of 33 and several relationships with 14 authors from other clusters through an average publication in 2019. The high citations obtained from authors are influenced by their number of links, meaning that there is a high chance of receiving citations with a high link.

Fig. 6. *Co-authorship network of authors*



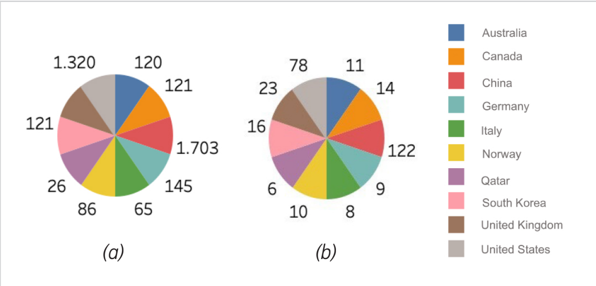
During 2012–2015, Zhang X weighed the research development of CCUS technology in China including enhanced oil recovery and onshore saline aquifer as the most dominant options for the large-scale CO_2 utilization and storage techniques for the development of a roadmap of CCUS technology in China, followed by estimating the potential of methanol through hydrogenation (CTM) and steel slag mineral carbonation and utilization (SCU) to optimize the efficiency of emission reduction, as well as the potential of CO_2 enhanced oil recovery (EOR) and CO_2 enhanced water recovery (EWR) for direct emission reduction.

Throughout the period of 2016–2018, Zhang X highlighted the scope of his research among the topic of the benefit of a vertical integration model that fits for considering the revenue of CCUS technology applied for national projects in China, especially to determine the economic benefits from enhance recovery oil (EOR) and the benefits of CO_2 EOR technology to ease the high investment cost by subsidizing the application of EOR to accelerate the CCUS development in China.

Countries

Fig. 7 shows the top 10 publications and citations based on their geographical location. The results of this study indicated China as the most productive country in conducting investigation on CCUS topics in 2012–2022, where the highest number of citations received was 43.39% and the publications reached 41.08% of the total citations amongst other 9 other countries. However, a similar study of CCUS by (Omoregbe et al., 2018) showed a contrary result, that USA generated more publications (4,416) than China, which generated only 1,876 publications.

Fig. 7. *Top 10 countries with the highest number of citations and publications: (a) citation and (b) publication*

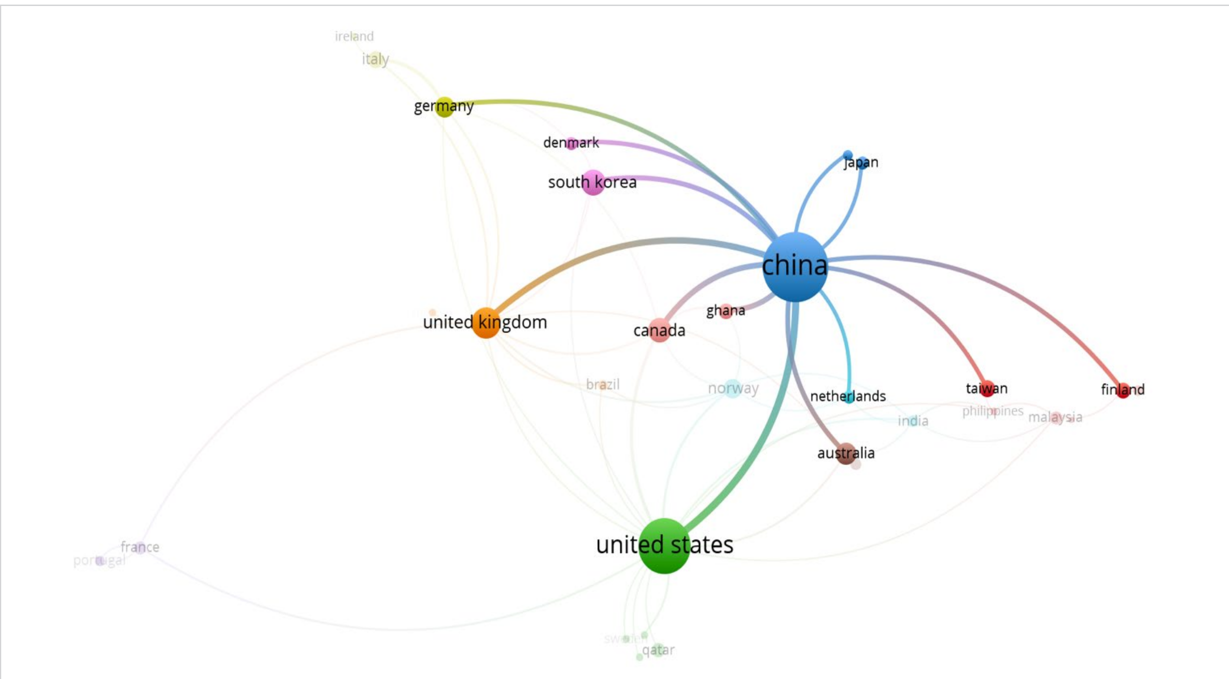


The second rank was occupied by the United States with publications and citations of 26.26% and 33.63%, respectively. As presented in *Fig. 8*, 32 countries were connected and divided into 10 clusters. The total link strength is the accumulated strength of the relationship between different items (Jiang and Ashworth, 2021). Based on countries analysis, the highest total link strength was achieved by China and the United States, namely 45 and 38. Meanwhile, the United Kingdom, Germany, South Korea, and Canada undertook a collaboration on research with China and the United States.

After the meeting of G8 in 2005, these above-mentioned countries were included into a pledge in Hokkaido for strengthening the climate change mitigation (Cosbey, 2009). Recently, Germany and United Kingdom reached the relative high rank for their international policy for climate change mitigation among other G20 countries, followed by the United States and China for their international level of climate negotiations performance. Meanwhile, the Republic of Korea (South Korea) and China received an appreciation amongst other G20 countries for their national climate policy. However, Canada showed the least willingness to improve their climate change mitigation performance due to political interest (Cosbey, 2009).

These remarkable achievements of respective countries were delineated from their Nationally Determined Contribution (NDC) for short-term that affects long-term goals, such as 55% of decarbonization goal belonging to Germany, 40% national reduction target of greenhouse gas emission in United Kingdom, and 25–28% reduction in greenhouse gas emission for the United States (Falduto and Rocha, 2020).

Fig. 8. *Co-authorship network of countries*



Organizations

In this study, the 296 publications were distributed across 687 organizations. This shows that this research was carried out from a diverse number of organizations including companies and mostly from universities. The top 10 organizations with the highest number of citations are shown in *Table 1*. The number of citations obtained from top 10 organizations with the highest citations was 1,553, belonging to the United States (47.39%), Taiwan (30.26%), and China (22.34%). However, the organizations with the highest citations were National Taiwan University and Taipei Medical University with citations of 235 each, while the lowest citations came from Amaren Corp United State (206).

Table 1. *Top 10 organizations with the highest citations*

Organization	Total Citation (%)
Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan	15.13%
Department of Biochemistry, Taipei Medical University, Taipei, Taiwan	15.13%
Indiana Geological Survey, Indiana University, Bloomington, United State	11.14%
Exxonmobil Upstream Company, Houston, United State	11.14%
Department of Geological Sciences, Indiana University, Bloomington, United State	11.14%
Laboratory of Low Carbon Energy, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of thermal Engineering, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Green Chemical Technology of Ministry of Education, Collaborative Innovation Center of Chemical Science and Engineering, School of Chemical Engineering and Technology, Tianjin University, China	7.15%
Department of Chemistry, University of North Carolina at Chapel Hill, United State	7.15%

National Taiwan University secured its most productive position in CCUS publication due to the efforts for weighing the importance of earth science, life science and social science which transformed into multi-disciplinary programs providing solutions particularly for climate change issues implemented in a number of climate change research and carbon capture practices as well as sustainable development related case studies and seminars (NTU, 2018). Meanwhile, Taipei Medical University put its remarkable efforts for CCUS related research topics such as carbonation, slags and steel making that plays a significant role into carbon capture, assigned under Department of Bio-chemistry.

Co-occurrence analysis

In this research, the keywords collected from 296 documents were 3,298. After setting the minimum number of occurrences at eight, 78 thresholds were generated. This shows that 78 keywords were repeated eight times in the 3,298 keywords. The co-occurrence visualization for all keywords is presented in *Fig. 9*, which is divided into four clusters marked with different colors: the first is red, second is green, third is blue, and fourth is yellow. Each cluster has one keyword with the highest total link strength. According to *Table 2*, cluster 1 is "carbon capture", 2 is "carbon sequestration", 3 is "CCUS" and 4 is "carbon dioxide".

The sphere shaped icons are called nodes and they have relationships with one another which indicate the relationships of different keywords. The node size shows the weight and repetition of a keyword, hence a larger size means that the keyword is more frequently used than the keyword of smaller nodes. The distance from one node to another illustrates the strength of their relationship, and the farther link between nodes means that both keywords have less research (Jiang and Ashworth, 2021). The keyword "carbon dioxide" contained in cluster 4 had the highest occurrence of 212, total link strength of 135 and up to 77 linkages compared to other keywords. Meanwhile, "slags" had the lowest occurrence which is 8, total strength of 46, and 19 linkages between keywords. The positions of the top 10 keywords with occurrences and citation scores are depicted in *Fig. 10*.

Fig. 9. *Network of co-occurrence (all keywords)*

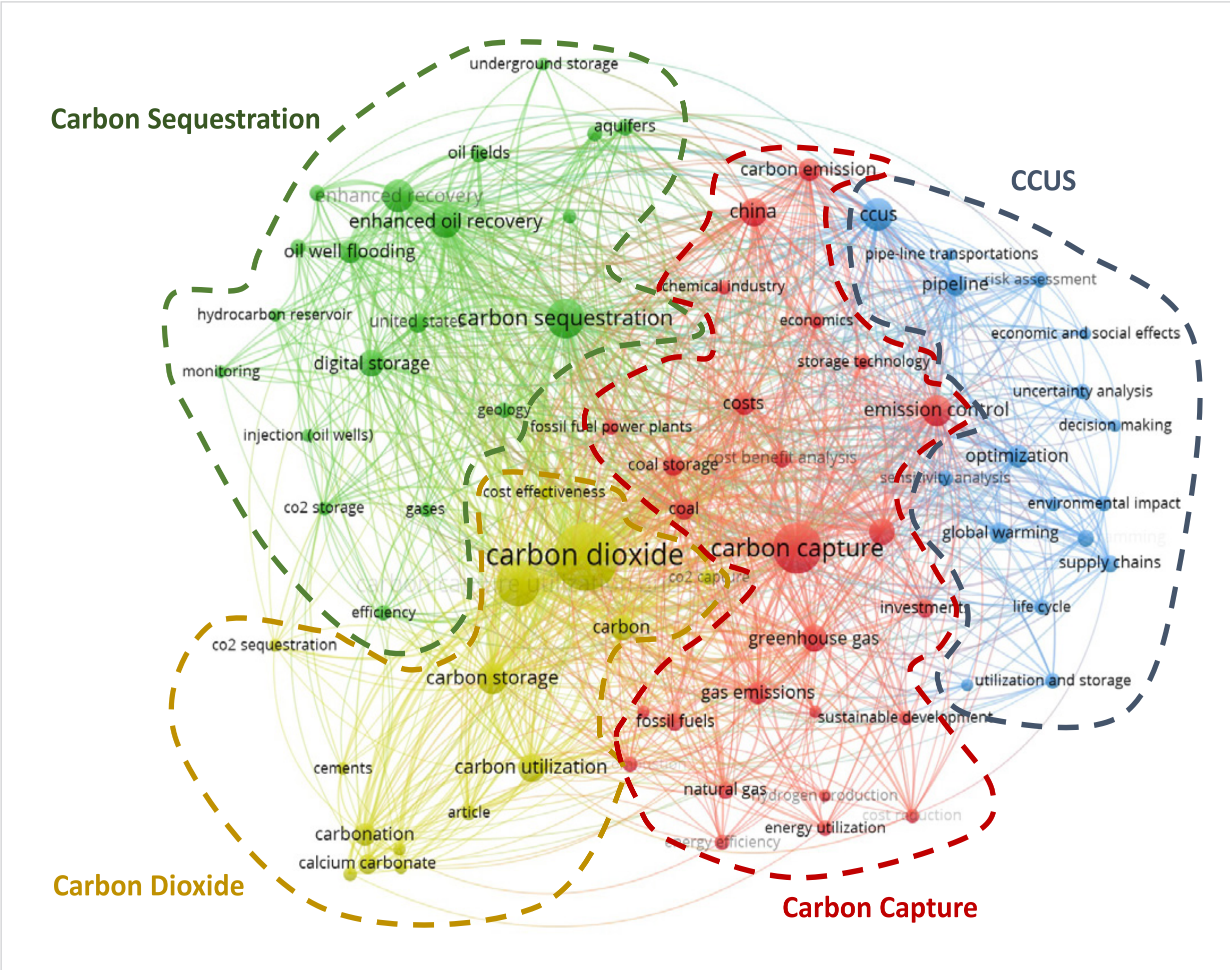


Fig. 10. *Top 10 keywords based on the number of occurrences and citations*

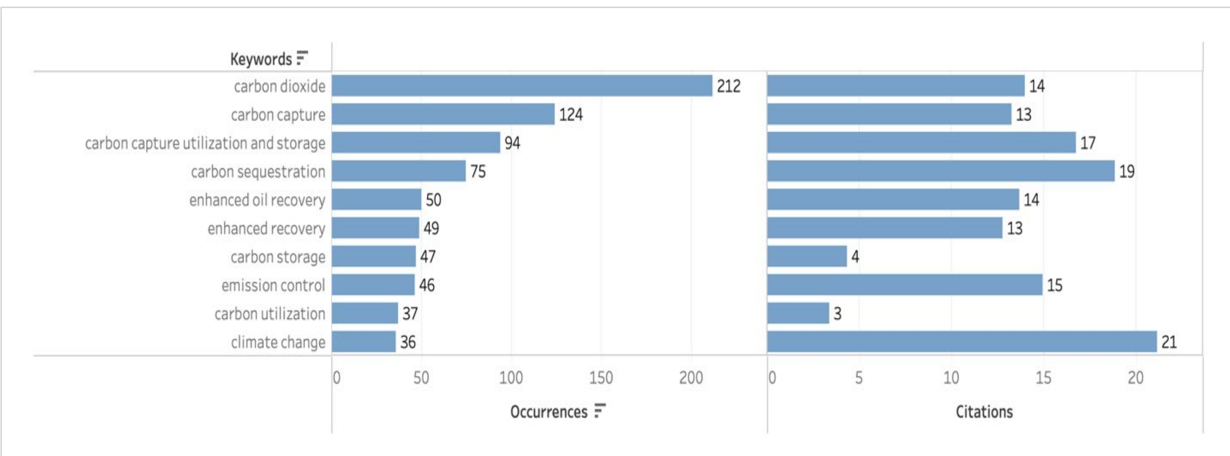
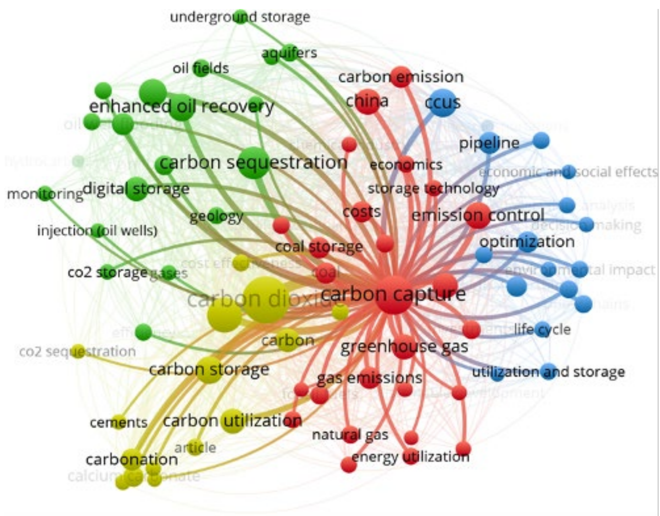
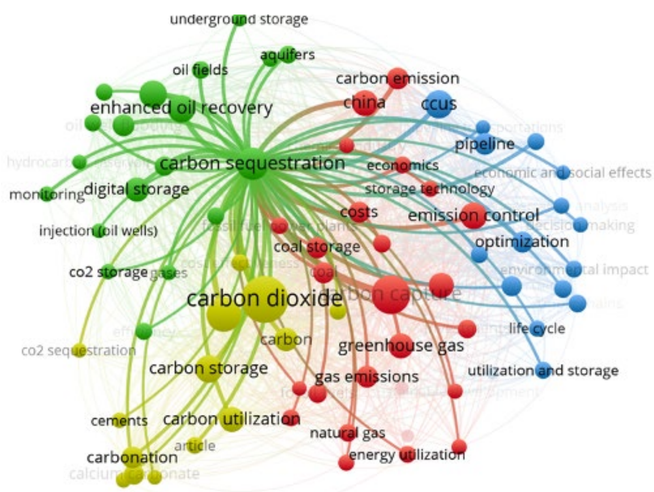
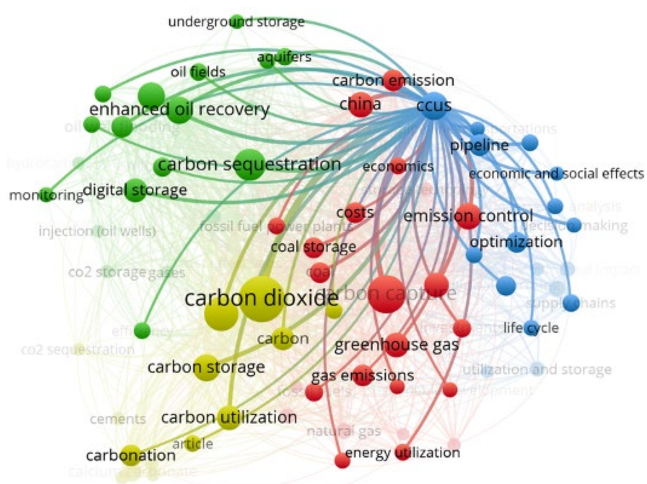
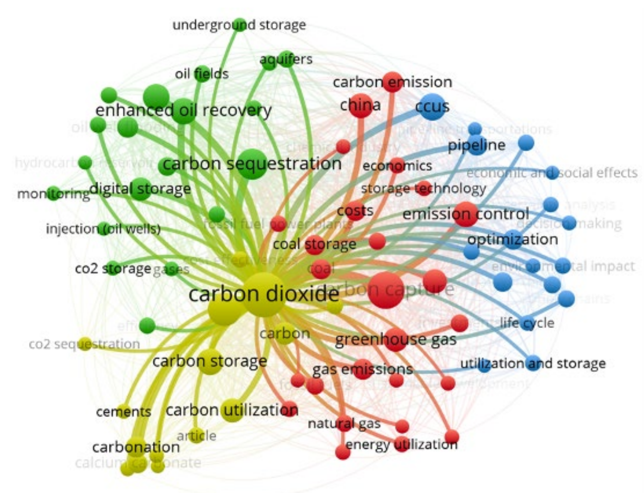


Table 2. *Network visualization keywords in each cluster*

<table>
<tr><th>Cluster</th><th>Visualization</th></tr>
<tr><td>1</td><td>


In cluster 1, “carbon capture” is the keyword that has the largest node size of 76 links with other keywords, and the total link strength of 875. This technology aims to reduce carbon emissions produced from power plants and industries driven by fossil fuels, thereby promoting clean energy transition (Orlov et al., 2022). A report of clean energy transition through the application of CCUS has mentioned Norway as one of the European countries expanding the project of CO_2 capture facilities executed by Norcem (cement factory) and Fortum Oslo Varme (waste-to-energy plant) as well as a large facilities of CO_2 storage in the North Sea established by a group of oil and gas companies. This project, which is known as Longship CCS project, aims to accelerate the capacity of CO_2 transport and storage at the maximum of 5 Mt/year (IEA, 2020).
</td></tr>
<tr><td>2</td><td>


In cluster 2, “carbon sequestration” has the largest node size, 74 links with other keywords and the total link strength of 560. This serves as an efficient and environmentally friendly approach by incorporating carbon dioxide emissions that have been captured into the soil in an organic matter form (Orlov et al., 2022). Even though soil carbon sequestration has been widely applied, analyzing a suitable management system and method to enhance its storage effect is still an important matter to be deepened (Hinge et al., 2020). Sanchez et al. (2018) weighed the potential of geologic sequestration for perpetual storage of CO_2 in saline aquifers, benefited by two corn-based ethanol companies in USA. The first company included the CCUS project established in Decatur, USA, to capture 1 $MtCO_2$/year which then sequestrated in the Mt. Simon sandstone, USA. Another company named Red Trail Energy had a plan to sequester 180,000 t CO_2/year in the Broom Creek Formation, North Dakota.
</td></tr>
</table>

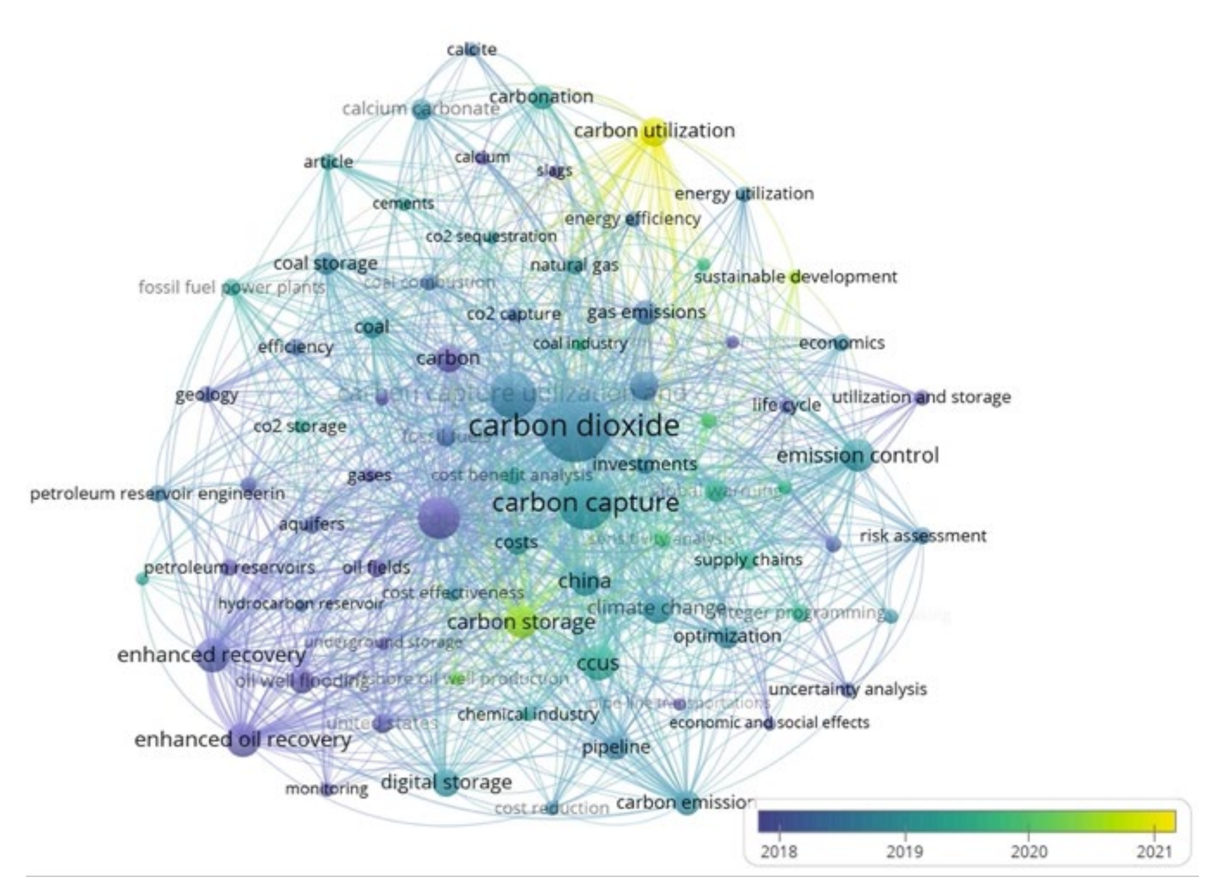
Cluster	Visualization	
3		In cluster 3, "CCUS" has the largest node size, 61 links with other keywords, and the total link strength of 318. CCUS is a technology that plays an important role in reducing carbon emissions in the energy sector so that net-zero emissions can be achieved by eliminating and balancing carbon emissions that are difficult to reduce or avoid. The role of CCUS is proven to be able to eliminate carbon emissions from the energy sector fall to zero by 2070 worldwide in the IEA Sustainable development scenario (IEA, 2020). It has a huge potential as a solution to generate low carbon heat and power, decarbonize industry and reduce CO_2 emissions in the atmosphere (Regufe et al., 2021). CO_2 enhanced oil recovery (CO_2- EOR) method as the technological basis to develop CCUS relies on the CO_2 injection and sequestration to be captured in geologic formation. China, the United States and Canada were the pioneers in the development of CO_2- EOR as this technology has the ability to mitigate CO_2 emission as well as proliferate the production of domestic crude oil, which then followed by some countries such as Brazil, Norway, Trinidad, Turkey, Saudi Arabia and the United Arab Emirates (Hill et al., 2020).
4		In cluster 4, "carbon dioxide" has the largest node size, 77 links with other keywords, and a total link strength of 1325. This is one of the most critical anthropogenic greenhouse gases due to being abundant and persistent in the atmosphere for a long time (Ali et al., 2020). Recently, the demand of energy has been soaring up; however, the energy supplies are dominated by fossil fuel power plants that generate CO_2 emission. In order to generate a net zero CO_2 emission path as a form of sustainable energy, CCUS technology has to create a synergy with the technology of renewable energy, hydrogen, and electrification. Notably, CCUS technology has been commenced since the era of processed natural gas, which are now challenged by the need to develop a modern global technology of CCUS that consist of 3 methods namely pre-combustion, post-combustion and oxy-combustion (Hill et al., 2020).

Carbon dioxide had the highest occurrence at 27.53% amongst the top 10 value of co-occurrence, although the number of citations for the publications with the keyword of "climate change" was higher than the number of citations for the publications with the keyword "carbon dioxide". This result was in line with the research conducted by Awolesi et al. (2019), which generated 38 publications related to the keyword of "carbon dioxide".

According to Awolesi et al. (2019), the highest publication appointed to the low carbon emission research occurred in 2012, within the 2011–2018 period. Meanwhile, Bergamschi (2019) mentioned that the publications of research on carbon capture technology increased gradually from 1998 to 2018 to reach 1,020 documents. Up to 3,800 citations were obtained in the research from 1998 to 2018, and they continued to increase along with the publications even though there were fluctuations. This indicates that the research topics regarding carbon capture, utilization and storage are in annual demand. The International Journal of Greenhouse Gas Control has the highest number of publications, namely 27 documents and 480 citations (Khosroabadi et al., 2021). *Fig. 4* is an overview of the top 10 journals based on the highest publications and citations.

The number of publications and citations on the topic of carbon capture technologies reached 4,532 and 166 with an average citation per publication of 553. This study showed the number of 17.78 as the average citation per publication. *Fig. 11* shows the visualization of all keywords based on the publication year of 2018–2021. The difference of node color indicates the year of publication; hence, a lighter color implies the

Fig. 11. *Overlay visualization co-occurrence (all keywords)*

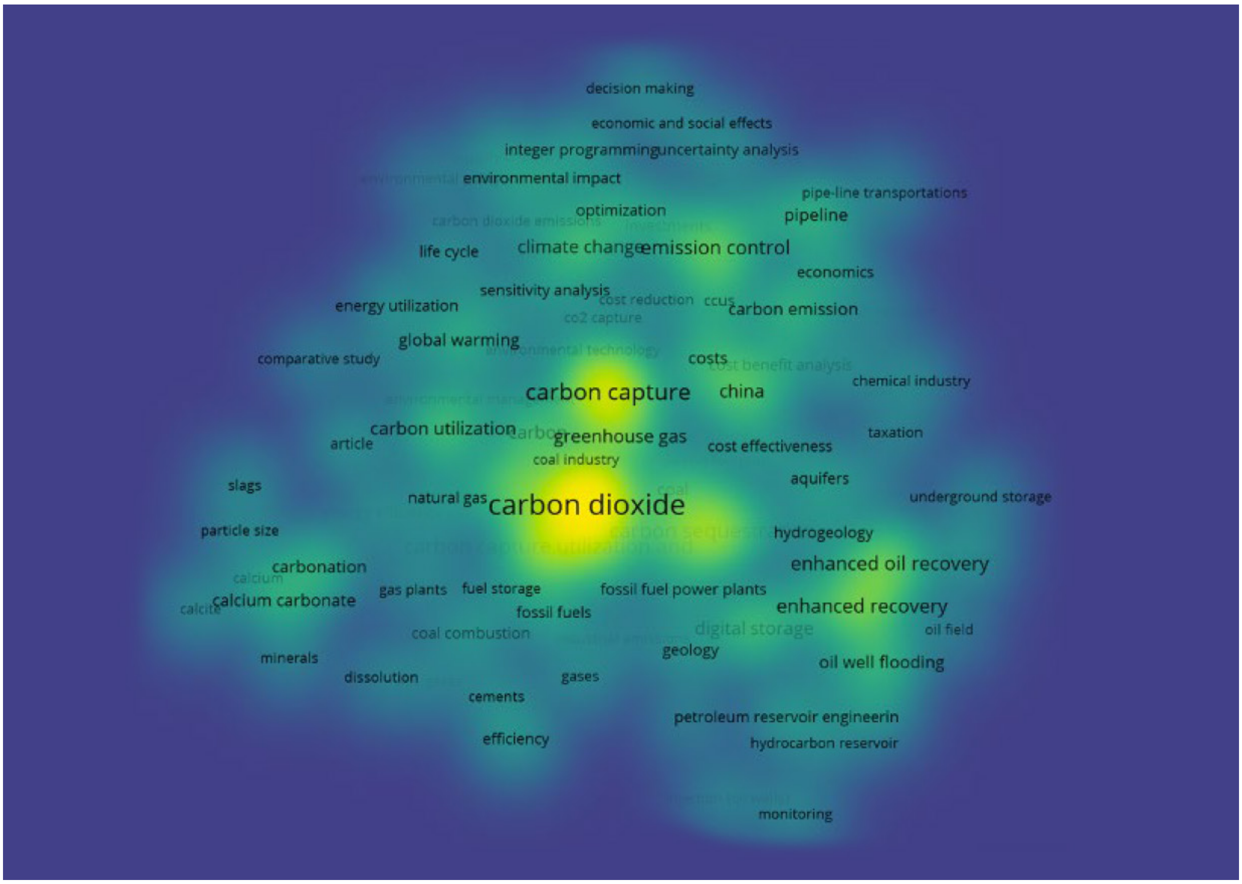


latest publication. The keyword “carbon dioxide” was widely investigated around 2018. “Carbon utilization” appeared around 2021 with 37 occurrences, total link strength of 259 and 62 linkages between keywords. This explains that the research related to carbon utilization was not largely conducted before 2021.

According to Ampah et al. (2021), the bibliometric research should be executed in a way that can strengthen the targeted discipline field through some approaches, namely (1) providing a comprehensive knowledge of the research area; (2) identifying research gaps; (3) highlighting the results of study for future studies. A number of journals identified through Vos Viewer have recognized the existence of CCUS incentive policies and regulations applied for some countries such as China (Zhang et al., 2013), United Kingdom (Leonzio et al., 2020), Hong Kong (Zhang et al., 2021) and United Arab Emirates (Al-Saleh et al., 2012). However, there is a lack of studies addressing the policies and regulations released by ISO standards and international regulation boards to inform on the property rights of the selected sites and accountability for stored $CO_2$with respect to the period of ownership and financial matters.

In addition, the density visualization of index keywords (*Fig. 12*) showed some keywords in the areas of hazy colors (e.g., green-blue color) that interpreted the research gaps in the literature that need to be identified, such as: “environmental impacts”, which can be correlated to the analysis of environmental impacts for CO_2 leakage during transportation; “cost reduction”, which relates to the knowledge of the reduced cost of capture, transport and storage capacity processes; and “carbonation” to be related to the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future,

Fig. 12. *Density visualization co-occurrence (index keywords)*



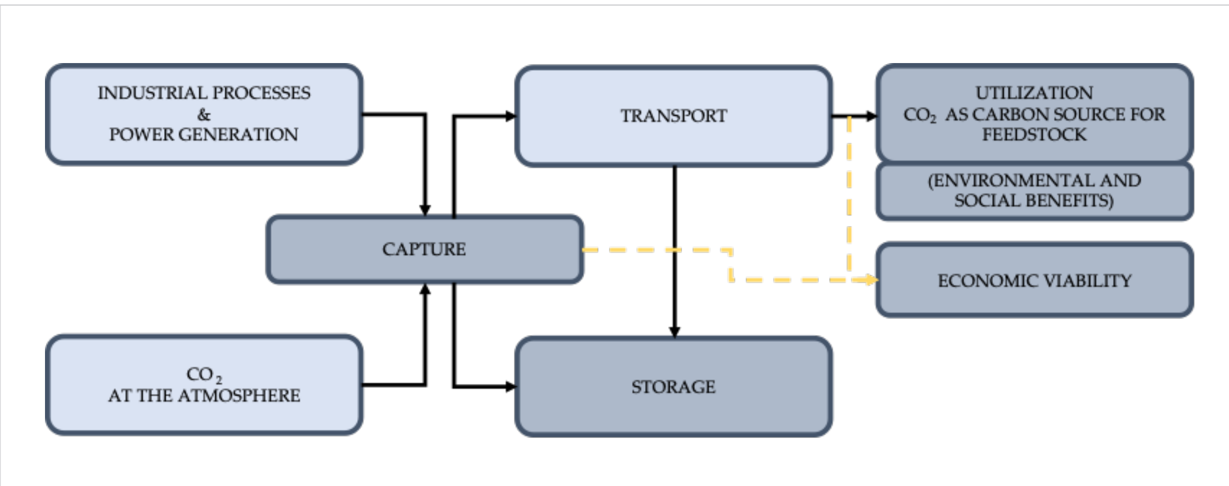
since the existing conventional method of carbonation still requires labor force and are cost-intensive (Simonson et al., 2020). Furthermore, the advanced carbonation method will contribute to the economic viability of carbon utilization, which can be achieved through the use of synthesized rare earth elements at the stage of the treatment process of mineral carbonation for accelerating the economic value of steel slags (Baciocchi and Costa, 2021).

CCUS technology is referred to as sustainable if the economic performance of the preferred method can be achieved without generating additional environmental negative impacts. Thus, CCUS, as one of the climate change mitigation technologies that may achieve the carbon emission reduction target, needs to provide economic, social, and environmental benefits as shown in *Fig. 13* (Assche and Comprenolle, 2022). In addition, the technology of CCU offers the area of social and environmental benefits to be investigated beyond its current initial stage and limited scope of research (Cosbey, 2009). Mitigation and adaptation are important in reducing carbon emissions and are an integrated approach to climate action and development. The integrated approach includes assessment, goal setting, identification, financing and implementation as well as monitoring, evaluation and learning (Jeffrey and Anika, 2022).

Conclusions

CCUS is proven as one of the ultimate technologies for mitigating climate change by capturing carbon emissions produced by industries, which are then being stored at 700 m below the sea level. Bibliometric analysis was used to examine the research trends such as CCUS by identifying keyword networks, authors, organizations, countries, growth trends in terms of the number of publications and citations by publishers and source titles in the period 2012–2022. The results of this study, derived from 296 documents of the Scopus database, showed the increase of publications concerning CCUS related keywords by 2,766.6% within the period of 2012–2022. Based on this study, the most productive country in conducting investigations on CCUS was China, empowered by Zhang X as the most prolific writer affiliated with China University of Petroleum. However, the organization that published the highest number of research on CCUS was National Taiwan University. On the basis of the publication and citation, this study found International Journal of Greenhouse Gas Control as the most productive journal that was published by Elsevier Ltd., that is widely known as a competent publisher of the highest number of publications and citations for research publications. Based on the co-occurrence analysis of index

Fig. 13. *The inclusion of environmental, social and economic impacts into a simplification of the CCUS process to illustrate a sustainable CCUS pathway*



keywords, the research gaps are identified in the literature, such as the analysis of environmental impacts for CO_2 leakage during transportation, the knowledge of the reduced cost of capture, transport and storage capacity processes as well as the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future since the existing conventional method of carbonation still requires labor force and is cost-intensive. This study identified the potential further research for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach. Hence, the importance of CCUS technology for CO_2 sequestration is clearly identified through this study, which is beneficial for the development of CCUS research, particularly to contribute to clean energy transition.

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Thalia

by J Maria Utha

Submission date: 12-Apr-2023 09:56AM (UTC+0700)
Submission ID: 2062163996
File name: Thalia.pdf (2.49M)
Word count: 8425
Character count: 45857

EREM 79/1

Journal of Environmental Research, Engineering and Management
Vol. 79 / No. 1 / 2023
pp. 37–55
DOI 10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

Received 2022/10 Accepted after revision 2023/02

https://doi.org/10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

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The continuous growth of energy consumption leads to the increase of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). Carbon capture, utilization and storage (CCUS), which consists of carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), is a technology that aims to capture CO_2. Therefore, this study evaluates and provides an overview of CCUS in the period 2012–2022, by using a bibliometric analysis to obtain a complete perspective and reference on CCUS. The data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into the Scopus database, and 296 documents were generated. Other software used included Open Refine, VOS viewer and Tableau to describe publication and citation trends, co-authorship, and co-occurrence. CCUS research trend increased by 2,766.6% from 2012 to 2022. The most productive country in investigating CCUS was China, and Zhang X. was the most prolific writer. The organization that published the highest number of research on the topic was the National Taiwan University. The publications and citations were dominated by the International Journal of Greenhouse Gas Control that was published by Elsevier Ltd., which also issues a number of significant publications and receives the highest number of citations.

Keywords: bibliometric analysis, carbon emission, carbon capture, carbon capture utilization, carbon capture storage.

Introduction

The increase of greenhouse gas (GHG) emissions has become a global climate issue that profoundly raises the world's attention due to the impact of climate change. The Intergovernmental Panel on Climate Change (IPCC) launched a Special Report on Global Warming of 1.50 °C, which contains various impacts created on human health, food security and ecosystems. This impact can be anticipated through the attempt of limiting the temperature rise by 1.50 °C above the average temperature prior to industrial era. Total GHG emissions in 2018 reached 55.3 gigatons of CO_2 equivalent. Consequently, hydro-meteorological disasters may occur due to extreme weather that changes the length of dry and rainy season and increases the frequency and duration of droughts. Another impact of climate change is a rise in temperature and sea level (Nerem et al., 2018; Zhao et al., 2020). According to Stone et al. (2009), carbon dioxide emissions have increased by 40% since the period of the Industrial Revolution, and human activities might have greatly contributed to CO_2 release since that time. Carbon dioxide is capable of absorbing long-wave IR radiation (heat) being emitted by the earth which can make the greenhouse effect stronger, hence any increase in CO_2 emissions ultimately causes a rise in the earth's temperature.

The largest CO_2 emissions are generated from agricultural activities, energy production and energy use. Furthermore, trade, transportation, and the growing manufacturing industry add to CO_2 emissions as stated by Adom (2012), which exacerbates the ecological aspects of environment such as climate and climate change. Moreover, the tourism industry elevates carbon dioxide emissions; thereby it is important to raise the awareness of global warming and climate change into the practice of business as usual (Balogh and Jambor, 2017). In order to abate the global warming, reducing the levels of carbon dioxide (CO_2) emissions from exhaust gases produced by industrial activities has to be promptly undertaken since the levels of carbon dioxide (CO_2) emissions have continued to increase from year to year (Rinanti et al., 2014). Global warming has an impact on all living things and nature such as rising sea levels, climate anomalies and natural disasters (Fachrul et al., 2019; Rinanti et al., 2013).

By 2100, the level of atmospheric CO_2 emissions is estimated to reach around 800 ppm and the earth's surface temperature tends to rise by 4 °C (Wang and Oko, 2017). According to The Summary for Policymakers of the IPCC Working Group III report, Climate Change 2022: Mitigation of Climate Change, 195 countries in the world have agreed to limit GHG emissions. A conference held in Paris from 30 November to 12 December 2015 propagated the Paris Agreement to the United Nations Framework Convention on Climate Change. Furthermore, the treaty aims to mitigate the climate change towards a low-carbon, resilient and sustainable future and ensures that global temperature elevations keep well below 2 °C (Wang and Oko, 2017). Carbon capture, utilization and storage (CCUS) comprises carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), both of which aim to capture CO_2 that is being released into the air. The difference between these two technologies lies mainly in the fact that, in CCS, CO_2 emissions are captured and injected into underground storage areas, while in CCU, the CO_2 is converted into commercial products. Based on Zaemi and Rohmana (2021), CCUS's goal is to capture 85% of CO_2 that is released from power plants and industries and the resulting emissions are to be transported into 700 meters depth below sea level through pipes.

Based on IPCC (2022), CCS is the most feasible/accessible technology to reduce emissions from carbon-intensive industries and power generation; however, the mitigation costs tend to reach 138% without CCS technology. This technology is applied for the downstream phase of CCS pathways, by capturing carbon emissions to be stored and utilized for other production processes (Prayitno et al., 2021). Meanwhile, Reiner (2016) has found that CCS technology is employed for climate mitigation and expected to decrease the GHG emissions by 32% until 2050. This target can be justified by the research done by Akbar et al. (2021) that CCS technology captures 85–95% of the CO_2 produced by an industry. Besides of that CCS technology is also

able to reduce carbon emissions with an accuracy level of 95% when applied in a waste-to-energy plant.

The Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCC) has summoned all countries in the world to commit to implementing actions to keep average global temperature below 2 °C and to continue with efforts for suppressing the increase to 1.5 °C. Afterward, targets for each country's commitment were created, where the Paris Agreement set a target to reduce GHG emissions, which is called the Nationally Determined Contribution (NDC). The achievement of GHG emission reductions is verified to ensure that the calculation process complies with the principles that have been recognized as transparent, accurate, consistent, comprehensive, and comparable (TACCC) at the national and international level. This mechanism works through the improvement of scrutinizing and disclosure for lowering the GHG emissions level to encourage the countries for acquiring the climate incentive. The report of TACCC will be beneficial for stakeholders to set a number of measureable goals for climate change mitigation that includes the efforts for reducing emission, resilience enhancement and for allocating financial resources (Weikmans et al., 2019).

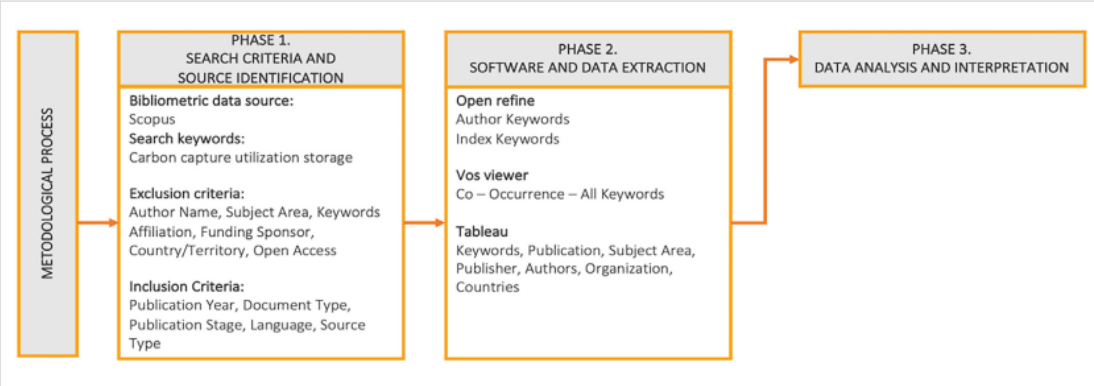
However, the technology of CCUS has not been widely applied, although data and references collection on the technology is largely available. Moreover, the implementation cost of CCUS varies greatly in the fields of electricity and industry (Adisaputro and Saputra, 2017). According to Zaemi and Rohmana (2021), the challenges of developing CCUS are to determine the location of infrastructure and the environment to be used as CO_2 storage areas plus the high required costs. Owing to the significant topic of the IPCC Agenda 2030 on greenhouse gases, CCUS remains to be an interesting global issue to be investigated as a climate change mitigation technology although many studies of greenhouse gases have been extensively conducted. In addition, a number of research works have investigated the application of CCUS technology in some countries, such as the United States (Alphen et al., 2010), China (Jiang and Ashworth, 2020), ASEAN countries (Kimura et al., 2020) and the United Kingdom (Gough et al., 2020). This review, therefore, offers the trend of research development in the field of CCUS to show the acceleration of technology used to apply the CCUS methods for industrialization in some countries within the year of 2012–2022.

The significant objective of this research is to evaluate the growing trend of investigation on CCUS from 2012–2022, as well as to determine the distribution and productivity of research by authors, organizations, and countries, plus the distribution of research work on subject areas and publishers through the following research questions namely: (1) How do the CCUS technologies provide a solution for reducing the carbon emission of industries around the world?; (2) What are the CCUS technologies that most frequently applied for the industry within 2012–2022?; (3) Who are the most prolific authors followed by the most productive countries and organizations?; (4) What are the potential areas of interest in the research development of CCUS technologies? Therefore, the bibliometric analysis which aims to find the research gaps for further exploration on the topic of carbon capture, utilization and storage, was conducted by using the Scopus database. This article divides its systematics of writing into the following parts, namely the introduction, methods, results and discussion, conclusion and references list.

Methods

According to Chen et al. (2015), Singh and Borthakur (2018), a bibliometric analysis is an effective method of analyzing research progress and quantitative trends in publications on a particular topic, by providing an overview of literature contribution both nationally and internationally (Zhang et al., 2020; Zyoud et al., 2022). Sweileh (2022) explains that any bibliometric study uses a statistic approach to identify growth patterns and development of publications as well as collaborative patterns among authors, institutions, and countries. Moreover, bibliometrics identify the research gaps through analyzing the research niche offered by the publication database, which is useful to provide the basis for conducting further research (Singh and Borthakur, 2018; Zhang et al., 2020). The method is divided into three phases, namely data mining, extraction and analysis, as presented in *Fig. 1*.

Fig. 1. *Study method diagram*



Search criteria and source identification

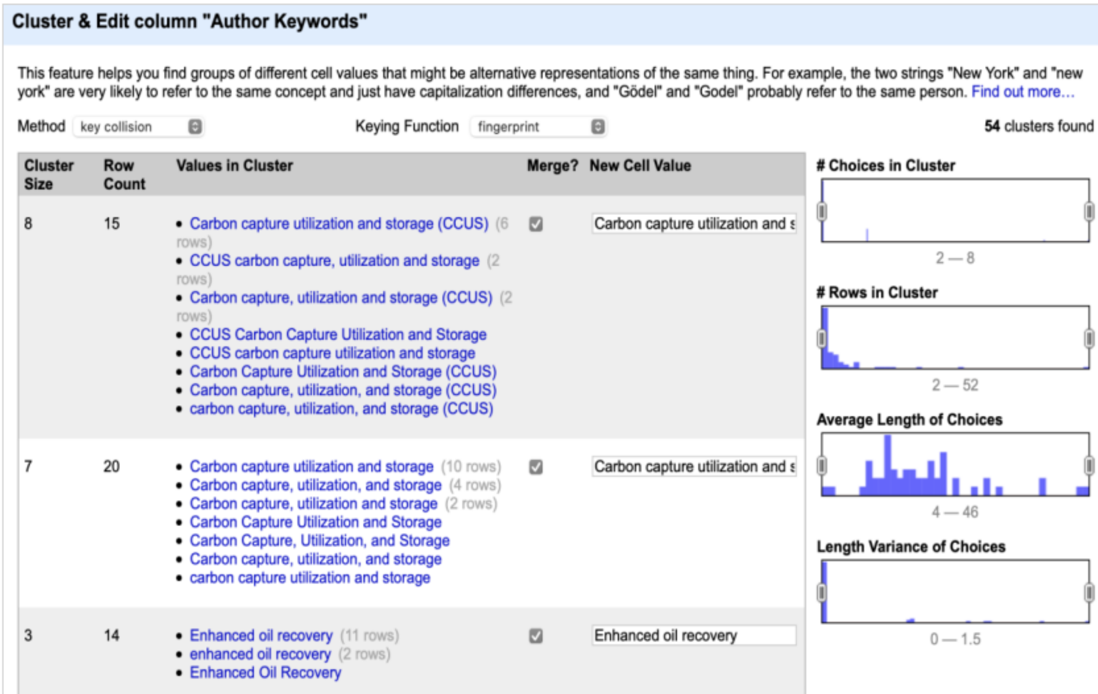
In phase I, data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into Scopus database. Owing to the nature of Scopus as the world's leading literature database published by Elsevier and known to have the highest number of citations (Herawati et al., 2022; Borthakur and Govind, 2017), the Scopus database fits into the expected outcomes of this study. Then, filtering was done with the year of publication, document type, publication stage, language, and source type to obtain more significant results. The data were mined from 2012 to 2022 by limiting the type of article document, final publication stage, journal source type and the English language used. After filtering, 296 available documents were generated and the search results were exported in the CSV format with citation information, bibliographical information, abstract, and keywords. Files exported from the Scopus database were fed into the Open Refine software to reduce inconsistent and repetitive keywords in the mined data.

Software and data extraction

The data obtained from the Scopus database was further extracted and processed by using Open Refine, Vos Viewer and Tableau Public software. The data were fed into Open Refine to reduce several keywords with different spellings but same meaning and to establish the keywords in an exact writing format for avoidance of repetition. Open Refine is able to clean the data from one format to another, overcomes inconsistencies in data sets and divides data into more detailed parts, in an automatic or manual attempt (NIH, 2022).

Fig. 2 shows repeated keywords, namely "Carbon Capture Utilization and Storage (CCUS)", "CCUS carbon capture, utilization and storage", "Carbon capture, utilization and storage (CCUS)", "CCUS Carbon Capture Utilization and Storage", "CCUS Carbon Capture Utilization and Storage", "Carbon Capture Utilization and Storage (CCUS)", "Carbon capture, utilization and Storage (CCUS)" and "carbon capture, utilization, and storage (CCUS)". Some of these have the same meaning but different spellings, hence they are reduced to one format of the keyword, i.e., "Carbon Capture Utilization and Storage (CCUS)". The reduced keywords generated through Open Refine were then fed into the VOS Viewer software, which presents and visualizes specific information about bibliometric chart maps for easier analysis of the relationships or networks about a research topic (Athar et al., 2019). Open Refine enables the author to select the preferred data set, thus the results contained a list of useful data that removes redundant keywords. It means that carbon capture utilization and storage (CCUS) has been tested as the natural result of removing data with redundant keywords. In addition, CCUS is the representative value of other related values (Bergamschi, 2019), to generate a more extensive subject field such as Carbon Capture and Carbon Storage, Carbon Capture Strategies and Carbon Storage Sustainable.

Fig. 2. *Extract data using Open Refine*



The software provides data visualization based on co-authorship, co-occurrence, citation, bibliometric coupling, and co-citation. In this study, co-occurrence of all keywords (author and index keywords) as well as co-authorship (authors) based on network and overlay visualization were used particularly. In co-occurrence analysis, all keywords were chosen as the selected unit with a full counting method. Based on the 296 documents from Scopus, 3,298 keywords were obtained. Once the minimum number of occurrences was set at eight, 78 thresholds were generated, indicating that 78 keywords were repeated eight times in the 3,298 keywords.

Even though the keywords were tidied up in Open Refine, some redundant keywords still appeared that had the same meaning as CO_2 and carbon dioxide. These were employed as a writing format using Thesaurus note, which were then imported into VOS Viewer. In co-authorship analysis, the applied unit analysis referred to authors with the full counting method. The total number of authors in the 296 Scopus-generated documents was 1,011. After setting the minimum number of an author's documents at three, the threshold obtained was 76 authors. Tableau software was used to simplify complex data in the form of interactive graphic visualizations, for easy analysis and understanding (Akhtar et al., 2020). Akhtar et al. (2017) and Murray (2013) stated that Tableau is the most powerful and flexible analytical platform for providing data information and managing their rows into various visualization types.

Data analysis and interpretation

296 research publications were processed by using Open Refine, VOS Viewer and Tableau software regarding publication and citation trends; co-authorship and co-occurrence were analyzed and interpreted, then comparative analysis was conducted within the aforementioned research publications.

The method should consist of research design, subject characteristics, data collection process and data analysis. If necessary, it should raise ethical issues

particularly when dealing with human participants. Appropriate statistical methods should be used, although the biological mechanism should be emphasized. The statistical model, classes, blocks, and experimental units must be designated. Consultation with a statistician is recommended to prevent any incorrect or inadequate statistical methods.

Results and Discussion

Global distribution of publication and citation trend (2012–2022)

One of the objectives mentioned in this article is the determination of global research distribution in 2012–2022. The trends of publications and citations in those years are presented in *Fig. 3*. The total number of publications obtained from Scopus regarding "Carbon Capture Utilization and Storage" was 296. This figure increases significantly from 3 publications in 2012 to 83 publications in 2021. The number of publications and citations in 2021 are inversely related. In 2022, the total number of published documents and citations seemed to decrease because the data were collected in January, hence they did not represent 2022 as a whole. From 2012 to 2015, the increase of published documents and citations was directly proportional, but in 2016, the number of citations increased. The highest citations occurred in 2016; however, the number decreased by 72% after 2016.

Research on carbon capture, utilization and storage (CCUS) has been issued from several journals and publishers including Elsevier Ltd., MDPI AG, Frontiers Media S.A., Italian Association of Chemical Engineering – AIDIC, and Blackwell Publisher Ltd, which are the top 5. Elsevier Ltd. has the highest number of publications and 1,322 citations of 97 documents, as well as journals reaching 28. Furthermore, its top 5 journals with the number of publications and citations respectively are Journal of 1) Greenhouse Gas Control (36.76%; 24.93%), 2) Cleaner Production (17.65%; 7.01%), 3) Applied Energy (17.65%; 38.40%), 4) Energy (16.18%; 13.28%), and 5) CO_2 Utilization (11.76%; 16.38%). Based on the results, 138 journals published articles on carbon capture, utilization and storage with up to 3,947 received citations.

Co-authorship analysis

This co-authorship analysis indicates the relationship between authors, countries and organizations, represented in a network diagram containing nodes and lines classified in different clusters. The clusters of nodes and lines are being distinguished by colors, while the size of nodes shows the weight and repetition of keywords. In addition, the distance from one node to another illustrates the strength of their relationship, and farther link between nodes means both keywords have less research (Khosroabadi et al., 2021).

Authors

The authors who conducted research on CCUS were 62, while their productivity is depicted in *Fig. 5* with the highest number of publications and citations. Zhang X is the most prolific writer in terms of the number of

Fig. 3. *Annual publication and citation spread (2012–2022)*

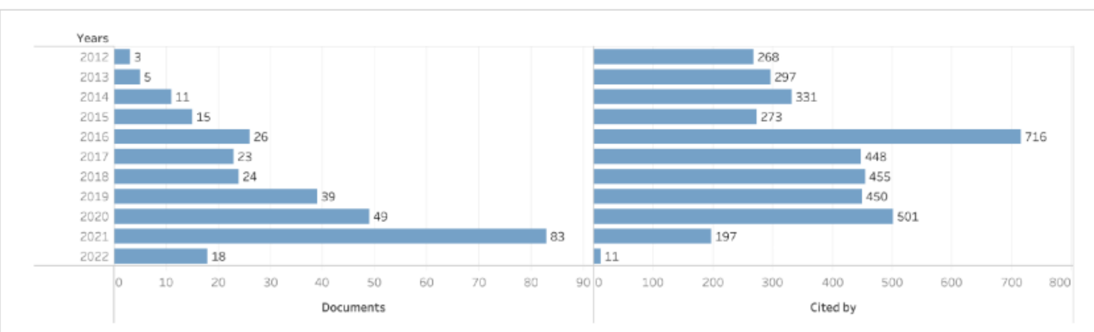


Fig. 4. *Distribution of publications and citations by journal: (a) publication and (b) citation*

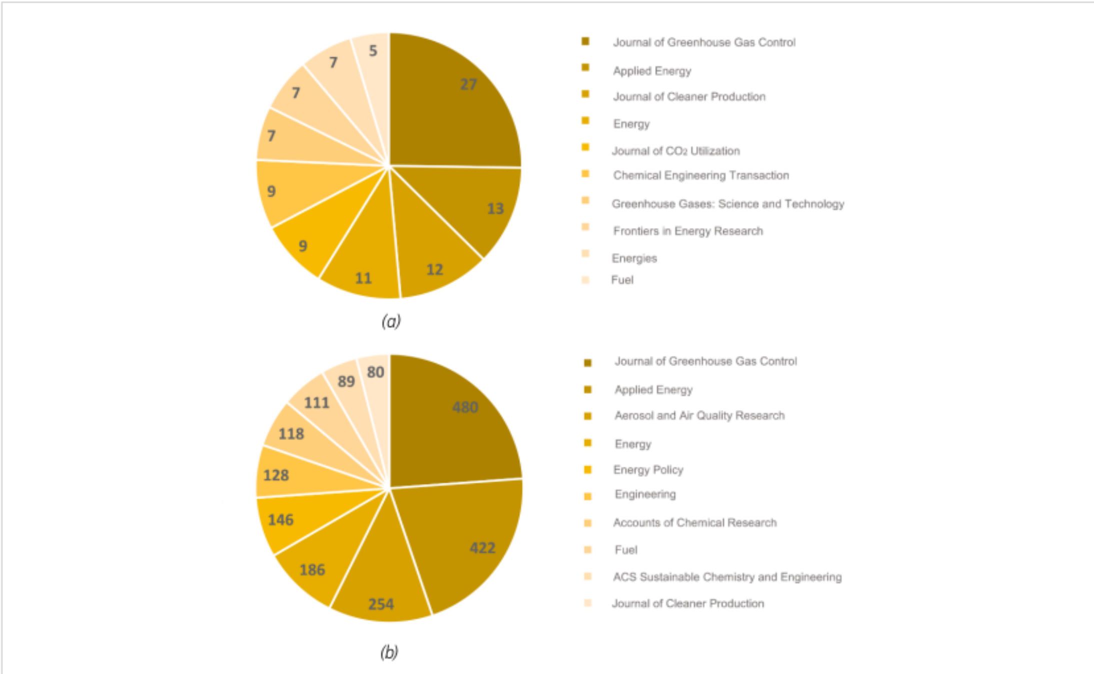
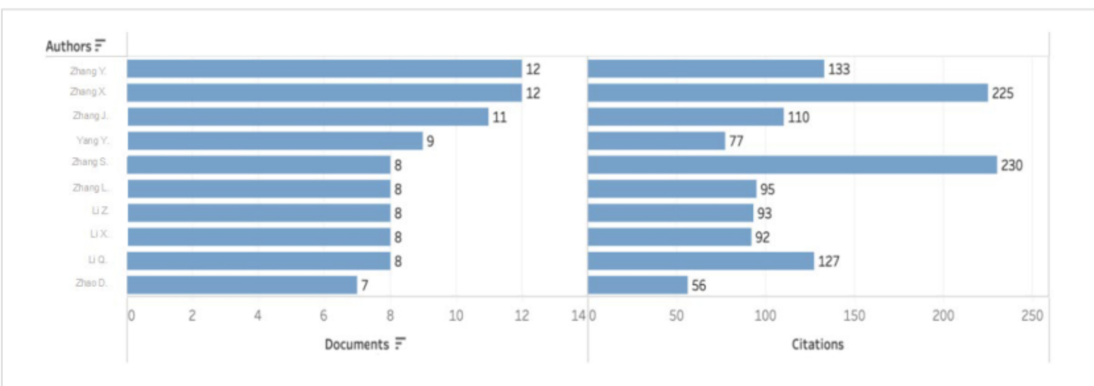
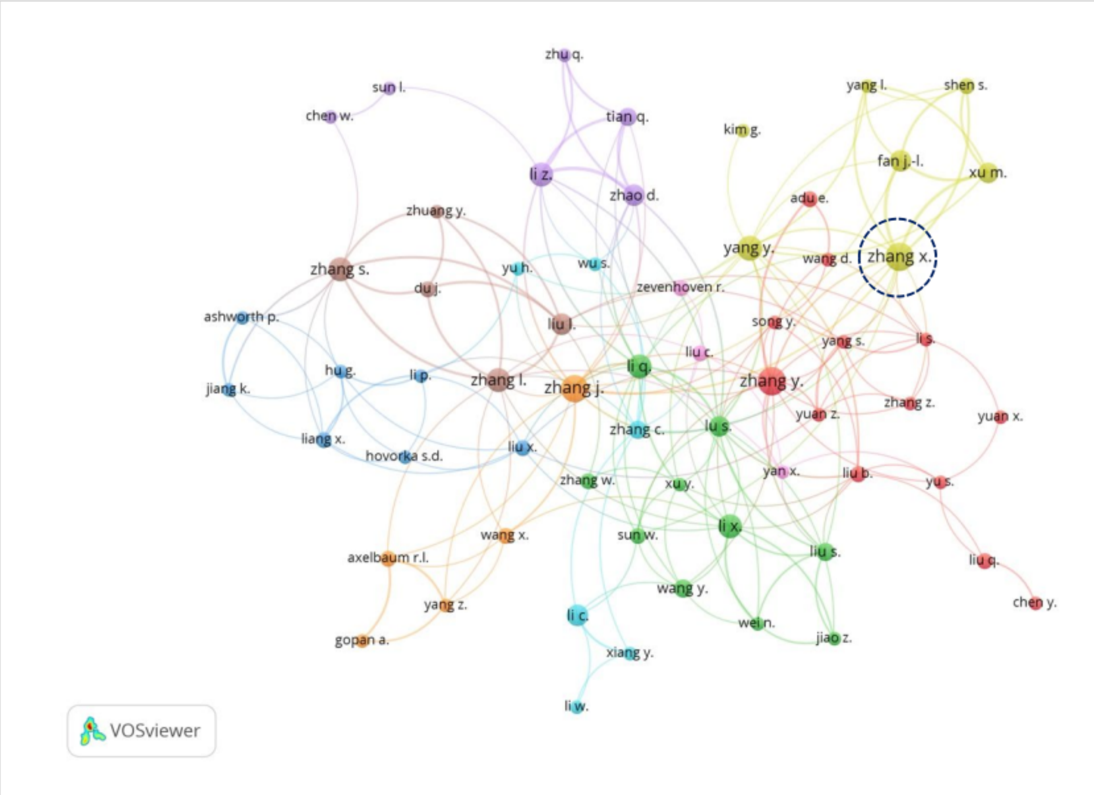


Fig. 5. *Author productivity in terms of publications and citations*



publications issued during 2012–2022, namely 12 documents that received 225 citations. These were lesser compared to Zhang S who reached 230 citations with a total of 8 documents published. The authors' relationship to one another is presented in *Fig. 6*, and in total, they are divided into 9 clusters distinguished by the nodes' color. Zhang X has the highest total link strength of 33 and several relationships with 14 authors from other clusters through an average publication in 2019. The high citations obtained from authors are influenced by their number of links, meaning that there is a high chance of receiving citations with a high link.

Fig. 6. *Co-authorship network of authors*



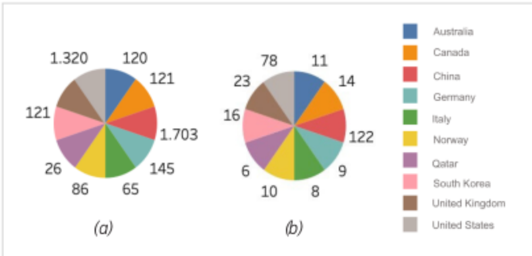
During 2012–2015, Zhang X weighed the research development of CCUS technology in China including enhanced oil recovery and onshore saline aquifer as the most dominant options for the large-scale CO_2 utilization and storage techniques for the development of a roadmap of CCUS technology in China, followed by estimating the potential of methanol through hydrogenation (CTM) and steel slag mineral carbonation and utilization (SCU) to optimize the efficiency of emission reduction, as well as the potential of CO_2 enhanced oil recovery (EOR) and CO_2 enhanced water recovery (EWR) for direct emission reduction.

Throughout the period of 2016–2018, Zhang X highlighted the scope of his research among the topic of the benefit of a vertical integration model that fits for considering the revenue of CCUS technology applied for national projects in China, especially to determine the economic benefits from enhance recovery oil (EOR) and the benefits of CO_2 EOR technology to ease the high investment cost by subsidizing the application of EOR to accelerate the CCUS development in China.

Countries

Fig. 7 shows the top 10 publications and citations based on their geographical location. The results of this study indicated China as the most productive country in conducting investigation on CCUS topics in 2012–2022, where the highest number of citations received was 43.39% and the publications reached 41.08% of the total citations amongst other 9 other countries. However, a similar study of CCUS by (Omoregbe et al., 2018) showed a contrary result, that USA generated more publications (4,416) than China, which generated only 1,876 publications.

Fig. 7. *Top 10 countries with the highest number of citations and publications: (a) citation and (b) publication*

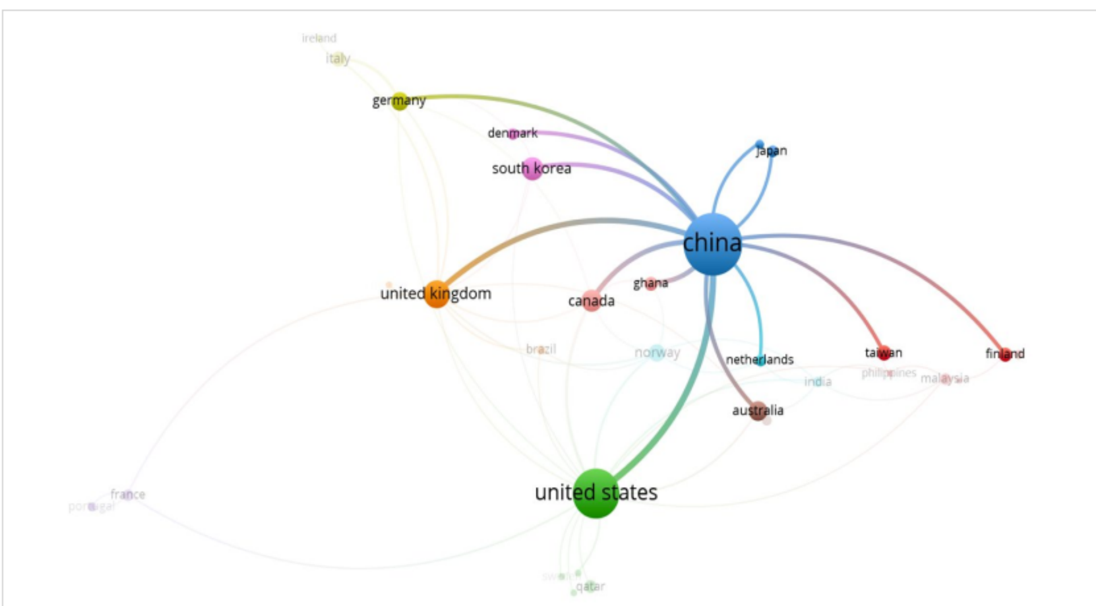


The second rank was occupied by the United States with publications and citations of 26.26% and 33.63%, respectively. As presented in *Fig. 8*, 32 countries were connected and divided into 10 clusters. The total link strength is the accumulated strength of the relationship between different items (Jiang and Ashworth, 2021). Based on countries analysis, the highest total link strength was achieved by China and the United States, namely 45 and 38. Meanwhile, the United Kingdom, Germany, South Korea, and Canada undertook a collaboration on research with China and the United States.

After the meeting of G8 in 2005, these above-mentioned countries were included into a pledge in Hokkaido for strengthening the climate change mitigation (Cosbey, 2009). Recently, Germany and United Kingdom reached the relative high rank for their international policy for climate change mitigation among other G20 countries, followed by the United States and China for their international level of climate negotiations performance. Meanwhile, the Republic of Korea (South Korea) and China received an appreciation amongst other G20 countries for their national climate policy. However, Canada showed the least willingness to improve their climate change mitigation performance due to political interest (Cosbey, 2009).

These remarkable achievements of respective countries were delineated from their Nationally Determined Contribution (NDC) for short-term that affects long-term goals, such as 55% of decarbonization goal belonging to Germany, 40% national reduction target of greenhouse gas emission in United Kingdom, and 25–28% reduction in greenhouse gas emission for the United States (Falduto and Rocha, 2020).

Fig. 8. *Co-authorship network of countries*



Organizations

In this study, the 296 publications were distributed across 687 organizations. This shows that this research was carried out from a diverse number of organizations including companies and mostly from universities. The top 10 organizations with the highest number of citations are shown in *Table 1*. The number of citations obtained from top 10 organizations with the highest citations was 1,553, belonging to the United States (47.39%), Taiwan (30.26%), and China (22.34%). However, the organizations with the highest citations were National Taiwan University and Taipei Medical University with citations of 235 each, while the lowest citations came from Amaren Corp United State (206).

Table 1. *Top 10 organizations with the highest citations*

Organization	Total Citation (%)
Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan	15.13%
Department of Biochemistry, Taipei Medical University, Taipei, Taiwan	15.13%
Indiana Geological Survey, Indiana University, Bloomington, United State	11.14%
Exxonmobil Upstream Company, Houston, United State	11.14%
Department of Geological Sciences, Indiana University, Bloomington, United State	11.14%
Laboratory of Low Carbon Energy, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of thermal Engineering, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Green Chemical Technology of Ministry of Education, Collaborative Innovation Center of Chemical Science and Engineering, School of Chemical Engineering and Technology, Tianjin University, China	7.15%
Department of Chemistry, University of North Carolina at Chapel Hill, United State	7.15%

National Taiwan University secured its most productive position in CCUS publication due to the efforts for weighing the importance of earth science, life science and social science which transformed into multi-disciplinary programs providing solutions particularly for climate change issues implemented in a number of climate change research and carbon capture practices as well as sustainable development related case studies and seminars (NTU, 2018). Meanwhile, Taipei Medical University put its remarkable efforts for CCUS related research topics such as carbonation, slags and steel making that plays a significant role into carbon capture, assigned under Department of Bio-chemistry.

Co-occurrence analysis

In this research, the keywords collected from 296 documents were 3,298. After setting the minimum number of occurrences at eight, 78 thresholds were generated. This shows that 78 keywords were repeated eight times in the 3,298 keywords. The co-occurrence visualization for all keywords is presented in *Fig. 9*, which is divided into four clusters marked with different colors: the first is red, second is green, third is blue, and fourth is yellow. Each cluster has one keyword with the highest total link strength. According to *Table 2*, cluster 1 is “carbon capture”, 2 is “carbon sequestration”, 3 is “CCUS” and 4 is “carbon dioxide”.

The sphere shaped icons are called nodes and they have relationships with one another which indicate the relationships of different keywords. The node size shows the weight and repetition of a keyword, hence a larger size means that the keyword is more frequently used than the keyword of smaller nodes. The distance from one node to another illustrates the strength of their relationship, and the farther link between nodes means that both keywords have less research (Jiang and Ashworth, 2021). The keyword “carbon dioxide” contained in cluster 4 had the highest occurrence of 212, total link strength of 135 and up to 77 linkages compared to other keywords. Meanwhile, “slags” had the lowest occurrence which is 8, total strength of 46, and 19 linkages between keywords. The positions of the top 10 keywords with occurrences and citation scores are depicted in *Fig. 10*.

Fig. 9. *Network of co-occurrence (all keywords)*

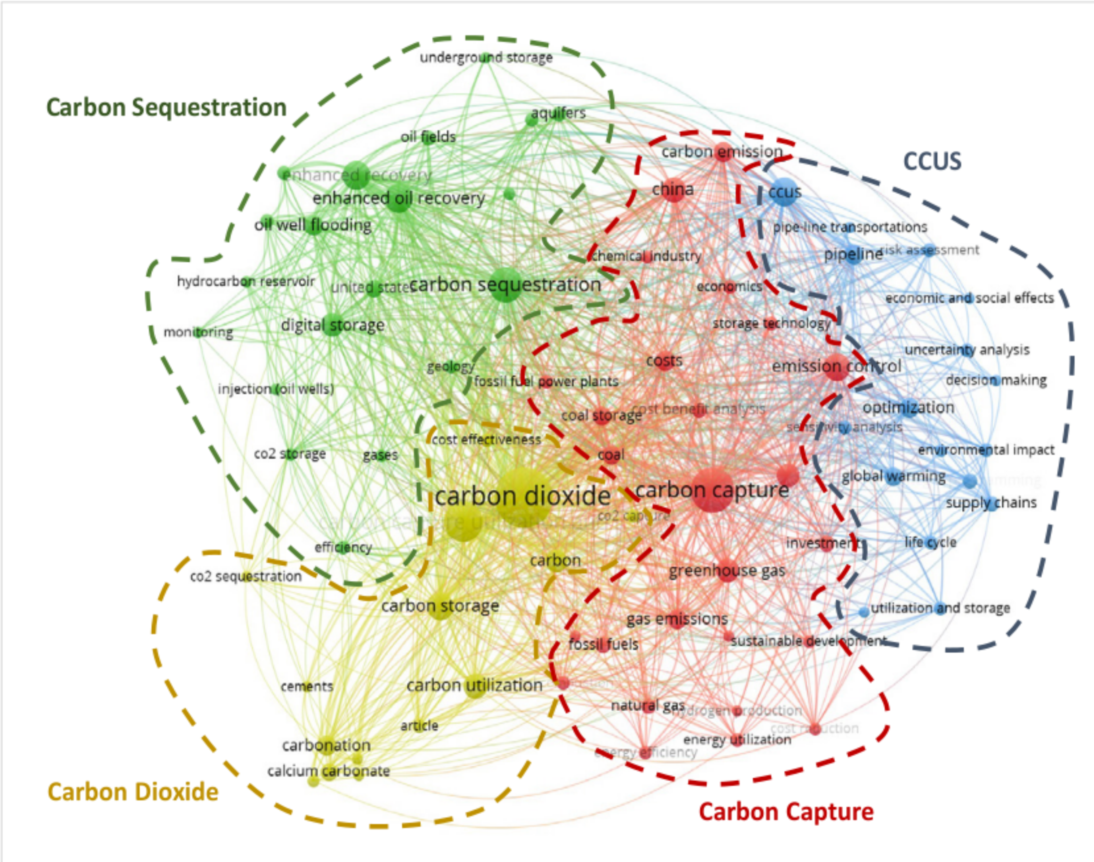


Fig. 10. *Top 10 keywords based on the number of occurrences and citations*

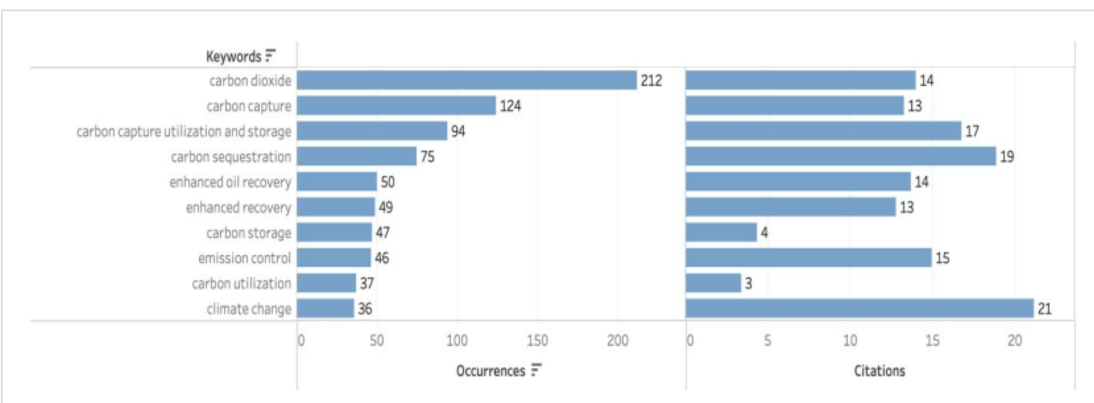
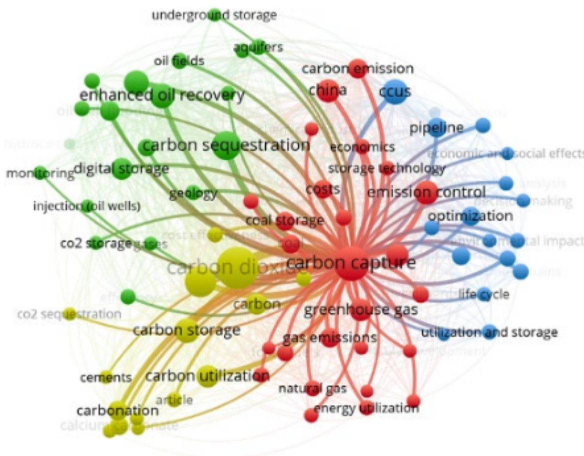
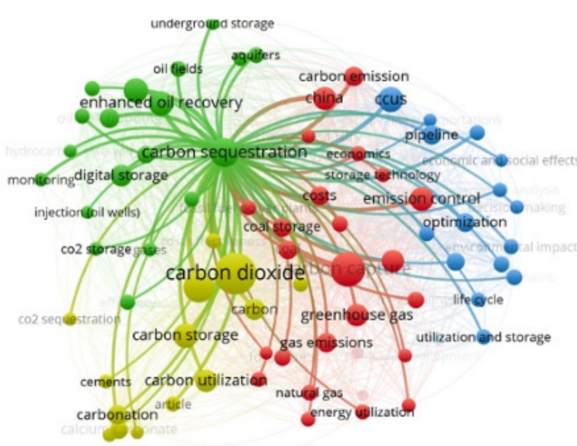


Table 2. *Network visualization keywords in each cluster*

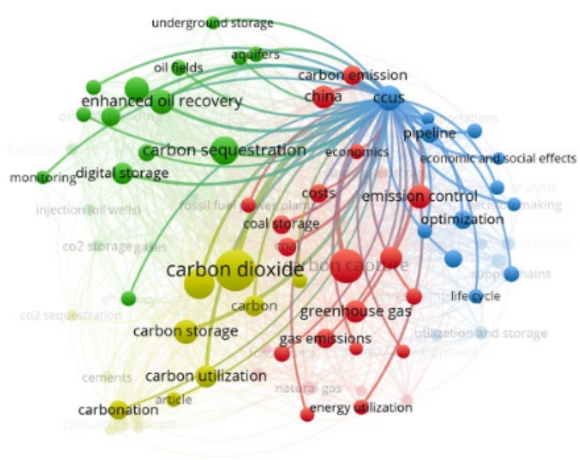
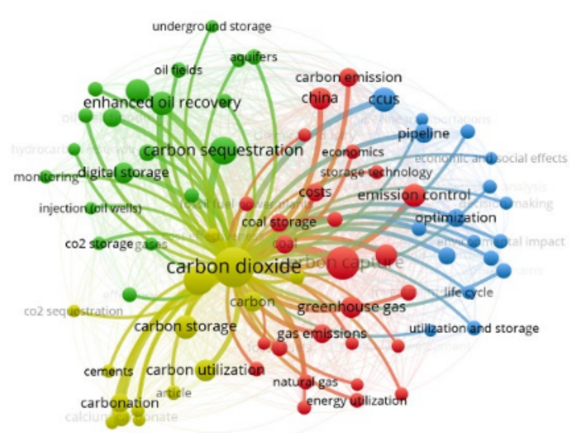
<table>
<tr><th>Cluster</th><th colspan="2">Visualization</th></tr>
<tr><td>1</td><td>



</td><td>In cluster 1, "carbon capture" is the keyword that has the largest node size of 76 links with other keywords, and the total link strength of 875. This technology aims to reduce carbon emissions produced from power plants and industries driven by fossil fuels, thereby promoting clean energy transition (Orlov et al., 2022). A report of clean energy transition through the application of CCUS has mentioned Norway as one of the European countries expanding the project of CO_2 capture facilities executed by Norcem (cement factory) and Fortum Oslo Varme (waste-to-energy plant) as well as a large facilities of CO_2 storage in the North Sea established by a group of oil and gas companies. This project, which is known as Longship CCS project, aims to accelerate the capacity of CO_2 transport and storage at the maximum of 5 Mt/year (IEA, 2020).</td></tr>
<tr><td>2</td><td>



</td><td>In cluster 2, "carbon sequestration" has the largest node size, 74 links with other keywords and the total link strength of 560. This serves as an efficient and environmentally friendly approach by incorporating carbon dioxide emissions that have been captured into the soil in an organic matter form (Orlov et al., 2022). Even though soil carbon sequestration has been widely applied, analyzing a suitable management system and method to enhance its storage effect is still an important matter to be deepened (Hinge et al., 2020). Sanchez et al. (2018) weighed the potential of geologic sequestration for perpetual storage of CO_2 in saline aquifers, benefited by two corn-based ethanol companies in USA. The first company included the CCUS project established in Decatur, USA, to capture 1 $MtCO_2$/year which then sequestrated in the Mt. Simon sandstone, USA. Another company named Red Trail Energy had a plan to sequester 180,000 t CO_2/year in the Broom Creek Formation, North Dakota.</td></tr>
</table>

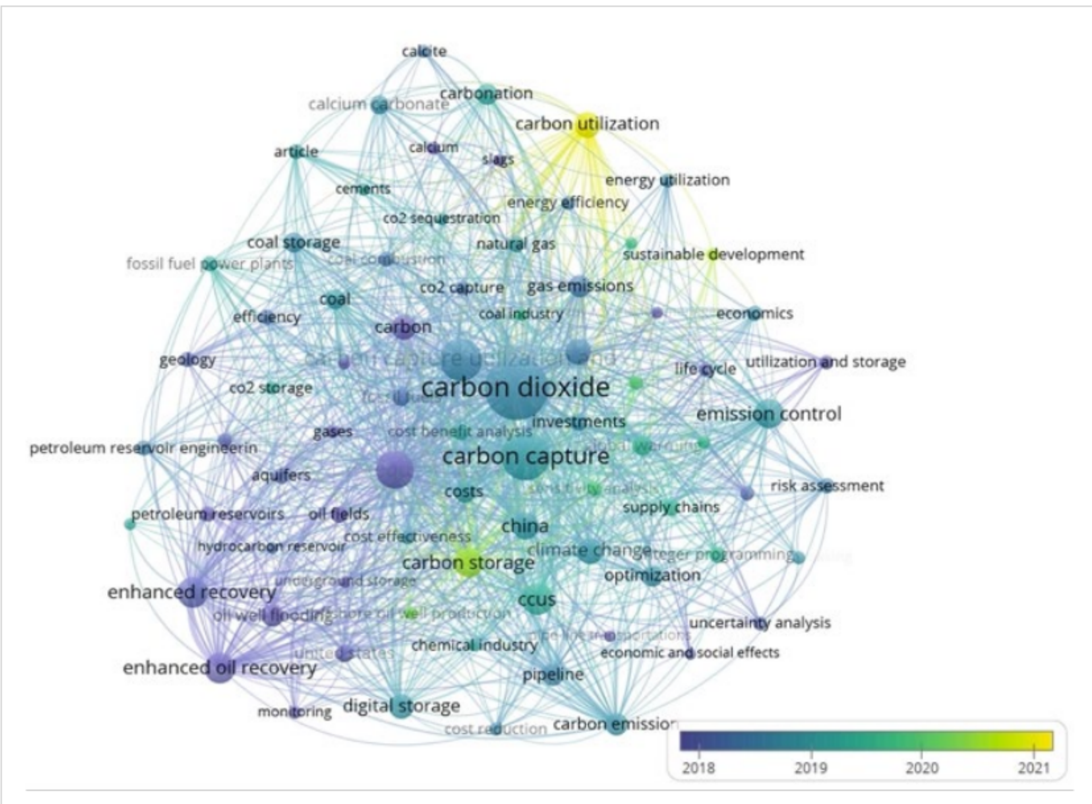
Cluster	Visualization
3	 In cluster 3, "CCUS" has the largest node size, 61 links with other keywords, and the total link strength of 318. CCUS is a technology that plays an important role in reducing carbon emissions in the energy sector so that net-zero emissions can be achieved by eliminating and balancing carbon emissions that are difficult to reduce or avoid. The role of CCUS is proven to be able to eliminate carbon emissions from the energy sector fall to zero by 2070 worldwide in the IEA Sustainable development scenario (IEA, 2020). It has a huge potential as a solution to generate low carbon heat and power, decarbonize industry and reduce CO_2 emissions in the atmosphere (Regufe et al., 2021). CO_2 enhanced oil recovery (CO_2- EOR) method as the technological basis to develop CCUS relies on the CO_2 injection and sequestration to be captured in geologic formation. China, the United States and Canada were the pioneers in the development of CO_2- EOR as this technology has the ability to mitigate CO_2 emission as well as proliferate the production of domestic crude oil, which then followed by some countries such as Brazil, Norway, Trinidad, Turkey, Saudi Arabia and the United Arab Emirates (Hill et al., 2020).
4	 In cluster 4, "carbon dioxide" has the largest node size, 77 links with other keywords, and a total link strength of 1325. This is one of the most critical anthropogenic greenhouse gases due to being abundant and persistent in the atmosphere for a long time (Ali et al., 2020). Recently, the demand of energy has been soaring up; however, the energy supplies are dominated by fossil fuel power plants that generate CO_2 emission. In order to generate a net zero CO_2 emission path as a form of sustainable energy, CCUS technology has to create a synergy with the technology of renewable energy, hydrogen, and electrification. Notably, CCUS technology has been commenced since the era of processed natural gas, which are now challenged by the need to develop a modern global technology of CCUS that consist of 3 methods namely pre-combustion, post-combustion and oxy-combustion (Hill et al., 2020).

Carbon dioxide had the highest occurrence at 27.53% amongst the top 10 value of co-occurrence, although the number of citations for the publications with the keyword of "climate change" was higher than the number of citations for the publications with the keyword "carbon dioxide". This result was in line with the research conducted by Awolesi et al. (2019), which generated 38 publications related to the keyword of "carbon dioxide".

According to Awolesi et al. (2019), the highest publication appointed to the low carbon emission research occurred in 2012, within the 2011–2018 period. Meanwhile, Bergamschi (2019) mentioned that the publications of research on carbon capture technology increased gradually from 1998 to 2018 to reach 1,020 documents. Up to 3,800 citations were obtained in the research from 1998 to 2018, and they continued to increase along with the publications even though there were fluctuations. This indicates that the research topics regarding carbon capture, utilization and storage are in annual demand. The International Journal of Greenhouse Gas Control has the highest number of publications, namely 27 documents and 480 citations (Khosroabadi et al., 2021). *Fig. 4* is an overview of the top 10 journals based on the highest publications and citations.

The number of publications and citations on the topic of carbon capture technologies reached 4,532 and 166 with an average citation per publication of 553. This study showed the number of 17.78 as the average citation per publication. *Fig. 11* shows the visualization of all keywords based on the publication year of 2018–2021. The difference of node color indicates the year of publication; hence, a lighter color implies the

Fig. 11. *Overlay visualization co-occurrence (all keywords)*

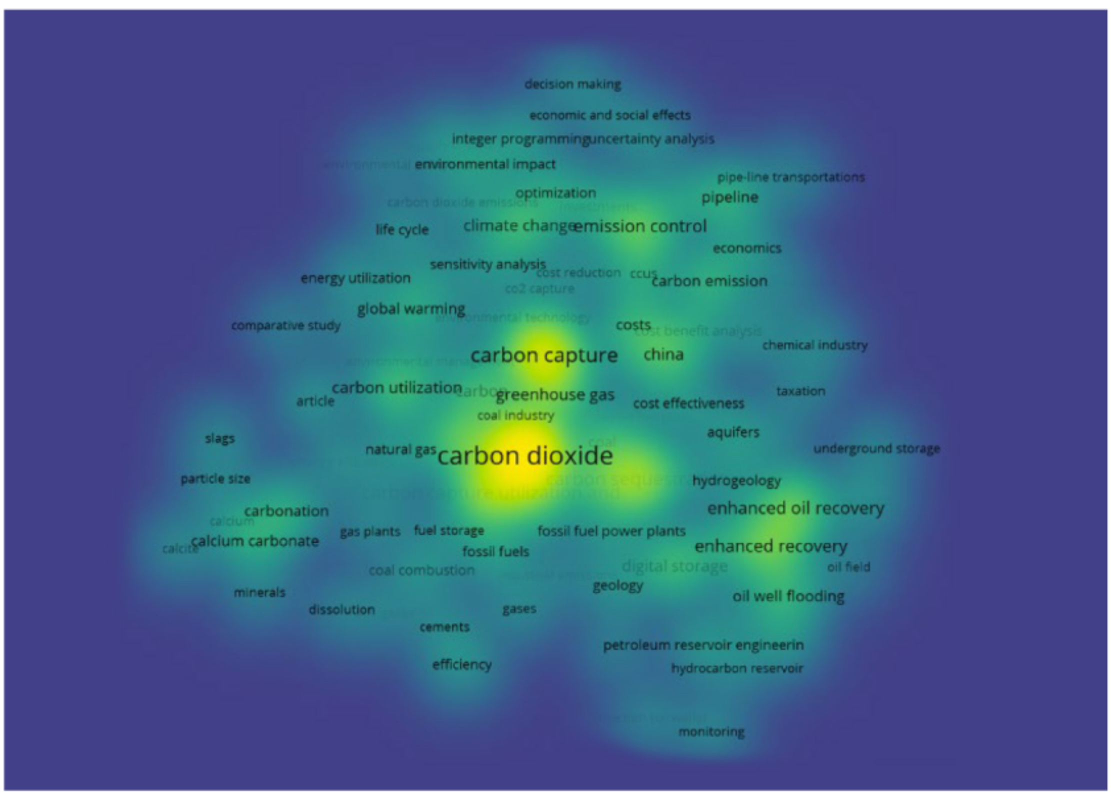


latest publication. The keyword "carbon dioxide" was widely investigated around 2018. "Carbon utilization" appeared around 2021 with 37 occurrences, total link strength of 259 and 62 linkages between keywords. This explains that the research related to carbon utilization was not largely conducted before 2021.

According to Ampah et al. (2021), the bibliometric research should be executed in a way that can strengthen the targeted discipline field through some approaches, namely (1) providing a comprehensive knowledge of the research area; (2) identifying research gaps; (3) highlighting the results of study for future studies. A number of journals identified through Vos Viewer have recognized the existence of CCUS incentive policies and regulations applied for some countries such as China (Zhang et al., 2013), United Kingdom (Leonzio et al., 2020), Hong Kong (Zhang et al., 2021) and United Arab Emirates (Al-Saleh et al., 2012). However, there is a lack of studies addressing the policies and regulations released by ISO standards and international regulation boards to inform on the property rights of the selected sites and accountability for stored CO_2 with respect to the period of ownership and financial matters.

In addition, the density visualization of index keywords (*Fig. 12*) showed some keywords in the areas of hazy colors (e.g., green-blue color) that interpreted the research gaps in the literature that need to be identified, such as: "environmental impacts", which can be correlated to the analysis of environmental impacts for CO_2 leakage during transportation; "cost reduction", which relates to the knowledge of the reduced cost of capture, transport and storage capacity processes; and "carbonation" to be related to the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future,

Fig. 12. *Density visualization co-occurrence (index keywords)*



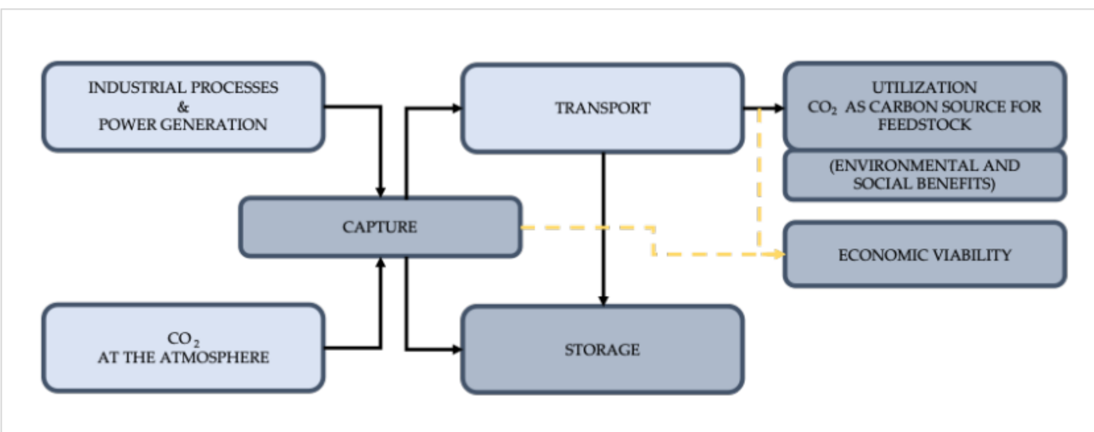
since the existing conventional method of carbonation still requires labor force and are cost-intensive (Simonson et al., 2020). Furthermore, the advanced carbonation method will contribute to the economic viability of carbon utilization, which can be achieved through the use of synthesized rare earth elements at the stage of the treatment process of mineral carbonation for accelerating the economic value of steel slags (Baciocchi and Costa, 2021).

CCUS technology is referred to as sustainable if the economic performance of the preferred method can be achieved without generating additional environmental negative impacts. Thus, CCUS, as one of the climate change mitigation technologies that may achieve the carbon emission reduction target, needs to provide economic, social, and environmental benefits as shown in *Fig. 13* (Assche and Comprenolle, 2022). In addition, the technology of CCU offers the area of social and environmental benefits to be investigated beyond its current initial stage and limited scope of research (Cosbey, 2009). Mitigation and adaptation are important in reducing carbon emissions and are an integrated approach to climate action and development. The integrated approach includes assessment, goal setting, identification, financing and implementation as well as monitoring, evaluation and learning (Jeffrey and Anika, 2022).

Conclusions

CCUS is proven as one of the ultimate technologies for mitigating climate change by capturing carbon emissions produced by industries, which are then being stored at 700 m below the sea level. Bibliometric analysis was used to examine the research trends such as CCUS by identifying keyword networks, authors, organizations, countries, growth trends in terms of the number of publications and citations by publishers and source titles in the period 2012–2022. The results of this study, derived from 296 documents of the Scopus database, showed the increase of publications concerning CCUS related keywords by 2,766.6% within the period of 2012–2022. Based on this study, the most productive country in conducting investigations on CCUS was China, empowered by Zhang X as the most prolific writer affiliated with China University of Petroleum. However, the organization that published the highest number of research on CCUS was National Taiwan University. On the basis of the publication and citation, this study found International Journal of Greenhouse Gas Control as the most productive journal that was published by Elsevier Ltd., that is widely known as a competent publisher of the highest number of publications and citations for research publications. Based on the co-occurrence analysis of index

Fig. 13. *The inclusion of environmental, social and economic impacts into a simplification of the CCUS process to illustrate a sustainable CCUS pathway*



keywords, the research gaps are identified in the literature, such as the analysis of environmental impacts for CO_2 leakage during transportation, the knowledge of the reduced cost of capture, transport and storage capacity processes as well as the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future since the existing conventional method of carbonation still requires labor force and is cost-intensive. This study identified the potential further research for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach. Hence, the importance of CCUS technology for CO_2 sequestration is clearly identified through this study, which is beneficial for the development of CCUS research, particularly to contribute to clean energy transition.

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Journal of Environmental Research, Engineering and Management
Vol. 79 / No. 1 / 2023
pp. 37–55
DOI 10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

Received 2022/10 | Accepted after revision 2023/02

https://doi.org/10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

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The continuous growth of energy consumption leads to the increase of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). Carbon capture, utilization and storage (CCUS), which consists of carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), is a technology that aims to capture CO_2. Therefore, this study evaluates and provides an overview of CCUS in the period 2012–2022, by using a bibliometric analysis to obtain a complete perspective and reference on CCUS. The data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into the Scopus database, and 296 documents were generated. Other software used included Open Refine, VOS viewer and Tableau to describe publication and citation trends, co-authorship, and co-occurrence. CCUS research trend increased by 2,766.6% from 2012 to 2022. The most productive country in investigating CCUS was China, and Zhang X. was the most prolific writer. The organization that published the highest number of research on the topic was the National Taiwan University. The publications and citations were dominated by the International Journal of Greenhouse Gas Control that was published by Elsevier Ltd., which also issues a number of significant publications and receives the highest number of citations.

Keywords: bibliometric analysis, carbon emission, carbon capture, carbon capture utilization, carbon capture storage.

Introduction

The increase of greenhouse gas (GHG) emissions has become a global climate issue that profoundly raises the world's attention due to the impact of climate change. The Intergovernmental Panel on Climate Change (IPCC) launched a Special Report on Global Warming of 1.50 °C, which contains various impacts created on human health, food security and ecosystems. This impact can be anticipated through the attempt of limiting the temperature rise by 1.50 °C above the average temperature prior to industrial era. Total GHG emissions in 2018 reached 55.3 gigatons of CO_2 equivalent. Consequently, hydro-meteorological disasters may occur due to extreme weather that changes the length of dry and rainy season and increases the frequency and duration of droughts. Another impact of climate change is a rise in temperature and sea level (Nerem et al., 2018; Zhao et al., 2020). According to Stone et al. (2009), carbon dioxide emissions have increased by 40% since the period of the Industrial Revolution, and human activities might have greatly contributed to CO_2 release since that time. Carbon dioxide is capable of absorbing long-wave IR radiation (heat) being emitted by the earth which can make the greenhouse effect stronger, hence any increase in CO_2 emissions ultimately causes a rise in the earth's temperature.

The largest CO_2 emissions are generated from agricultural activities, energy production and energy use. Furthermore, trade, transportation, and the growing manufacturing industry add to CO_2 emissions as stated by Adom (2012), which exacerbates the ecological aspects of environment such as climate and climate change. Moreover, the tourism industry elevates carbon dioxide emissions; thereby it is important to raise the awareness of global warming and climate change into the practice of business as usual (Balogh and Jambor, 2017). In order to abate the global warming, reducing the levels of carbon dioxide (CO_2) emissions from exhaust gases produced by industrial activities has to be promptly undertaken since the levels of carbon dioxide (CO_2) emissions have continued to increase from year to year (Rinanti et al., 2014). Global warming has an impact on all living things and nature such as rising sea levels, climate anomalies and natural disasters (Fachrul et al., 2019; Rinanti et al., 2013).

By 2100, the level of atmospheric CO_2 emissions is estimated to reach around 800 ppm and the earth's surface temperature tends to rise by 4 °C (Wang and Oko, 2017). According to The Summary for Policymakers of the IPCC Working Group III report, Climate Change 2022: Mitigation of Climate Change, 195 countries in the world have agreed to limit GHG emissions. A conference held in Paris from 30 November to 12 December 2015 propagated the Paris Agreement to the United Nations Framework Convention on Climate Change. Furthermore, the treaty aims to mitigate the climate change towards a low-carbon, resilient and sustainable future and ensures that global temperature elevations keep well below 2 °C (Wang and Oko, 2017). Carbon capture, utilization and storage (CCUS) comprises carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), both of which aim to capture CO_2 that is being released into the air. The difference between these two technologies lies mainly in the fact that, in CCS, CO_2 emissions are captured and injected into underground storage areas, while in CCU, the CO_2 is converted into commercial products. Based on Zaemi and Rohmana (2021), CCUS's goal is to capture 85% of CO_2 that is released from power plants and industries and the resulting emissions are to be transported into 700 meters depth below sea level through pipes.

Based on IPCC (2022), CCS is the most feasible/accessible technology to reduce emissions from carbon-intensive industries and power generation; however, the mitigation costs tend to reach 138% without CCS technology. This technology is applied for the downstream phase of CCS pathways, by capturing carbon emissions to be stored and utilized for other production processes (Prayitno et al., 2021). Meanwhile, Reiner (2016) has found that CCS technology is employed for climate mitigation and expected to decrease the GHG emissions by 32% until 2050. This target can be justified by the research done by Akbar et al. (2021) that CCS technology captures 85–95% of the CO_2 produced by an industry. Besides of that CCS technology is also

able to reduce carbon emissions with an accuracy level of 95% when applied in a waste-to-energy plant.

The Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCC) has summoned all countries in the world to commit to implementing actions to keep average global temperature below 2 °C and to continue with efforts for suppressing the increase to 1.5 °C. Afterward, targets for each country's commitment were created, where the Paris Agreement set a target to reduce GHG emissions, which is called the Nationally Determined Contribution (NDC). The achievement of GHG emission reductions is verified to ensure that the calculation process complies with the principles that have been recognized as transparent, accurate, consistent, comprehensive, and comparable (TACCC) at the national and international level. This mechanism works through the improvement of scrutinizing and disclosure for lowering the GHG emissions level to encourage the countries for acquiring the climate incentive. The report of TACCC will be beneficial for stakeholders to set a number of measureable goals for climate change mitigation that includes the efforts for reducing emission, resilience enhancement and for allocating financial resources (Weikmans et al., 2019).

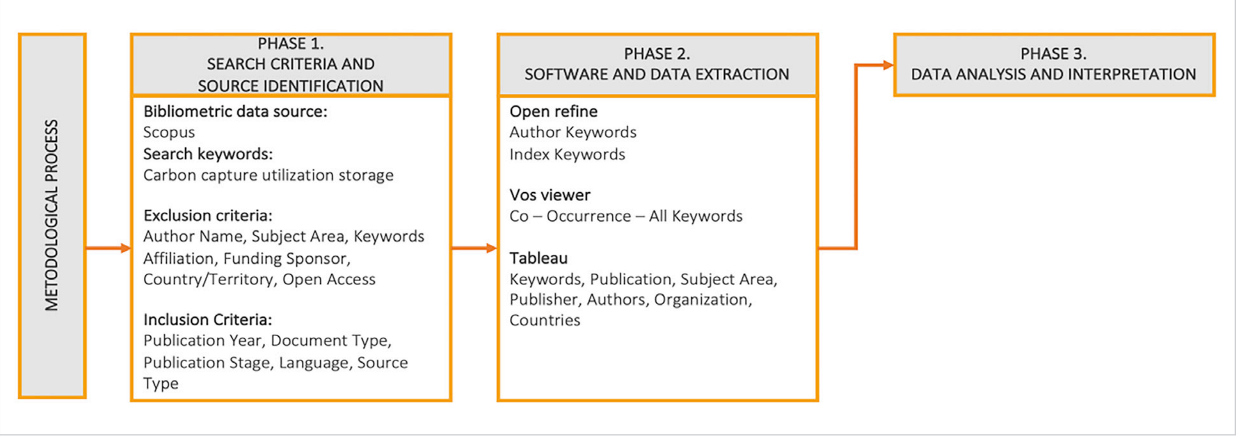
However, the technology of CCUS has not been widely applied, although data and references collection on the technology is largely available. Moreover, the implementation cost of CCUS varies greatly in the fields of electricity and industry (Adisaputro and Saputra, 2017). According to Zaemi and Rohmana (2021), the challenges of developing CCUS are to determine the location of infrastructure and the environment to be used as CO_2 storage areas plus the high required costs. Owing to the significant topic of the IPCC Agenda 2030 on greenhouse gases, CCUS remains to be an interesting global issue to be investigated as a climate change mitigation technology although many studies of greenhouse gases have been extensively conducted. In addition, a number of research works have investigated the application of CCUS technology in some countries, such as the United States (Alphen et al., 2010), China (Jiang and Ashworth, 2020), ASEAN countries (Kimura et al., 2020) and the United Kingdom (Gough et al., 2020). This review, therefore, offers the trend of research development in the field of CCUS to show the acceleration of technology used to apply the CCUS methods for industrialization in some countries within the year of 2012–2022.

The significant objective of this research is to evaluate the growing trend of investigation on CCUS from 2012–2022, as well as to determine the distribution and productivity of research by authors, organizations, and countries, plus the distribution of research work on subject areas and publishers through the following research questions namely: (1) How do the CCUS technologies provide a solution for reducing the carbon emission of industries around the world?; (2) What are the CCUS technologies that most frequently applied for the industry within 2012–2022?; (3) Who are the most prolific authors followed by the most productive countries and organizations?; (4) What are the potential areas of interest in the research development of CCUS technologies? Therefore, the bibliometric analysis which aims to find the research gaps for further exploration on the topic of carbon capture, utilization and storage, was conducted by using the Scopus database. This article divides its systematics of writing into the following parts, namely the introduction, methods, results and discussion, conclusion and references list.

Methods

According to Chen et al. (2015), Singh and Borthakur (2018), a bibliometric analysis is an effective method of analyzing research progress and quantitative trends in publications on a particular topic, by providing an overview of literature contribution both nationally and internationally (Zhang et al., 2020; Zyoud et al., 2022). Sweileh (2022) explains that any bibliometric study uses a statistic approach to identify growth patterns and development of publications as well as collaborative patterns among authors, institutions, and countries. Moreover, bibliometrics identify the research gaps through analyzing the research niche offered by the publication database, which is useful to provide the basis for conducting further research (Singh and Borthakur, 2018; Zhang et al., 2020). The method is divided into three phases, namely data mining, extraction and analysis, as presented in *Fig. 1*.

Fig. 1. *Study method diagram*



Search criteria and source identification

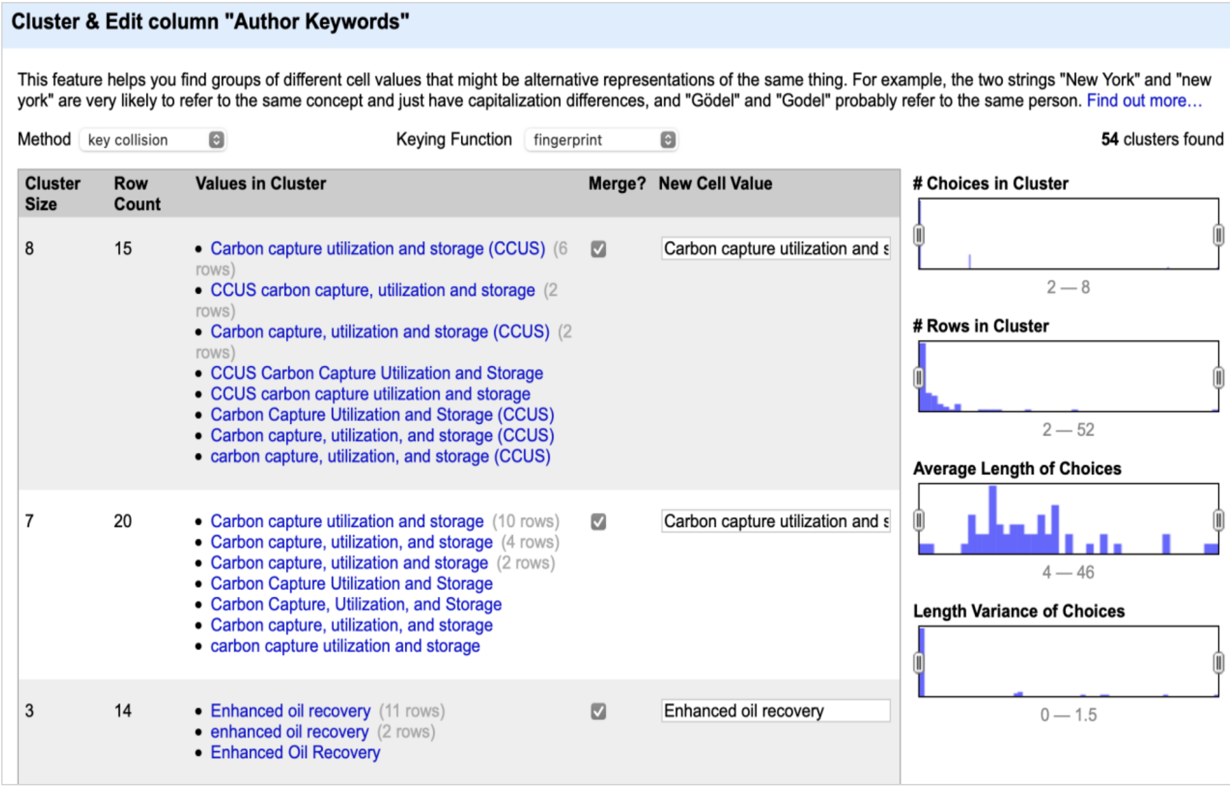
In phase I, data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into Scopus database. Owing to the nature of Scopus as the world's leading literature database published by Elsevier and known to have the highest number of citations (Herawati et al., 2022; Borthakur and Govind, 2017), the Scopus database fits into the expected outcomes of this study. Then, filtering was done with the year of publication, document type, publication stage, language, and source type to obtain more significant results. The data were mined from 2012 to 2022 by limiting the type of article document, final publication stage, journal source type and the English language used. After filtering, 296 available documents were generated and the search results were exported in the CSV format with citation information, bibliographical information, abstract, and keywords. Files exported from the Scopus database were fed into the Open Refine software to reduce inconsistent and repetitive keywords in the mined data.

Software and data extraction

The data obtained from the Scopus database was further extracted and processed by using Open Refine, Vos Viewer and Tableau Public software. The data were fed into Open Refine to reduce several keywords with different spellings but same meaning and to establish the keywords in an exact writing format for avoidance of repetition. Open Refine is able to clean the data from one format to another, overcomes inconsistencies in data sets and divides data into more detailed parts, in an automatic or manual attempt (NIH, 2022).

Fig. 2 shows repeated keywords, namely "Carbon Capture Utilization and Storage (CCUS)", "CCUS carbon capture, utilization and storage", "Carbon capture, utilization and storage (CCUS)", "CCUS Carbon Capture Utilization and Storage", "CCUS Carbon Capture Utilization and Storage", "Carbon Capture Utilization and Storage (CCUS)", "Carbon capture, utilization and Storage (CCUS)" and "carbon capture, utilization, and storage (CCUS)". Some of these have the same meaning but different spellings, hence they are reduced to one format of the keyword, i.e., "Carbon Capture Utilization and Storage (CCUS)". The reduced keywords generated through Open Refine were then fed into the VOS Viewer software, which presents and visualizes specific information about bibliometric chart maps for easier analysis of the relationships or networks about a research topic (Athar et al., 2019). Open Refine enables the author to select the preferred data set, thus the results contained a list of useful data that removes redundant keywords. It means that carbon capture utilization and storage (CCUS) has been tested as the natural result of removing data with redundant keywords. In addition, CCUS is the representative value of other related values (Bergamschi, 2019), to generate a more extensive subject field such as Carbon Capture and Carbon Storage, Carbon Capture Strategies and Carbon Storage Sustainable.

Fig. 2. *Extract data using Open Refine*



The software provides data visualization based on co-authorship, co-occurrence, citation, bibliometric coupling, and co-citation. In this study, co-occurrence of all keywords (author and index keywords) as well as co-authorship (authors) based on network and overlay visualization were used particularly. In co-occurrence analysis, all keywords were chosen as the selected unit with a full counting method. Based on the 296 documents from Scopus, 3,298 keywords were obtained. Once the minimum number of occurrences was set at eight, 78 thresholds were generated, indicating that 78 keywords were repeated eight times in the 3,298 keywords.

Even though the keywords were tidied up in Open Refine, some redundant keywords still appeared that had the same meaning as CO_2 and carbon dioxide. These were employed as a writing format using Thesaurus note, which were then imported into VOS Viewer. In co-authorship analysis, the applied unit analysis referred to authors with the full counting method. The total number of authors in the 296 Scopus-generated documents was 1,011. After setting the minimum number of an author's documents at three, the threshold obtained was 76 authors. Tableau software was used to simplify complex data in the form of interactive graphic visualizations, for easy analysis and understanding (Akhtar et al., 2020). Akhtar et al. (2017) and Murray (2013) stated that Tableau is the most powerful and flexible analytical platform for providing data information and managing their rows into various visualization types.

Data analysis and interpretation

296 research publications were processed by using Open Refine, VOS Viewer and Tableau software regarding publication and citation trends; co-authorship and co-occurrence were analyzed and interpreted, then comparative analysis was conducted within the aforementioned research publications.

The method should consist of research design, subject characteristics, data collection process and data analysis. If necessary, it should raise ethical issues

particularly when dealing with human participants. Appropriate statistical methods should be used, although the biological mechanism should be emphasized. The statistical model, classes, blocks, and experimental units must be designated. Consultation with a statistician is recommended to prevent any incorrect or inadequate statistical methods.

Results and Discussion

Global distribution of publication and citation trend (2012–2022)

One of the objectives mentioned in this article is the determination of global research distribution in 2012–2022. The trends of publications and citations in those years are presented in *Fig. 3*. The total number of publications obtained from Scopus regarding "Carbon Capture Utilization and Storage" was 296. This figure increases significantly from 3 publications in 2012 to 83 publications in 2021. The number of publications and citations in 2021 are inversely related. In 2022, the total number of published documents and citations seemed to decrease because the data were collected in January, hence they did not represent 2022 as a whole. From 2012 to 2015, the increase of published documents and citations was directly proportional, but in 2016, the number of citations increased. The highest citations occurred in 2016; however, the number decreased by 72% after 2016.

Research on carbon capture, utilization and storage (CCUS) has been issued from several journals and publishers including Elsevier Ltd., MDPI AG, Frontiers Media S.A., Italian Association of Chemical Engineering – AIDIC, and Blackwell Publisher Ltd, which are the top 5. Elsevier Ltd. has the highest number of publications and 1,322 citations of 97 documents, as well as journals reaching 28. Furthermore, its top 5 journals with the number of publications and citations respectively are Journal of 1) Greenhouse Gas Control (36.76%; 24.93%), 2) Cleaner Production (17.65%; 7.01%), 3) Applied Energy (17.65%; 38.40%), 4) Energy (16.18%; 13.28%), and 5) CO_2 Utilization (11.76%; 16.38%). Based on the results, 138 journals published articles on carbon capture, utilization and storage with up to 3,947 received citations.

Co-authorship analysis

This co-authorship analysis indicates the relationship between authors, countries and organizations, represented in a network diagram containing nodes and lines classified in different clusters. The clusters of nodes and lines are being distinguished by colors, while the size of nodes shows the weight and repetition of keywords. In addition, the distance from one node to another illustrates the strength of their relationship, and farther link between nodes means both keywords have less research (Khosroabadi et al., 2021).

Authors

The authors who conducted research on CCUS were 62, while their productivity is depicted in *Fig. 5* with the highest number of publications and citations. Zhang X is the most prolific writer in terms of the number of

Fig. 3. *Annual publication and citation spread (2012–2022)*

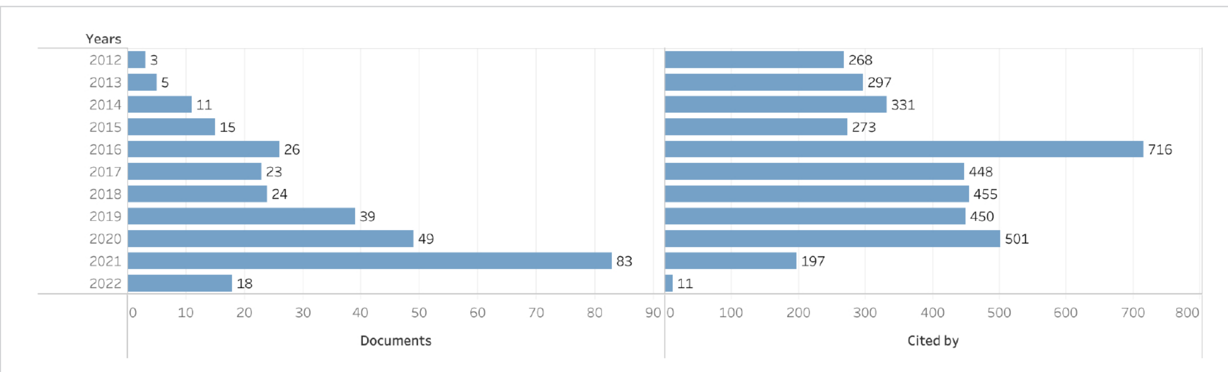


Fig. 4. *Distribution of publications and citations by journal: (a) publication and (b) citation*

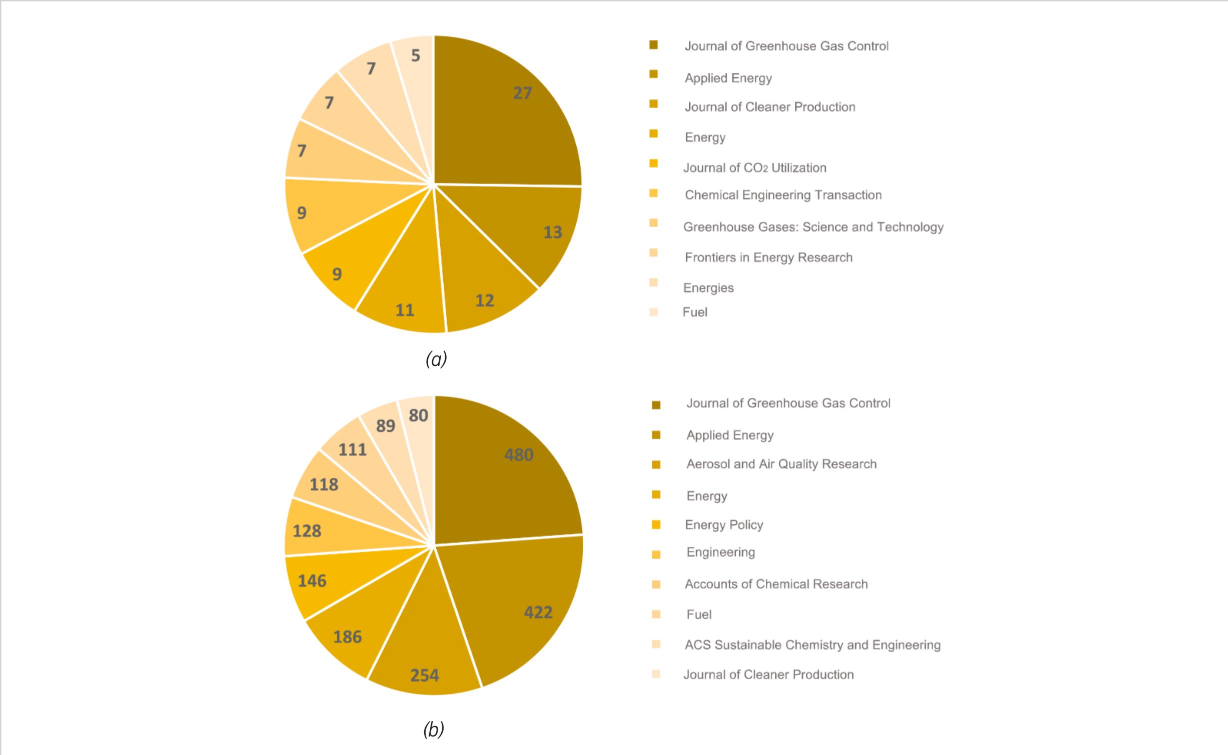
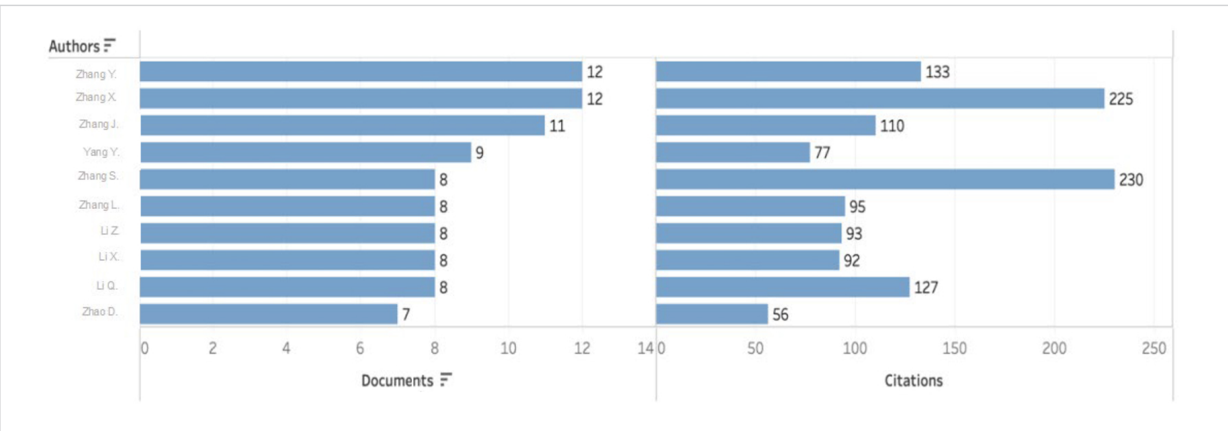
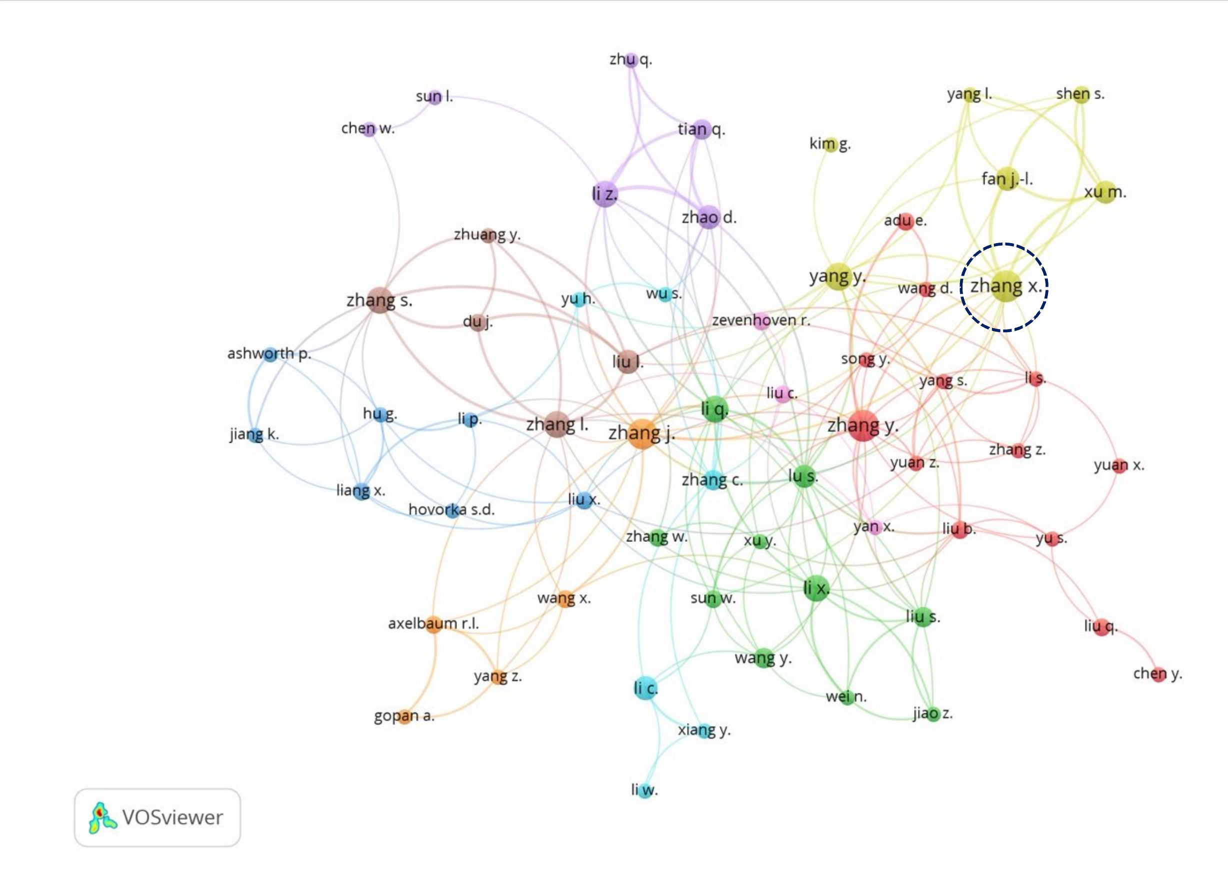


Fig. 5. *Author productivity in terms of publications and citations*



publications issued during 2012–2022, namely 12 documents that received 225 citations. These were lesser compared to Zhang S who reached 230 citations with a total of 8 documents published. The authors' relationship to one another is presented in *Fig. 6*, and in total, they are divided into 9 clusters distinguished by the nodes' color. Zhang X has the highest total link strength of 33 and several relationships with 14 authors from other clusters through an average publication in 2019. The high citations obtained from authors are influenced by their number of links, meaning that there is a high chance of receiving citations with a high link.

Fig. 6. *Co-authorship network of authors*



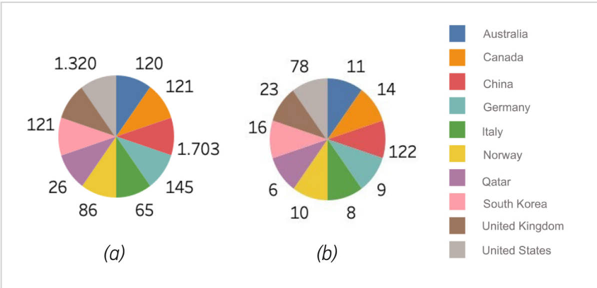
During 2012–2015, Zhang X weighed the research development of CCUS technology in China including enhanced oil recovery and onshore saline aquifer as the most dominant options for the large-scale CO_2 utilization and storage techniques for the development of a roadmap of CCUS technology in China, followed by estimating the potential of methanol through hydrogenation (CTM) and steel slag mineral carbonation and utilization (SCU) to optimize the efficiency of emission reduction, as well as the potential of CO_2 enhanced oil recovery (EOR) and CO_2 enhanced water recovery (EWR) for direct emission reduction.

Throughout the period of 2016–2018, Zhang X highlighted the scope of his research among the topic of the benefit of a vertical integration model that fits for considering the revenue of CCUS technology applied for national projects in China, especially to determine the economic benefits from enhance recovery oil (EOR) and the benefits of CO_2 EOR technology to ease the high investment cost by subsidizing the application of EOR to accelerate the CCUS development in China.

Countries

Fig. 7 shows the top 10 publications and citations based on their geographical location. The results of this study indicated China as the most productive country in conducting investigation on CCUS topics in 2012–2022, where the highest number of citations received was 43.39% and the publications reached 41.08% of the total citations amongst other 9 other countries. However, a similar study of CCUS by (Omoregbe et al., 2018) showed a contrary result, that USA generated more publications (4,416) than China, which generated only 1,876 publications.

Fig. 7. *Top 10 countries with the highest number of citations and publications: (a) citation and (b) publication*

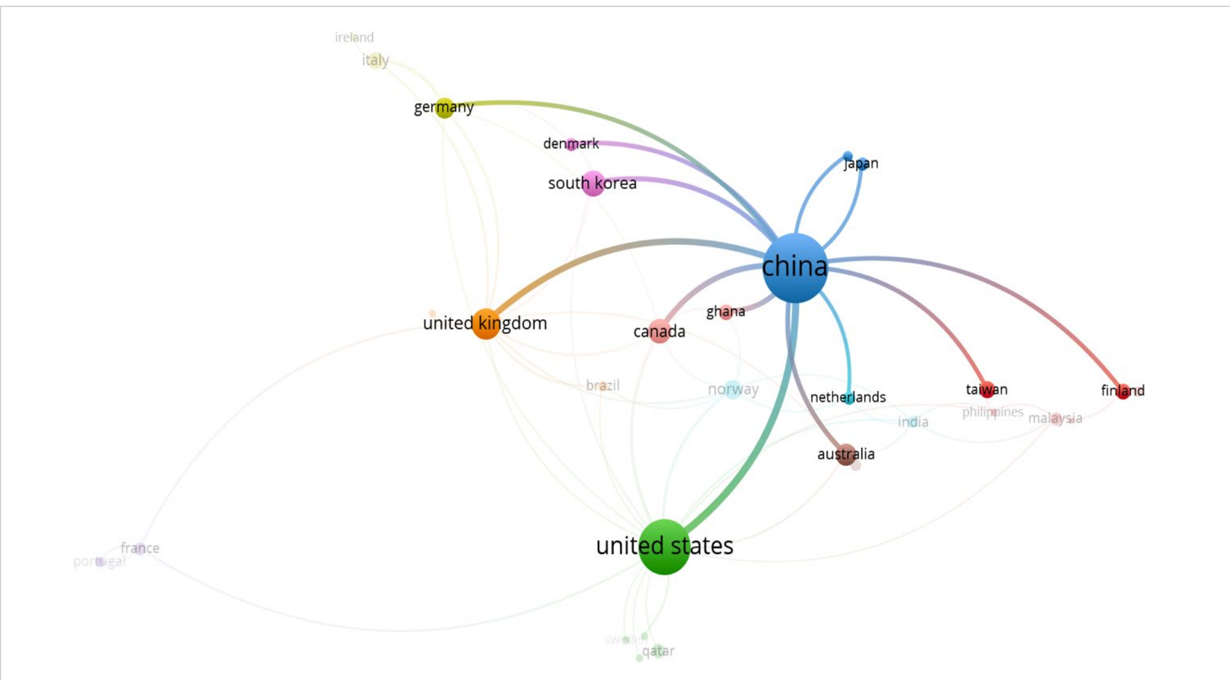


The second rank was occupied by the United States with publications and citations of 26.26% and 33.63%, respectively. As presented in *Fig. 8*, 32 countries were connected and divided into 10 clusters. The total link strength is the accumulated strength of the relationship between different items (Jiang and Ashworth, 2021). Based on countries analysis, the highest total link strength was achieved by China and the United States, namely 45 and 38. Meanwhile, the United Kingdom, Germany, South Korea, and Canada undertook a collaboration on research with China and the United States.

After the meeting of G8 in 2005, these above-mentioned countries were included into a pledge in Hokkaido for strengthening the climate change mitigation (Cosbey, 2009). Recently, Germany and United Kingdom reached the relative high rank for their international policy for climate change mitigation among other G20 countries, followed by the United States and China for their international level of climate negotiations performance. Meanwhile, the Republic of Korea (South Korea) and China received an appreciation amongst other G20 countries for their national climate policy. However, Canada showed the least willingness to improve their climate change mitigation performance due to political interest (Cosbey, 2009).

These remarkable achievements of respective countries were delineated from their Nationally Determined Contribution (NDC) for short-term that affects long-term goals, such as 55% of decarbonization goal belonging to Germany, 40% national reduction target of greenhouse gas emission in United Kingdom, and 25–28% reduction in greenhouse gas emission for the United States (Falduto and Rocha, 2020).

Fig. 8. *Co-authorship network of countries*



Organizations

In this study, the 296 publications were distributed across 687 organizations. This shows that this research was carried out from a diverse number of organizations including companies and mostly from universities. The top 10 organizations with the highest number of citations are shown in *Table 1*. The number of citations obtained from top 10 organizations with the highest citations was 1,553, belonging to the United States (47.39%), Taiwan (30.26%), and China (22.34%). However, the organizations with the highest citations were National Taiwan University and Taipei Medical University with citations of 235 each, while the lowest citations came from Amaren Corp United State (206).

Table 1. *Top 10 organizations with the highest citations*

Organization	Total Citation (%)
Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan	15.13%
Department of Biochemistry, Taipei Medical University, Taipei, Taiwan	15.13%
Indiana Geological Survey, Indiana University, Bloomington, United State	11.14%
Exxonmobil Upstream Company, Houston, United State	11.14%
Department of Geological Sciences, Indiana University, Bloomington, United State	11.14%
Laboratory of Low Carbon Energy, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of thermal Engineering, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Green Chemical Technology of Ministry of Education, Collaborative Innovation Center of Chemical Science and Engineering, School of Chemical Engineering and Technology, Tianjin University, China	7.15%
Department of Chemistry, University of North Carolina at Chapel Hill, United State	7.15%

National Taiwan University secured its most productive position in CCUS publication due to the efforts for weighing the importance of earth science, life science and social science which transformed into multi-disciplinary programs providing solutions particularly for climate change issues implemented in a number of climate change research and carbon capture practices as well as sustainable development related case studies and seminars (NTU, 2018). Meanwhile, Taipei Medical University put its remarkable efforts for CCUS related research topics such as carbonation, slags and steel making that plays a significant role into carbon capture, assigned under Department of Bio-chemistry.

Co-occurrence analysis

In this research, the keywords collected from 296 documents were 3,298. After setting the minimum number of occurrences at eight, 78 thresholds were generated. This shows that 78 keywords were repeated eight times in the 3,298 keywords. The co-occurrence visualization for all keywords is presented in *Fig. 9*, which is divided into four clusters marked with different colors: the first is red, second is green, third is blue, and fourth is yellow. Each cluster has one keyword with the highest total link strength. According to *Table 2*, cluster 1 is “carbon capture”, 2 is “carbon sequestration”, 3 is “CCUS” and 4 is “carbon dioxide”.

The sphere shaped icons are called nodes and they have relationships with one another which indicate the relationships of different keywords. The node size shows the weight and repetition of a keyword, hence a larger size means that the keyword is more frequently used than the keyword of smaller nodes. The distance from one node to another illustrates the strength of their relationship, and the farther link between nodes means that both keywords have less research (Jiang and Ashworth, 2021). The keyword “carbon dioxide” contained in cluster 4 had the highest occurrence of 212, total link strength of 135 and up to 77 linkages compared to other keywords. Meanwhile, “slags” had the lowest occurrence which is 8, total strength of 46, and 19 linkages between keywords. The positions of the top 10 keywords with occurrences and citation scores are depicted in *Fig. 10*.

Fig. 9. *Network of co-occurrence (all keywords)*

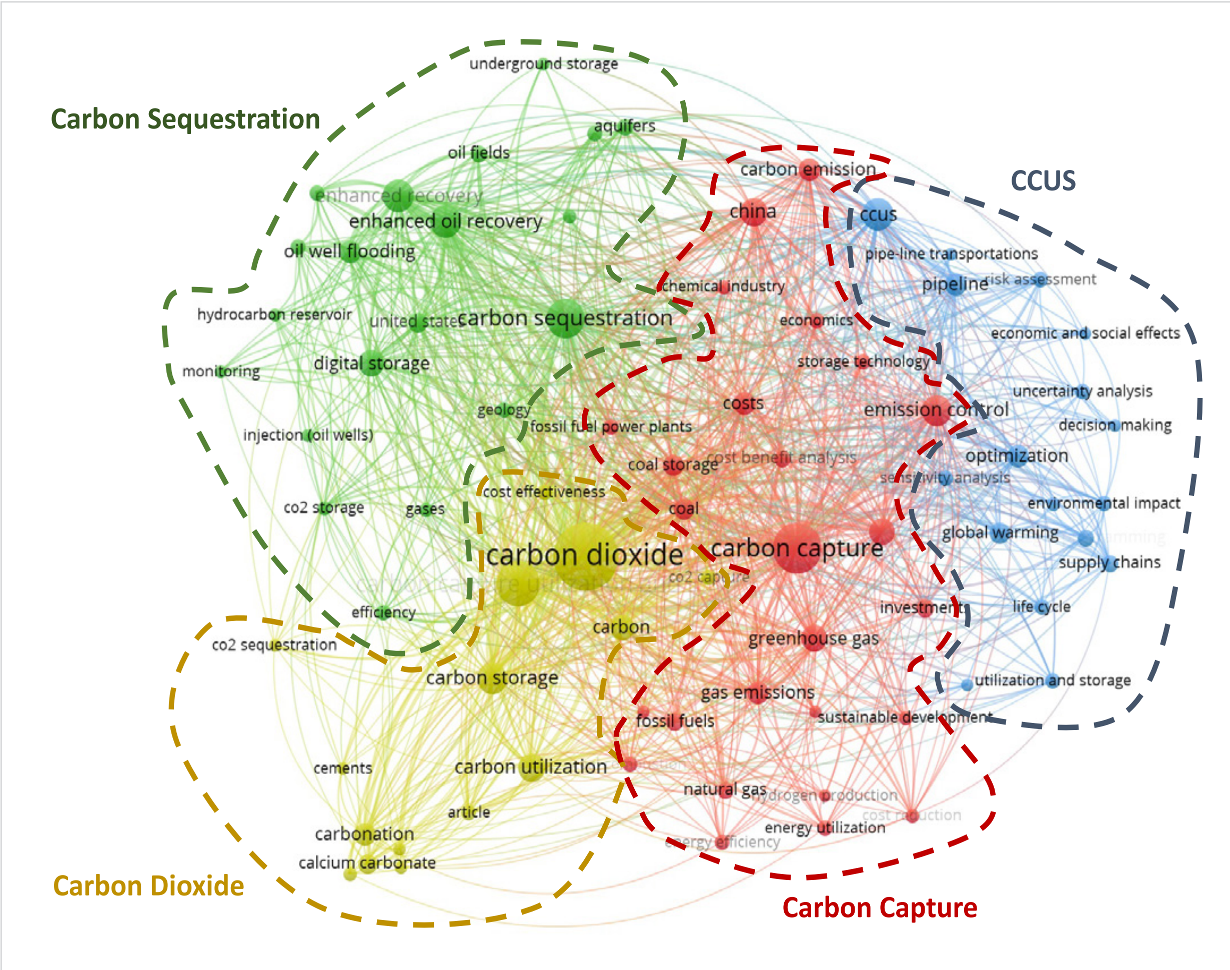


Fig. 10. *Top 10 keywords based on the number of occurrences and citations*

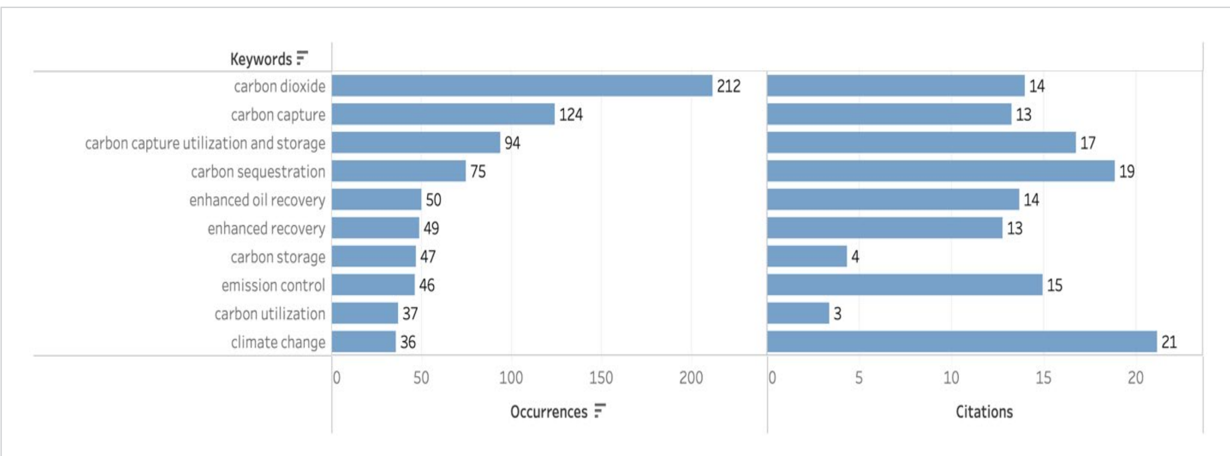
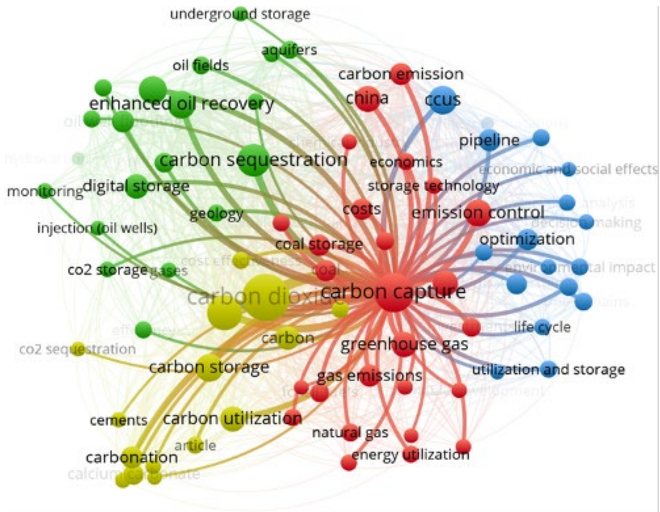
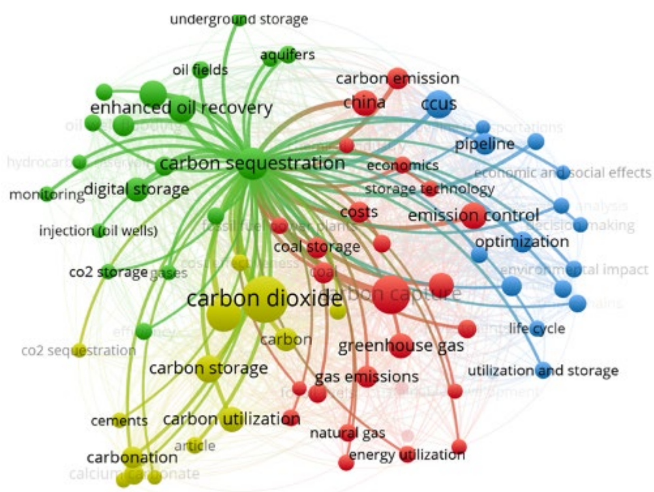
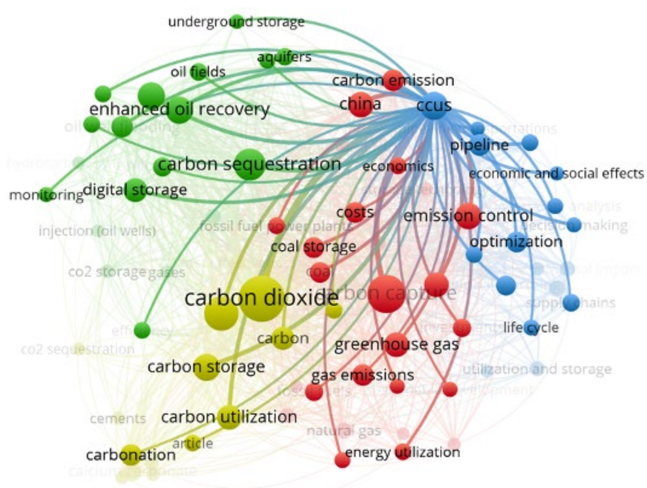
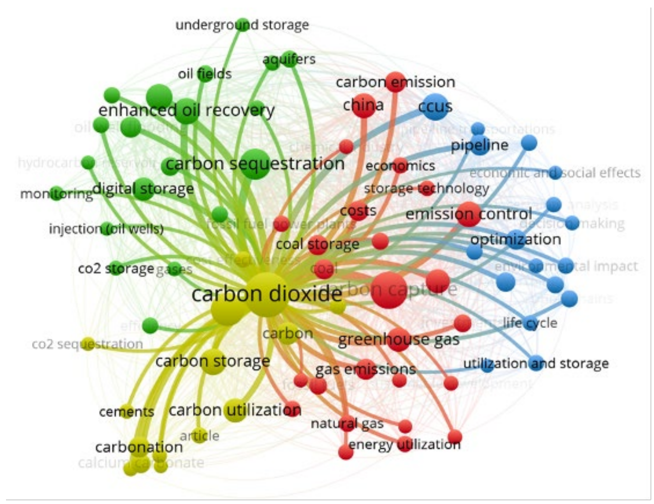


Table 2. *Network visualization keywords in each cluster*

Cluster	Visualization
1	 In cluster 1, “carbon capture” is the keyword that has the largest node size of 76 links with other keywords, and the total link strength of 875. This technology aims to reduce carbon emissions produced from power plants and industries driven by fossil fuels, thereby promoting clean energy transition (Orlov et al., 2022). A report of clean energy transition through the application of CCUS has mentioned Norway as one of the European countries expanding the project of CO_2 capture facilities executed by Norcem (cement factory) and Fortum Oslo Varme (waste-to-energy plant) as well as a large facilities of CO_2 storage in the North Sea established by a group of oil and gas companies. This project, which is known as Longship CCS project, aims to accelerate the capacity of CO_2 transport and storage at the maximum of 5 Mt/year (IEA, 2020).
2	 In cluster 2, “carbon sequestration” has the largest node size, 74 links with other keywords and the total link strength of 560. This serves as an efficient and environmentally friendly approach by incorporating carbon dioxide emissions that have been captured into the soil in an organic matter form (Orlov et al., 2022). Even though soil carbon sequestration has been widely applied, analyzing a suitable management system and method to enhance its storage effect is still an important matter to be deepened (Hinge et al., 2020). Sanchez et al. (2018) weighed the potential of geologic sequestration for perpetual storage of CO_2 in saline aquifers, benefited by two corn-based ethanol companies in USA. The first company included the CCUS project established in Decatur, USA, to capture 1 $MtCO_2$/year which then sequestrated in the Mt. Simon sandstone, USA. Another company named Red Trail Energy had a plan to sequester 180,000 t CO_2/year in the Broom Creek Formation, North Dakota.

<table>
<tr><th>Cluster</th><th>Visualization</th></tr>
<tr><td>3</td><td>


In cluster 3, “CCUS” has the largest node size, 61 links with other keywords, and the total link strength of 318. CCUS is a technology that plays an important role in reducing carbon emissions in the energy sector so that net-zero emissions can be achieved by eliminating and balancing carbon emissions that are difficult to reduce or avoid. The role of CCUS is proven to be able to eliminate carbon emissions from the energy sector fall to zero by 2070 worldwide in the IEA Sustainable development scenario (IEA, 2020). It has a huge potential as a solution to generate low carbon heat and power, decarbonize industry and reduce CO_2 emissions in the atmosphere (Regufe et al., 2021). CO_2 enhanced oil recovery (CO_2- EOR) method as the technological basis to develop CCUS relies on the CO_2 injection and sequestration to be captured in geologic formation. China, the United States and Canada were the pioneers in the development of CO_2- EOR as this technology has the ability to mitigate CO_2 emission as well as proliferate the production of domestic crude oil, which then followed by some countries such as Brazil, Norway, Trinidad, Turkey, Saudi Arabia and the United Arab Emirates (Hill et al., 2020).
</td></tr>
<tr><td>4</td><td>


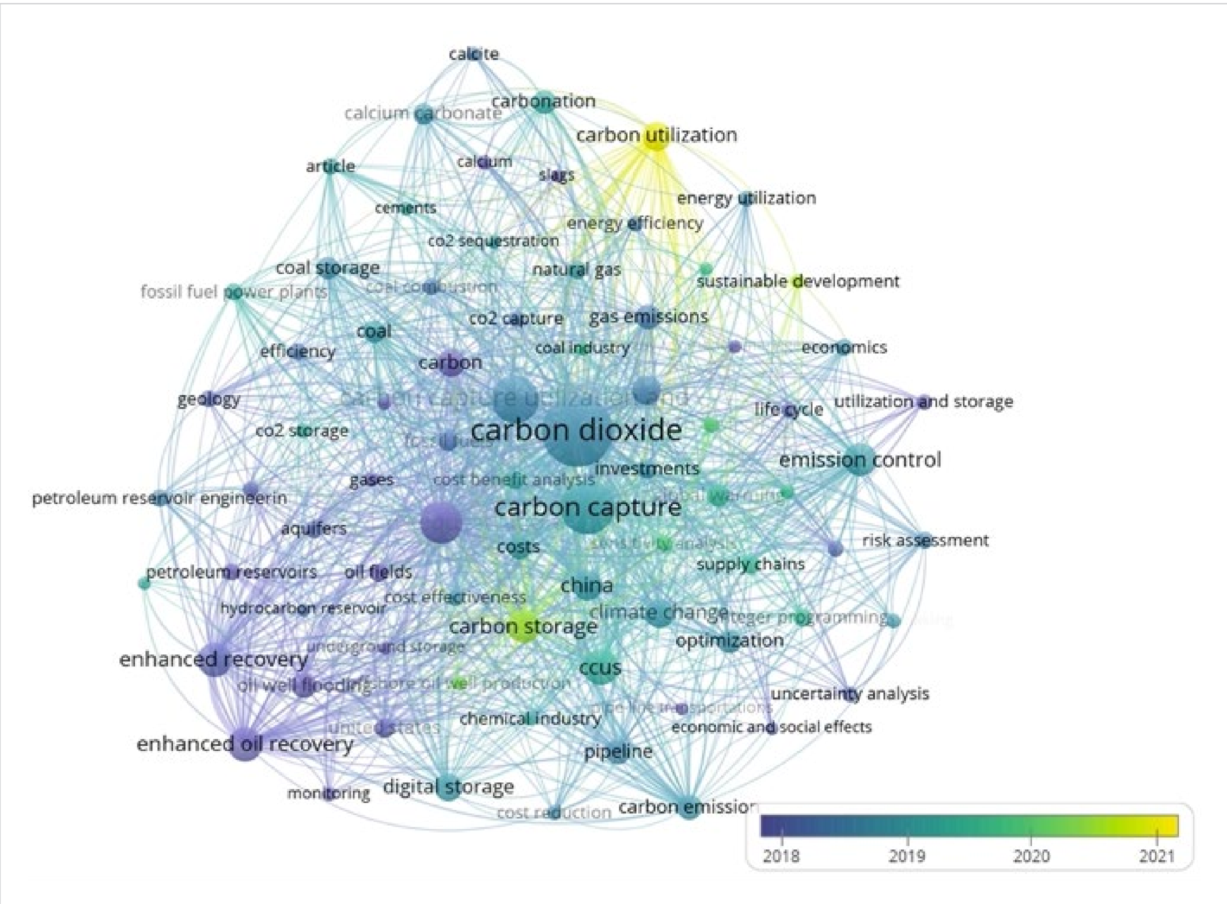
In cluster 4, “carbon dioxide” has the largest node size, 77 links with other keywords, and a total link strength of 1325. This is one of the most critical anthropogenic greenhouse gases due to being abundant and persistent in the atmosphere for a long time (Ali et al., 2020). Recently, the demand of energy has been soaring up; however, the energy supplies are dominated by fossil fuel power plants that generate CO_2 emission. In order to generate a net zero CO_2 emission path as a form of sustainable energy, CCUS technology has to create a synergy with the technology of renewable energy, hydrogen, and electrification. Notably, CCUS technology has been commenced since the era of processed natural gas, which are now challenged by the need to develop a modern global technology of CCUS that consist of 3 methods namely pre-combustion, post-combustion and oxy-combustion (Hill et al., 2020).
</td></tr>
</table>

Carbon dioxide had the highest occurrence at 27.53% amongst the top 10 value of co-occurrence, although the number of citations for the publications with the keyword of “climate change” was higher than the number of citations for the publications with the keyword “carbon dioxide”. This result was in line with the research conducted by Awolesi et al. (2019), which generated 38 publications related to the keyword of “carbon dioxide”.

According to Awolesi et al. (2019), the highest publication appointed to the low carbon emission research occurred in 2012, within the 2011–2018 period. Meanwhile, Bergamschi (2019) mentioned that the publications of research on carbon capture technology increased gradually from 1998 to 2018 to reach 1,020 documents. Up to 3,800 citations were obtained in the research from 1998 to 2018, and they continued to increase along with the publications even though there were fluctuations. This indicates that the research topics regarding carbon capture, utilization and storage are in annual demand. The International Journal of Greenhouse Gas Control has the highest number of publications, namely 27 documents and 480 citations (Khosroabadi et al., 2021). *Fig. 4* is an overview of the top 10 journals based on the highest publications and citations.

The number of publications and citations on the topic of carbon capture technologies reached 4,532 and 166 with an average citation per publication of 553. This study showed the number of 17.78 as the average citation per publication. *Fig. 11* shows the visualization of all keywords based on the publication year of 2018–2021. The difference of node color indicates the year of publication; hence, a lighter color implies the

Fig. 11. *Overlay visualization co-occurrence (all keywords)*

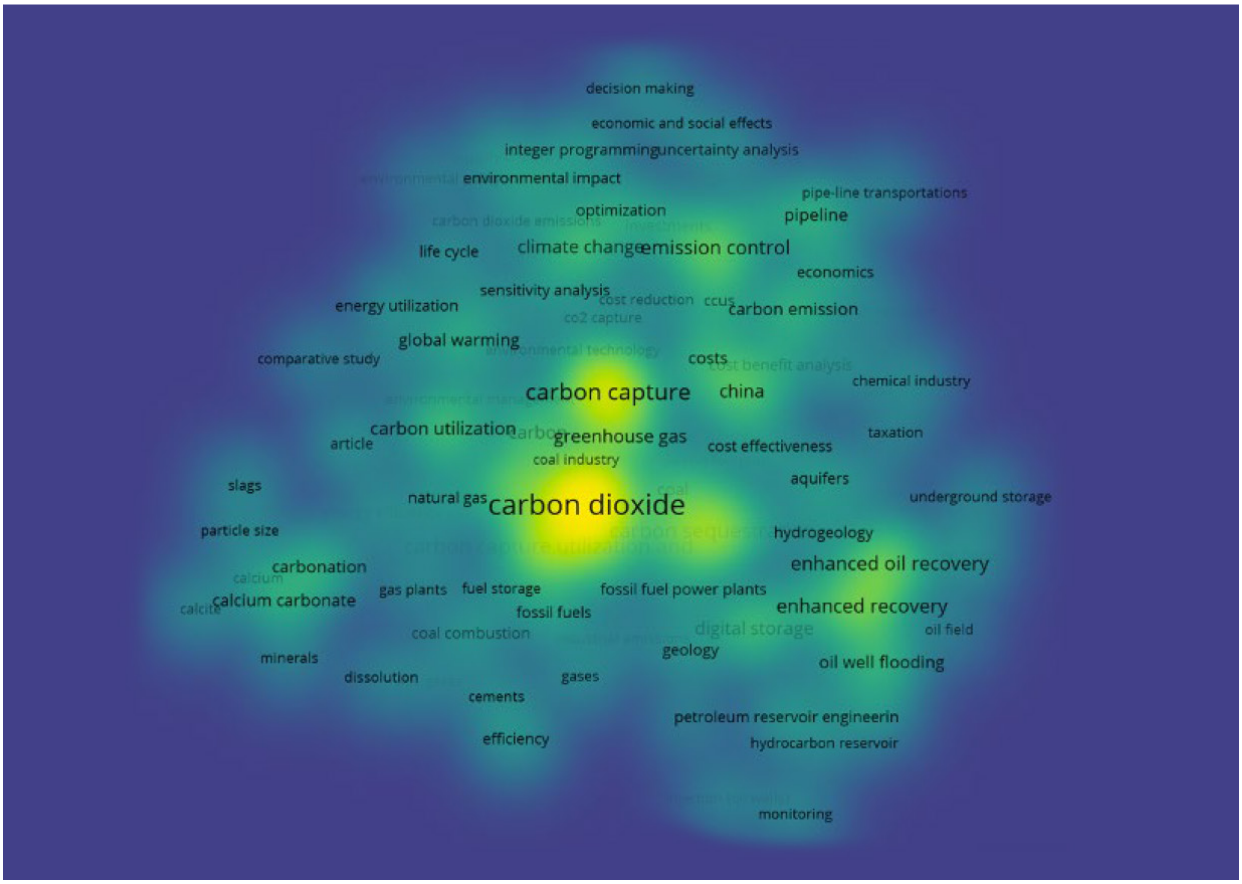


latest publication. The keyword "carbon dioxide" was widely investigated around 2018. "Carbon utilization" appeared around 2021 with 37 occurrences, total link strength of 259 and 62 linkages between keywords. This explains that the research related to carbon utilization was not largely conducted before 2021.

According to Ampah et al. (2021), the bibliometric research should be executed in a way that can strengthen the targeted discipline field through some approaches, namely (1) providing a comprehensive knowledge of the research area; (2) identifying research gaps; (3) highlighting the results of study for future studies. A number of journals identified through Vos Viewer have recognized the existence of CCUS incentive policies and regulations applied for some countries such as China (Zhang et al., 2013), United Kingdom (Leonzio et al., 2020), Hong Kong (Zhang et al., 2021) and United Arab Emirates (Al-Saleh et al., 2012). However, there is a lack of studies addressing the policies and regulations released by ISO standards and international regulation boards to inform on the property rights of the selected sites and accountability for stored $CO_2$with respect to the period of ownership and financial matters.

In addition, the density visualization of index keywords (*Fig. 12*) showed some keywords in the areas of hazy colors (e.g., green-blue color) that interpreted the research gaps in the literature that need to be identified, such as: "environmental impacts", which can be correlated to the analysis of environmental impacts for CO_2 leakage during transportation; "cost reduction", which relates to the knowledge of the reduced cost of capture, transport and storage capacity processes; and "carbonation" to be related to the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future,

Fig. 12. *Density visualization co-occurrence (index keywords)*



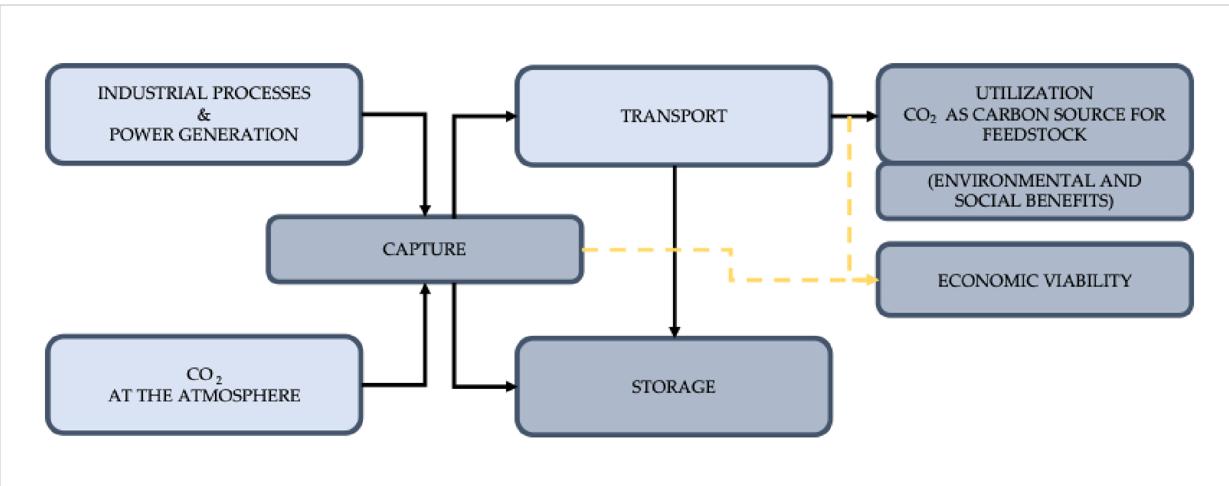
since the existing conventional method of carbonation still requires labor force and are cost-intensive (Simonson et al., 2020). Furthermore, the advanced carbonation method will contribute to the economic viability of carbon utilization, which can be achieved through the use of synthesized rare earth elements at the stage of the treatment process of mineral carbonation for accelerating the economic value of steel slags (Baciocchi and Costa, 2021).

CCUS technology is referred to as sustainable if the economic performance of the preferred method can be achieved without generating additional environmental negative impacts. Thus, CCUS, as one of the climate change mitigation technologies that may achieve the carbon emission reduction target, needs to provide economic, social, and environmental benefits as shown in *Fig. 13* (Assche and Comprenolle, 2022). In addition, the technology of CCU offers the area of social and environmental benefits to be investigated beyond its current initial stage and limited scope of research (Cosbey, 2009). Mitigation and adaptation are important in reducing carbon emissions and are an integrated approach to climate action and development. The integrated approach includes assessment, goal setting, identification, financing and implementation as well as monitoring, evaluation and learning (Jeffrey and Anika, 2022).

Conclusions

CCUS is proven as one of the ultimate technologies for mitigating climate change by capturing carbon emissions produced by industries, which are then being stored at 700 m below the sea level. Bibliometric analysis was used to examine the research trends such as CCUS by identifying keyword networks, authors, organizations, countries, growth trends in terms of the number of publications and citations by publishers and source titles in the period 2012–2022. The results of this study, derived from 296 documents of the Scopus database, showed the increase of publications concerning CCUS related keywords by 2,766.6% within the period of 2012–2022. Based on this study, the most productive country in conducting investigations on CCUS was China, empowered by Zhang X as the most prolific writer affiliated with China University of Petroleum. However, the organization that published the highest number of research on CCUS was National Taiwan University. On the basis of the publication and citation, this study found International Journal of Greenhouse Gas Control as the most productive journal that was published by Elsevier Ltd., that is widely known as a competent publisher of the highest number of publications and citations for research publications. Based on the co-occurrence analysis of index

Fig. 13. *The inclusion of environmental, social and economic impacts into a simplification of the CCUS process to illustrate a sustainable CCUS pathway*



keywords, the research gaps are identified in the literature, such as the analysis of environmental impacts for CO_2 leakage during transportation, the knowledge of the reduced cost of capture, transport and storage capacity processes as well as the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future since the existing conventional method of carbonation still requires labor force and is cost-intensive. This study identified the potential further research for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach. Hence, the importance of CCUS technology for CO_2 sequestration is clearly identified through this study, which is beneficial for the development of CCUS research, particularly to contribute to clean energy transition.

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PUBLICATION TYPE	ISSN	COVERAGE	INFORMATION
Journals	13921649, 20292139	2015-2021	Homepage How to publish in this journal erem@ktu.lt

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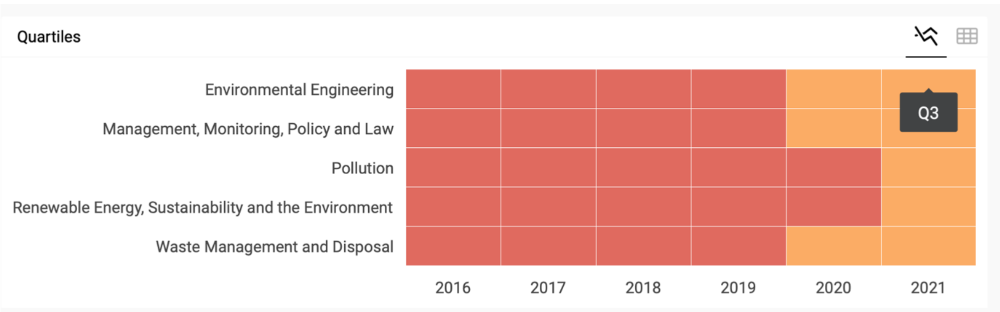

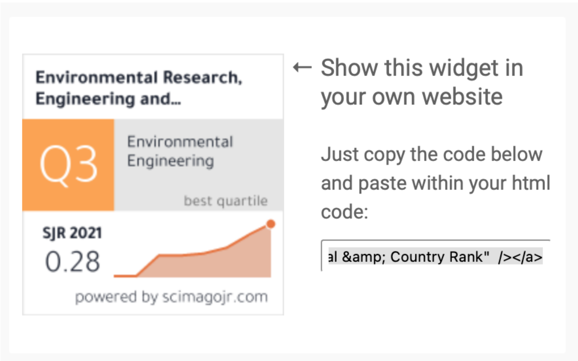

2023 / Nr. 79 (1)

ISSN 1392-1649 (print)
ISSN 2029-2139 (online)

Electronic version
www.erem.ktu.lt

ENVIRONMENTAL RESEARCH, ENGINEERING AND MANAGEMENT

Aplinkos tyrimai, inžinerija ir vadyba

ktu
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engineering

Environmental Research, Engineering and Management No. 79 (1)

The papers published in journal Environmental Research, Engineering and Management are abstracted by SCOPUS database (since 2016), EBSCO: Central & Eastern European Academic Source, EBSCO: Environment Complete, and EBSCO: Environment Index (since 2005), also Aerospace Database, Civil Engineering Abstracts, Metadex.

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Techninis redaktorius Aušra Randė

Dizainerė Evelina Garliauskienė

CONTENT

EREM 79/1

Journal of Environmental Research, Engineering and Management
Vol. 79 / No. 1 / 2023
pp. 37–55
DOI 10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

Received 2022/10 | Accepted after revision 2023/02

https://doi.org/10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

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The continuous growth of energy consumption leads to the increase of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). Carbon capture, utilization and storage (CCUS), which consists of carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), is a technology that aims to capture CO_2. Therefore, this study evaluates and provides an overview of CCUS in the period 2012–2022, by using a bibliometric analysis to obtain a complete perspective and reference on CCUS. The data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into the Scopus database, and 296 documents were generated. Other software used included Open Refine, VOS viewer and Tableau to describe publication and citation trends, co-authorship, and co-occurrence. CCUS research trend increased by 2,766.6% from 2012 to 2022. The most productive country in investigating CCUS was China, and Zhang X. was the most prolific writer. The organization that published the highest number of research on the topic was the National Taiwan University. The publications and citations were dominated by the International Journal of Greenhouse Gas Control that was published by Elsevier Ltd., which also issues a number of significant publications and receives the highest number of citations.

Keywords: bibliometric analysis, carbon emission, carbon capture, carbon capture utilization, carbon capture storage.

Introduction

The increase of greenhouse gas (GHG) emissions has become a global climate issue that profoundly raises the world's attention due to the impact of climate change. The Intergovernmental Panel on Climate Change (IPCC) launched a Special Report on Global Warming of 1.50 °C, which contains various impacts created on human health, food security and ecosystems. This impact can be anticipated through the attempt of limiting the temperature rise by 1.50 °C above the average temperature prior to industrial era. Total GHG emissions in 2018 reached 55.3 gigatons of CO_2 equivalent. Consequently, hydro-meteorological disasters may occur due to extreme weather that changes the length of dry and rainy season and increases the frequency and duration of droughts. Another impact of climate change is a rise in temperature and sea level (Nerem et al., 2018; Zhao et al., 2020). According to Stone et al. (2009), carbon dioxide emissions have increased by 40% since the period of the Industrial Revolution, and human activities might have greatly contributed to CO_2 release since that time. Carbon dioxide is capable of absorbing long-wave IR radiation (heat) being emitted by the earth which can make the greenhouse effect stronger, hence any increase in CO_2 emissions ultimately causes a rise in the earth's temperature.

The largest CO_2 emissions are generated from agricultural activities, energy production and energy use. Furthermore, trade, transportation, and the growing manufacturing industry add to CO_2 emissions as stated by Adom (2012), which exacerbates the ecological aspects of environment such as climate and climate change. Moreover, the tourism industry elevates carbon dioxide emissions; thereby it is important to raise the awareness of global warming and climate change into the practice of business as usual (Balogh and Jambor, 2017). In order to abate the global warming, reducing the levels of carbon dioxide (CO_2) emissions from exhaust gases produced by industrial activities has to be promptly undertaken since the levels of carbon dioxide (CO_2) emissions have continued to increase from year to year (Rinanti et al., 2014). Global warming has an impact on all living things and nature such as rising sea levels, climate anomalies and natural disasters (Fachrul et al., 2019; Rinanti et al., 2013).

By 2100, the level of atmospheric CO_2 emissions is estimated to reach around 800 ppm and the earth's surface temperature tends to rise by 4 °C (Wang and Oko, 2017). According to The Summary for Policymakers of the IPCC Working Group III report, Climate Change 2022: Mitigation of Climate Change, 195 countries in the world have agreed to limit GHG emissions. A conference held in Paris from 30 November to 12 December 2015 propagated the Paris Agreement to the United Nations Framework Convention on Climate Change. Furthermore, the treaty aims to mitigate the climate change towards a low-carbon, resilient and sustainable future and ensures that global temperature elevations keep well below 2 °C (Wang and Oko, 2017). Carbon capture, utilization and storage (CCUS) comprises carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), both of which aim to capture CO_2 that is being released into the air. The difference between these two technologies lies mainly in the fact that, in CCS, CO_2 emissions are captured and injected into underground storage areas, while in CCU, the CO_2 is converted into commercial products. Based on Zaemi and Rohmana (2021), CCUS's goal is to capture 85% of CO_2 that is released from power plants and industries and the resulting emissions are to be transported into 700 meters depth below sea level through pipes.

Based on IPCC (2022), CCS is the most feasible/accessible technology to reduce emissions from carbon-intensive industries and power generation; however, the mitigation costs tend to reach 138% without CCS technology. This technology is applied for the downstream phase of CCS pathways, by capturing carbon emissions to be stored and utilized for other production processes (Prayitno et al., 2021). Meanwhile, Reiner (2016) has found that CCS technology is employed for climate mitigation and expected to decrease the GHG emissions by 32% until 2050. This target can be justified by the research done by Akbar et al. (2021) that CCS technology captures 85–95% of the CO_2 produced by an industry. Besides of that CCS technology is also

able to reduce carbon emissions with an accuracy level of 95% when applied in a waste-to-energy plant.

The Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCC) has summoned all countries in the world to commit to implementing actions to keep average global temperature below 2 °C and to continue with efforts for suppressing the increase to 1.5 °C. Afterward, targets for each country's commitment were created, where the Paris Agreement set a target to reduce GHG emissions, which is called the Nationally Determined Contribution (NDC). The achievement of GHG emission reductions is verified to ensure that the calculation process complies with the principles that have been recognized as transparent, accurate, consistent, comprehensive, and comparable (TACCC) at the national and international level. This mechanism works through the improvement of scrutinizing and disclosure for lowering the GHG emissions level to encourage the countries for acquiring the climate incentive. The report of TACCC will be beneficial for stakeholders to set a number of measureable goals for climate change mitigation that includes the efforts for reducing emission, resilience enhancement and for allocating financial resources (Weikmans et al., 2019).

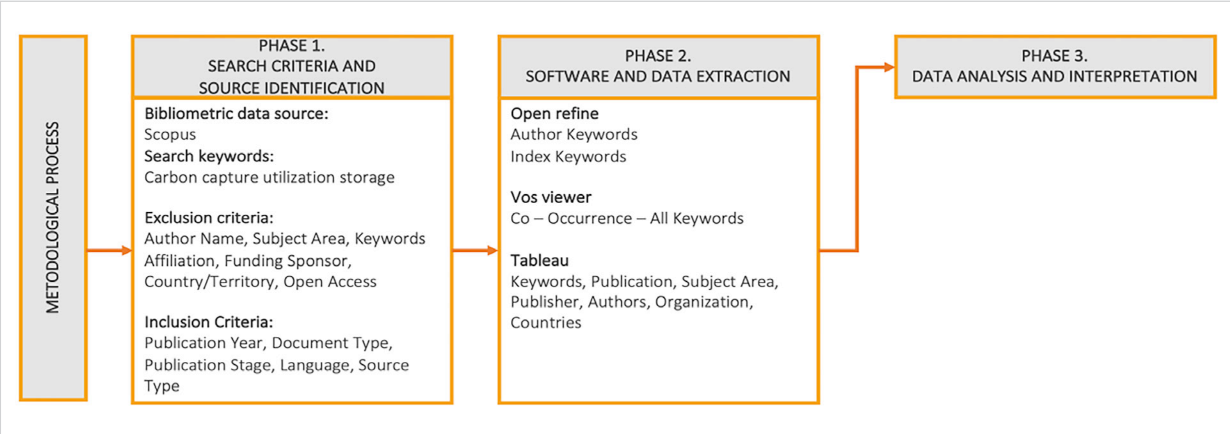
However, the technology of CCUS has not been widely applied, although data and references collection on the technology is largely available. Moreover, the implementation cost of CCUS varies greatly in the fields of electricity and industry (Adisaputro and Saputra, 2017). According to Zaemi and Rohmana (2021), the challenges of developing CCUS are to determine the location of infrastructure and the environment to be used as CO_2 storage areas plus the high required costs. Owing to the significant topic of the IPCC Agenda 2030 on greenhouse gases, CCUS remains to be an interesting global issue to be investigated as a climate change mitigation technology although many studies of greenhouse gases have been extensively conducted. In addition, a number of research works have investigated the application of CCUS technology in some countries, such as the United States (Alphen et al., 2010), China (Jiang and Ashworth, 2020), ASEAN countries (Kimura et al., 2020) and the United Kingdom (Gough et al., 2020). This review, therefore, offers the trend of research development in the field of CCUS to show the acceleration of technology used to apply the CCUS methods for industrialization in some countries within the year of 2012–2022.

The significant objective of this research is to evaluate the growing trend of investigation on CCUS from 2012–2022, as well as to determine the distribution and productivity of research by authors, organizations, and countries, plus the distribution of research work on subject areas and publishers through the following research questions namely: (1) How do the CCUS technologies provide a solution for reducing the carbon emission of industries around the world?; (2) What are the CCUS technologies that most frequently applied for the industry within 2012–2022?; (3) Who are the most prolific authors followed by the most productive countries and organizations?; (4) What are the potential areas of interest in the research development of CCUS technologies? Therefore, the bibliometric analysis which aims to find the research gaps for further exploration on the topic of carbon capture, utilization and storage, was conducted by using the Scopus database. This article divides its systematics of writing into the following parts, namely the introduction, methods, results and discussion, conclusion and references list.

Methods

According to Chen et al. (2015), Singh and Borthakur (2018), a bibliometric analysis is an effective method of analyzing research progress and quantitative trends in publications on a particular topic, by providing an overview of literature contribution both nationally and internationally (Zhang et al., 2020; Zyoud et al., 2022). Sweileh (2022) explains that any bibliometric study uses a statistic approach to identify growth patterns and development of publications as well as collaborative patterns among authors, institutions, and countries. Moreover, bibliometrics identify the research gaps through analyzing the research niche offered by the publication database, which is useful to provide the basis for conducting further research (Singh and Borthakur, 2018; Zhang et al., 2020). The method is divided into three phases, namely data mining, extraction and analysis, as presented in *Fig. 1*.

Fig. 1. *Study method diagram*



Search criteria and source identification

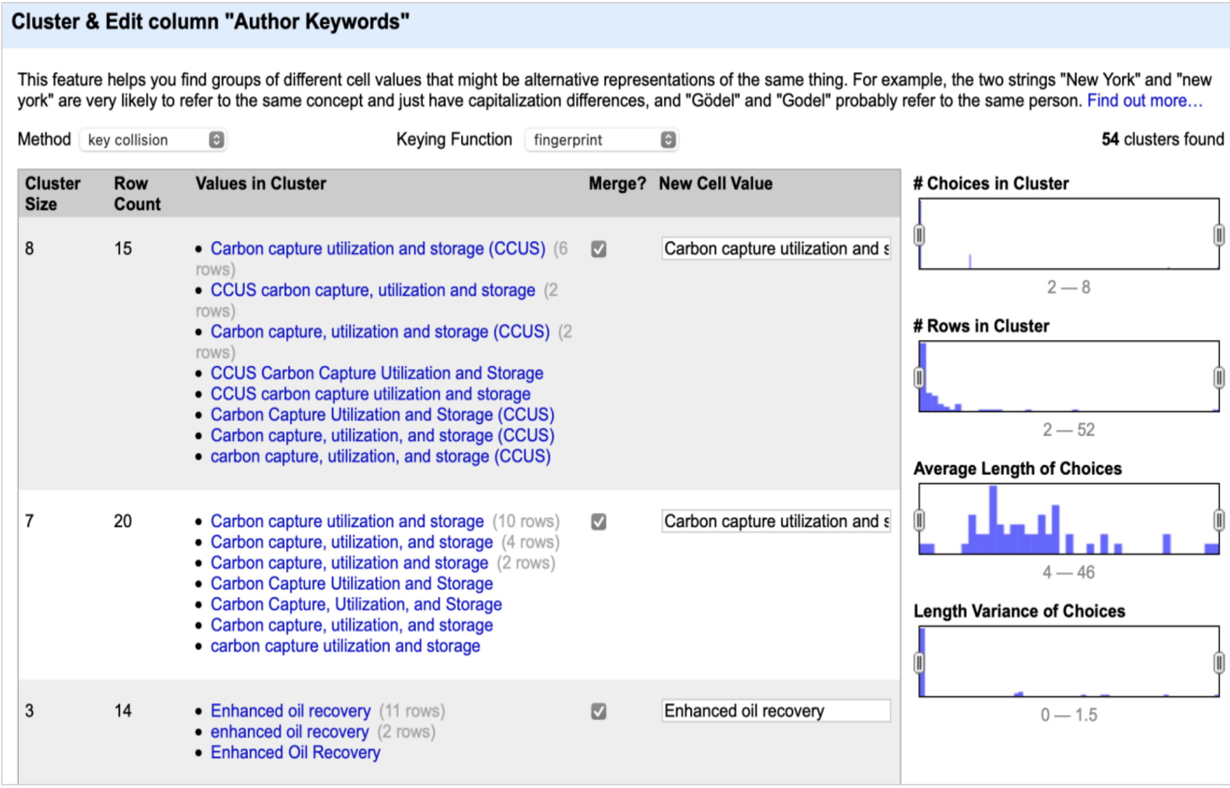
In phase I, data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into Scopus database. Owing to the nature of Scopus as the world's leading literature database published by Elsevier and known to have the highest number of citations (Herawati et al., 2022; Borthakur and Govind, 2017), the Scopus database fits into the expected outcomes of this study. Then, filtering was done with the year of publication, document type, publication stage, language, and source type to obtain more significant results. The data were mined from 2012 to 2022 by limiting the type of article document, final publication stage, journal source type and the English language used. After filtering, 296 available documents were generated and the search results were exported in the CSV format with citation information, bibliographical information, abstract, and keywords. Files exported from the Scopus database were fed into the Open Refine software to reduce inconsistent and repetitive keywords in the mined data.

Software and data extraction

The data obtained from the Scopus database was further extracted and processed by using Open Refine, Vos Viewer and Tableau Public software. The data were fed into Open Refine to reduce several keywords with different spellings but same meaning and to establish the keywords in an exact writing format for avoidance of repetition. Open Refine is able to clean the data from one format to another, overcomes inconsistencies in data sets and divides data into more detailed parts, in an automatic or manual attempt (NIH, 2022).

Fig. 2 shows repeated keywords, namely "Carbon Capture Utilization and Storage (CCUS)", "CCUS carbon capture, utilization and storage", "Carbon capture, utilization and storage (CCUS)", "CCUS Carbon Capture Utilization and Storage", "CCUS Carbon Capture Utilization and Storage", "Carbon Capture Utilization and Storage (CCUS)", "Carbon capture, utilization and Storage (CCUS)" and "carbon capture, utilization, and storage (CCUS)". Some of these have the same meaning but different spellings, hence they are reduced to one format of the keyword, i.e., "Carbon Capture Utilization and Storage (CCUS)". The reduced keywords generated through Open Refine were then fed into the VOS Viewer software, which presents and visualizes specific information about bibliometric chart maps for easier analysis of the relationships or networks about a research topic (Athar et al., 2019). Open Refine enables the author to select the preferred data set, thus the results contained a list of useful data that removes redundant keywords. It means that carbon capture utilization and storage (CCUS) has been tested as the natural result of removing data with redundant keywords. In addition, CCUS is the representative value of other related values (Bergamschi, 2019), to generate a more extensive subject field such as Carbon Capture and Carbon Storage, Carbon Capture Strategies and Carbon Storage Sustainable.

Fig. 2. *Extract data using Open Refine*



The software provides data visualization based on co-authorship, co-occurrence, citation, bibliometric coupling, and co-citation. In this study, co-occurrence of all keywords (author and index keywords) as well as co-authorship (authors) based on network and overlay visualization were used particularly. In co-occurrence analysis, all keywords were chosen as the selected unit with a full counting method. Based on the 296 documents from Scopus, 3,298 keywords were obtained. Once the minimum number of occurrences was set at eight, 78 thresholds were generated, indicating that 78 keywords were repeated eight times in the 3,298 keywords.

Even though the keywords were tidied up in Open Refine, some redundant keywords still appeared that had the same meaning as CO_2 and carbon dioxide. These were employed as a writing format using Thesaurus note, which were then imported into VOS Viewer. In co-authorship analysis, the applied unit analysis referred to authors with the full counting method. The total number of authors in the 296 Scopus-generated documents was 1,011. After setting the minimum number of an author's documents at three, the threshold obtained was 76 authors. Tableau software was used to simplify complex data in the form of interactive graphic visualizations, for easy analysis and understanding (Akhtar et al., 2020). Akhtar et al. (2017) and Murray (2013) stated that Tableau is the most powerful and flexible analytical platform for providing data information and managing their rows into various visualization types.

Data analysis and interpretation

296 research publications were processed by using Open Refine, VOS Viewer and Tableau software regarding publication and citation trends; co-authorship and co-occurrence were analyzed and interpreted, then comparative analysis was conducted within the aforementioned research publications.

The method should consist of research design, subject characteristics, data collection process and data analysis. If necessary, it should raise ethical issues

particularly when dealing with human participants. Appropriate statistical methods should be used, although the biological mechanism should be emphasized. The statistical model, classes, blocks, and experimental units must be designated. Consultation with a statistician is recommended to prevent any incorrect or inadequate statistical methods.

Results and Discussion

Global distribution of publication and citation trend (2012–2022)

One of the objectives mentioned in this article is the determination of global research distribution in 2012–2022. The trends of publications and citations in those years are presented in *Fig. 3*. The total number of publications obtained from Scopus regarding "Carbon Capture Utilization and Storage" was 296. This figure increases significantly from 3 publications in 2012 to 83 publications in 2021. The number of publications and citations in 2021 are inversely related. In 2022, the total number of published documents and citations seemed to decrease because the data were collected in January, hence they did not represent 2022 as a whole. From 2012 to 2015, the increase of published documents and citations was directly proportional, but in 2016, the number of citations increased. The highest citations occurred in 2016; however, the number decreased by 72% after 2016.

Research on carbon capture, utilization and storage (CCUS) has been issued from several journals and publishers including Elsevier Ltd., MDPI AG, Frontiers Media S.A., Italian Association of Chemical Engineering – AIDIC, and Blackwell Publisher Ltd, which are the top 5. Elsevier Ltd. has the highest number of publications and 1,322 citations of 97 documents, as well as journals reaching 28. Furthermore, its top 5 journals with the number of publications and citations respectively are Journal of 1) Greenhouse Gas Control (36.76%; 24.93%), 2) Cleaner Production (17.65%; 7.01%), 3) Applied Energy (17.65%; 38.40%), 4) Energy (16.18%; 13.28%), and 5) CO_2 Utilization (11.76%; 16.38%). Based on the results, 138 journals published articles on carbon capture, utilization and storage with up to 3,947 received citations.

Co-authorship analysis

This co-authorship analysis indicates the relationship between authors, countries and organizations, represented in a network diagram containing nodes and lines classified in different clusters. The clusters of nodes and lines are being distinguished by colors, while the size of nodes shows the weight and repetition of keywords. In addition, the distance from one node to another illustrates the strength of their relationship, and farther link between nodes means both keywords have less research (Khosroabadi et al., 2021).

Authors

The authors who conducted research on CCUS were 62, while their productivity is depicted in *Fig. 5* with the highest number of publications and citations. Zhang X is the most prolific writer in terms of the number of

Fig. 3. *Annual publication and citation spread (2012–2022)*

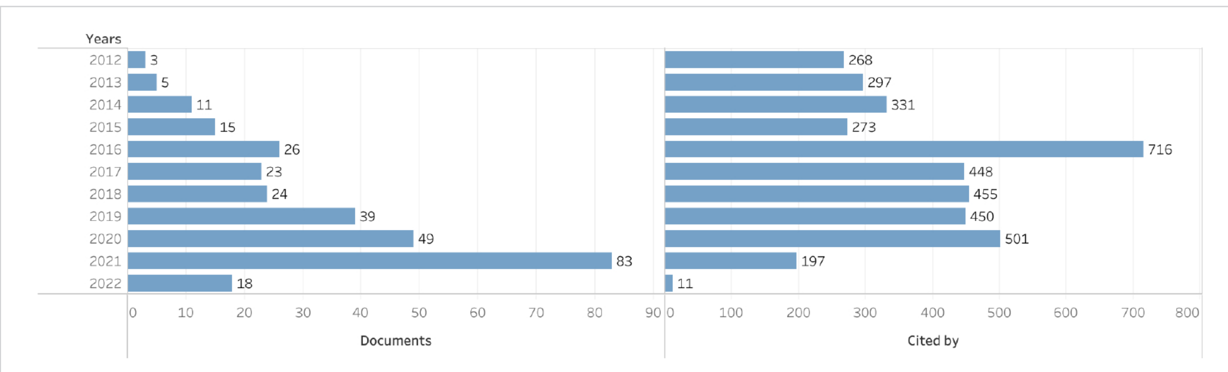


Fig. 4. *Distribution of publications and citations by journal: (a) publication and (b) citation*

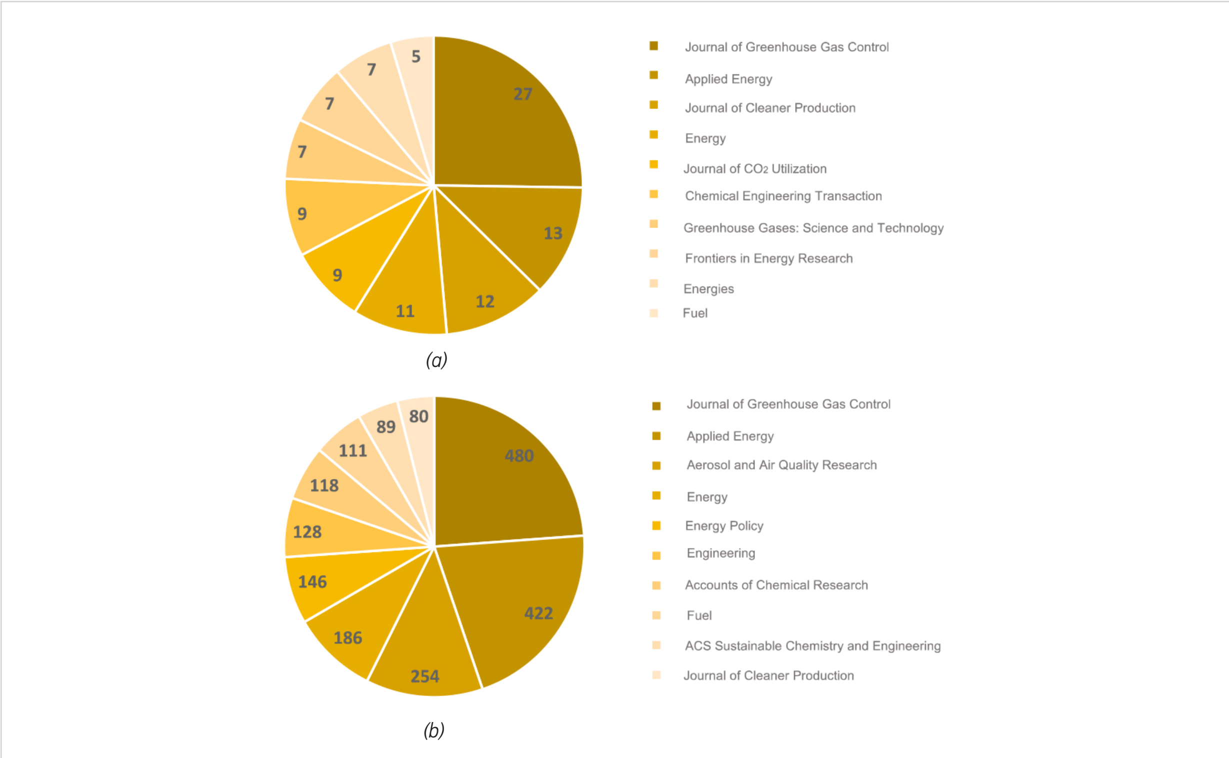
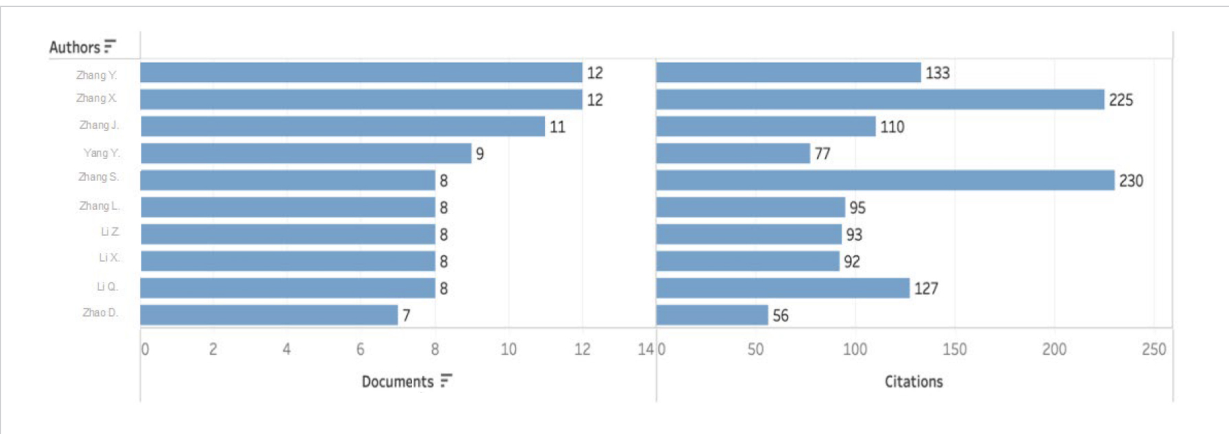
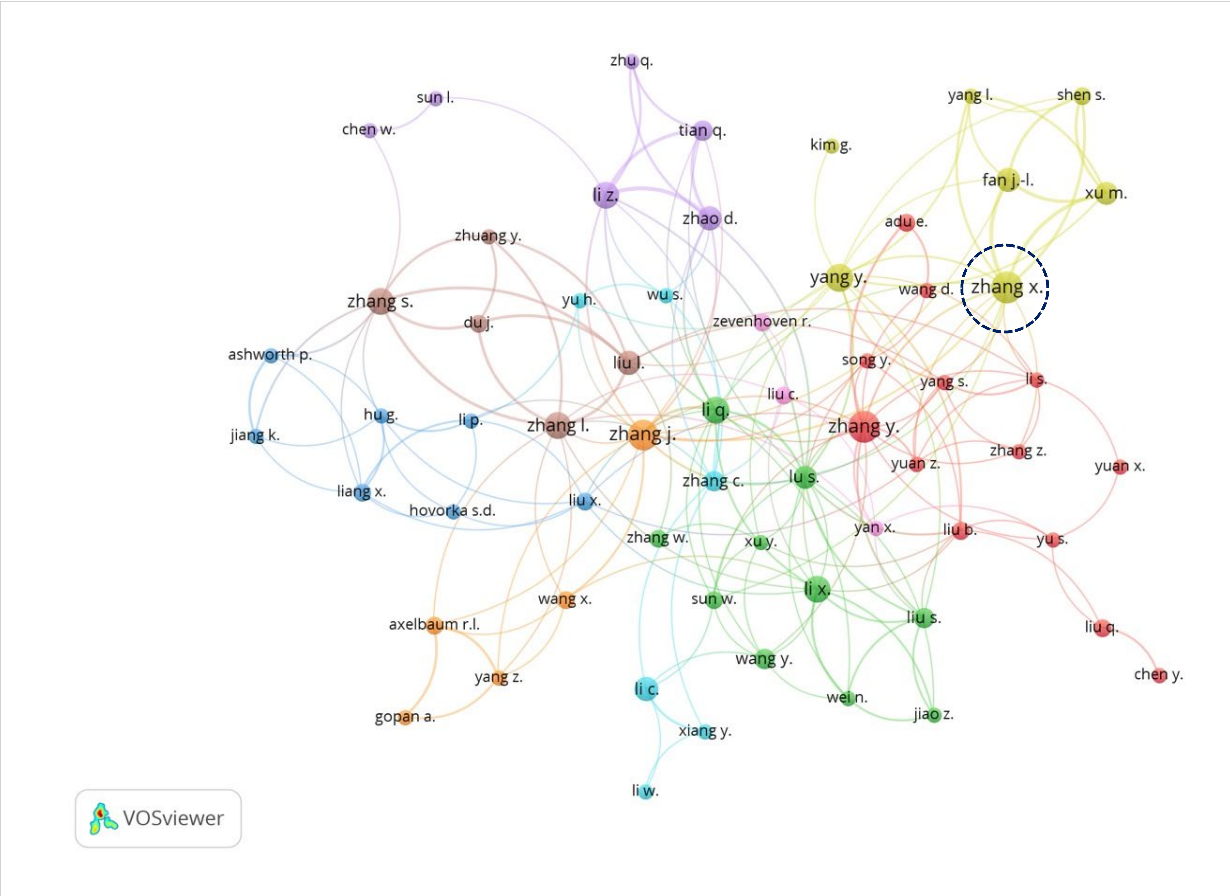


Fig. 5. *Author productivity in terms of publications and citations*



publications issued during 2012–2022, namely 12 documents that received 225 citations. These were lesser compared to Zhang S who reached 230 citations with a total of 8 documents published. The authors' relationship to one another is presented in *Fig. 6*, and in total, they are divided into 9 clusters distinguished by the nodes' color. Zhang X has the highest total link strength of 33 and several relationships with 14 authors from other clusters through an average publication in 2019. The high citations obtained from authors are influenced by their number of links, meaning that there is a high chance of receiving citations with a high link.

Fig. 6. *Co-authorship network of authors*



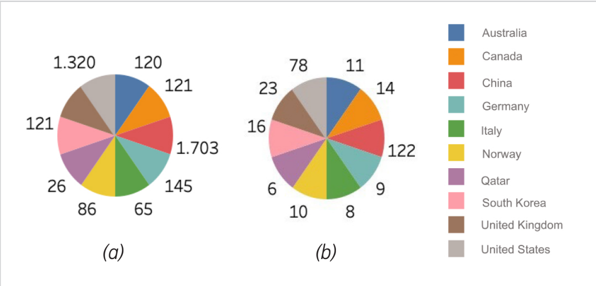
During 2012–2015, Zhang X weighed the research development of CCUS technology in China including enhanced oil recovery and onshore saline aquifer as the most dominant options for the large-scale CO_2 utilization and storage techniques for the development of a roadmap of CCUS technology in China, followed by estimating the potential of methanol through hydrogenation (CTM) and steel slag mineral carbonation and utilization (SCU) to optimize the efficiency of emission reduction, as well as the potential of CO_2 enhanced oil recovery (EOR) and CO_2 enhanced water recovery (EWR) for direct emission reduction.

Throughout the period of 2016–2018, Zhang X highlighted the scope of his research among the topic of the benefit of a vertical integration model that fits for considering the revenue of CCUS technology applied for national projects in China, especially to determine the economic benefits from enhance recovery oil (EOR) and the benefits of CO_2 EOR technology to ease the high investment cost by subsidizing the application of EOR to accelerate the CCUS development in China.

Countries

Fig. 7 shows the top 10 publications and citations based on their geographical location. The results of this study indicated China as the most productive country in conducting investigation on CCUS topics in 2012–2022, where the highest number of citations received was 43.39% and the publications reached 41.08% of the total citations amongst other 9 other countries. However, a similar study of CCUS by (Omoregbe et al., 2018) showed a contrary result, that USA generated more publications (4,416) than China, which generated only 1,876 publications.

Fig. 7. *Top 10 countries with the highest number of citations and publications: (a) citation and (b) publication*

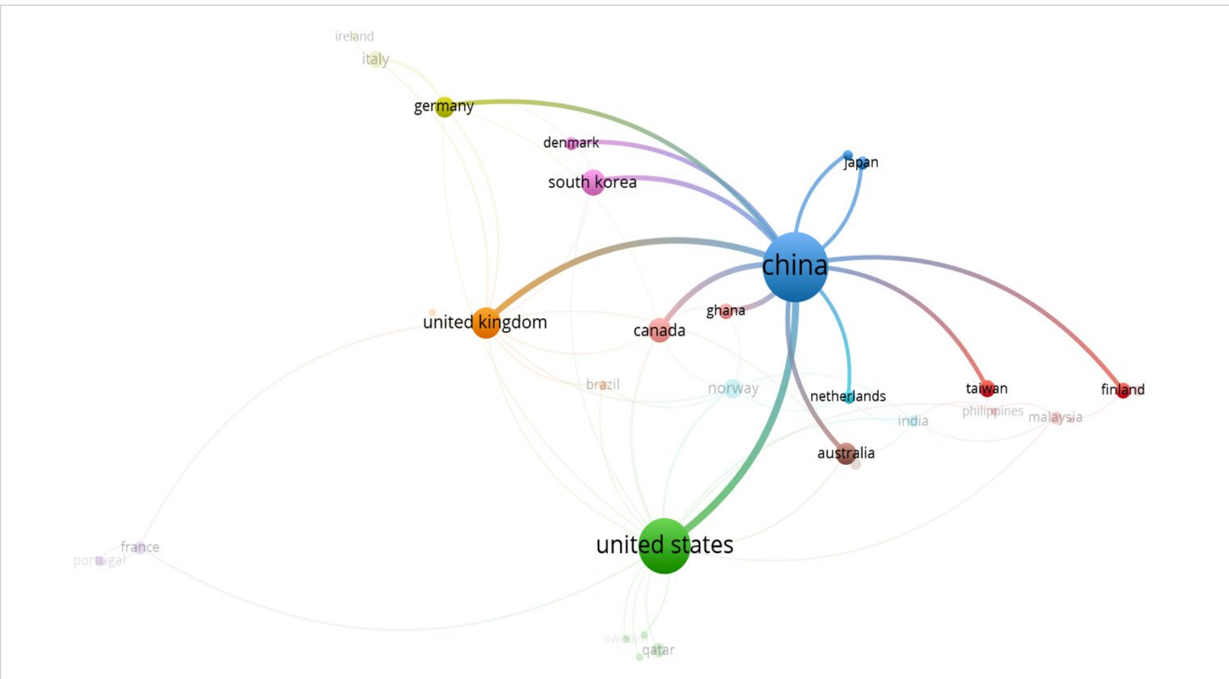


The second rank was occupied by the United States with publications and citations of 26.26% and 33.63%, respectively. As presented in *Fig. 8*, 32 countries were connected and divided into 10 clusters. The total link strength is the accumulated strength of the relationship between different items (Jiang and Ashworth, 2021). Based on countries analysis, the highest total link strength was achieved by China and the United States, namely 45 and 38. Meanwhile, the United Kingdom, Germany, South Korea, and Canada undertook a collaboration on research with China and the United States.

After the meeting of G8 in 2005, these above-mentioned countries were included into a pledge in Hokkaido for strengthening the climate change mitigation (Cosbey, 2009). Recently, Germany and United Kingdom reached the relative high rank for their international policy for climate change mitigation among other G20 countries, followed by the United States and China for their international level of climate negotiations performance. Meanwhile, the Republic of Korea (South Korea) and China received an appreciation amongst other G20 countries for their national climate policy. However, Canada showed the least willingness to improve their climate change mitigation performance due to political interest (Cosbey, 2009).

These remarkable achievements of respective countries were delineated from their Nationally Determined Contribution (NDC) for short-term that affects long-term goals, such as 55% of decarbonization goal belonging to Germany, 40% national reduction target of greenhouse gas emission in United Kingdom, and 25–28% reduction in greenhouse gas emission for the United States (Falduto and Rocha, 2020).

Fig. 8. *Co-authorship network of countries*



Organizations

In this study, the 296 publications were distributed across 687 organizations. This shows that this research was carried out from a diverse number of organizations including companies and mostly from universities. The top 10 organizations with the highest number of citations are shown in *Table 1*. The number of citations obtained from top 10 organizations with the highest citations was 1,553, belonging to the United States (47.39%), Taiwan (30.26%), and China (22.34%). However, the organizations with the highest citations were National Taiwan University and Taipei Medical University with citations of 235 each, while the lowest citations came from Amaren Corp United State (206).

Table 1. *Top 10 organizations with the highest citations*

Organization	Total Citation (%)
Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan	15.13%
Department of Biochemistry, Taipei Medical University, Taipei, Taiwan	15.13%
Indiana Geological Survey, Indiana University, Bloomington, United State	11.14%
Exxonmobil Upstream Company, Houston, United State	11.14%
Department of Geological Sciences, Indiana University, Bloomington, United State	11.14%
Laboratory of Low Carbon Energy, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of thermal Engineering, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Green Chemical Technology of Ministry of Education, Collaborative Innovation Center of Chemical Science and Engineering, School of Chemical Engineering and Technology, Tianjin University, China	7.15%
Department of Chemistry, University of North Carolina at Chapel Hill, United State	7.15%

National Taiwan University secured its most productive position in CCUS publication due to the efforts for weighing the importance of earth science, life science and social science which transformed into multi-disciplinary programs providing solutions particularly for climate change issues implemented in a number of climate change research and carbon capture practices as well as sustainable development related case studies and seminars (NTU, 2018). Meanwhile, Taipei Medical University put its remarkable efforts for CCUS related research topics such as carbonation, slags and steel making that plays a significant role into carbon capture, assigned under Department of Bio-chemistry.

Co-occurrence analysis

In this research, the keywords collected from 296 documents were 3,298. After setting the minimum number of occurrences at eight, 78 thresholds were generated. This shows that 78 keywords were repeated eight times in the 3,298 keywords. The co-occurrence visualization for all keywords is presented in *Fig. 9*, which is divided into four clusters marked with different colors: the first is red, second is green, third is blue, and fourth is yellow. Each cluster has one keyword with the highest total link strength. According to *Table 2*, cluster 1 is “carbon capture”, 2 is “carbon sequestration”, 3 is “CCUS” and 4 is “carbon dioxide”.

The sphere shaped icons are called nodes and they have relationships with one another which indicate the relationships of different keywords. The node size shows the weight and repetition of a keyword, hence a larger size means that the keyword is more frequently used than the keyword of smaller nodes. The distance from one node to another illustrates the strength of their relationship, and the farther link between nodes means that both keywords have less research (Jiang and Ashworth, 2021). The keyword “carbon dioxide” contained in cluster 4 had the highest occurrence of 212, total link strength of 135 and up to 77 linkages compared to other keywords. Meanwhile, “slags” had the lowest occurrence which is 8, total strength of 46, and 19 linkages between keywords. The positions of the top 10 keywords with occurrences and citation scores are depicted in *Fig. 10*.

Fig. 9. *Network of co-occurrence (all keywords)*

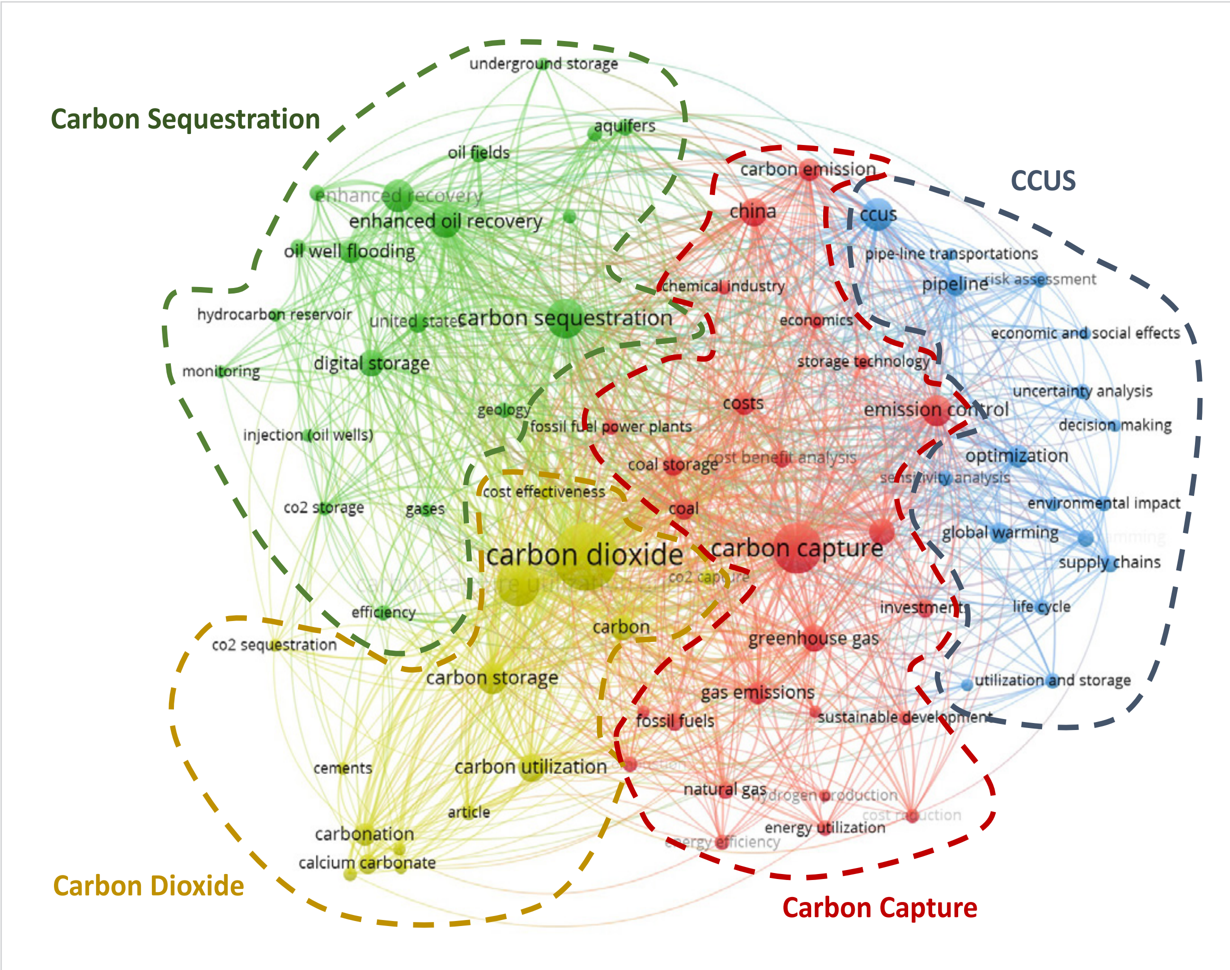


Fig. 10. *Top 10 keywords based on the number of occurrences and citations*

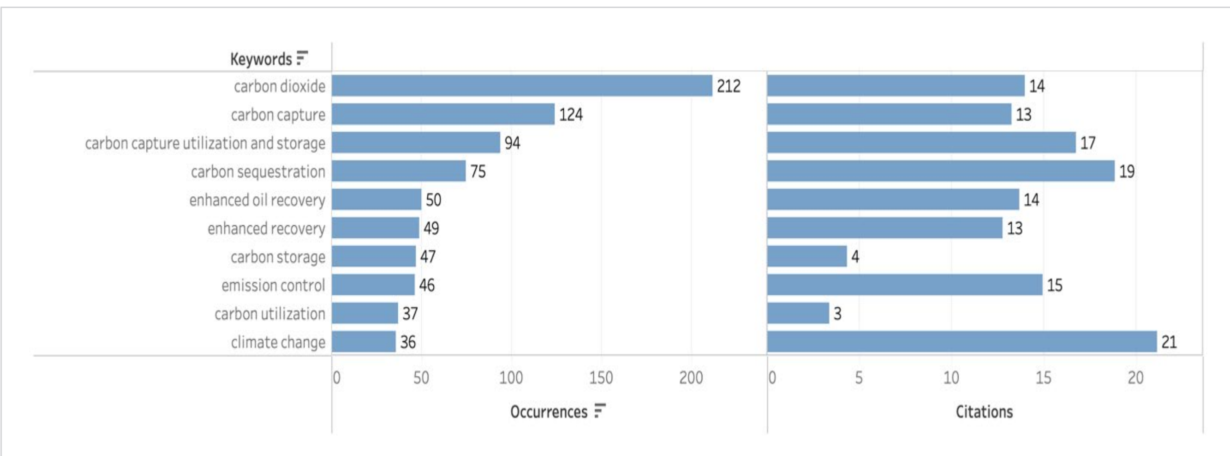
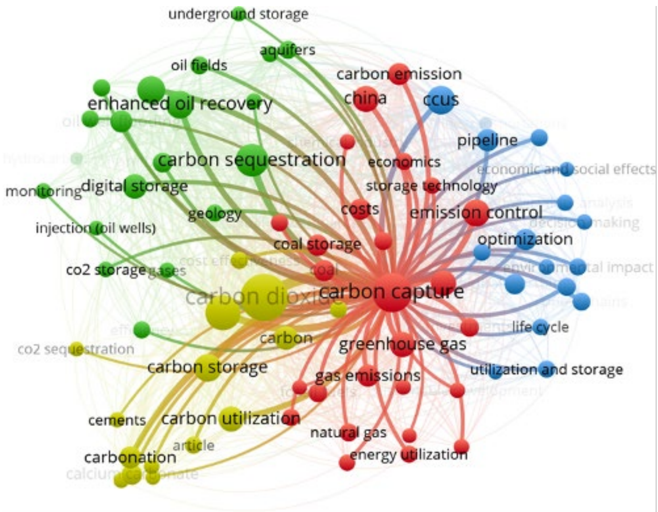
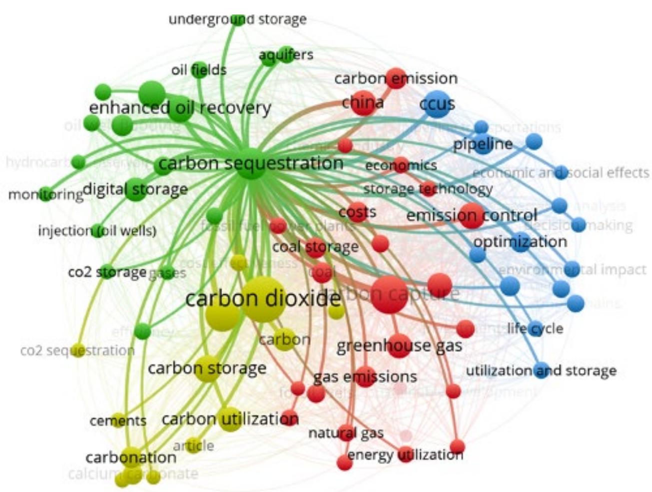
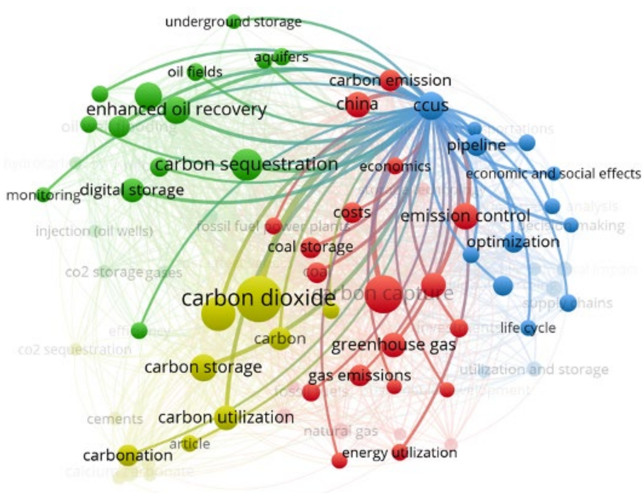
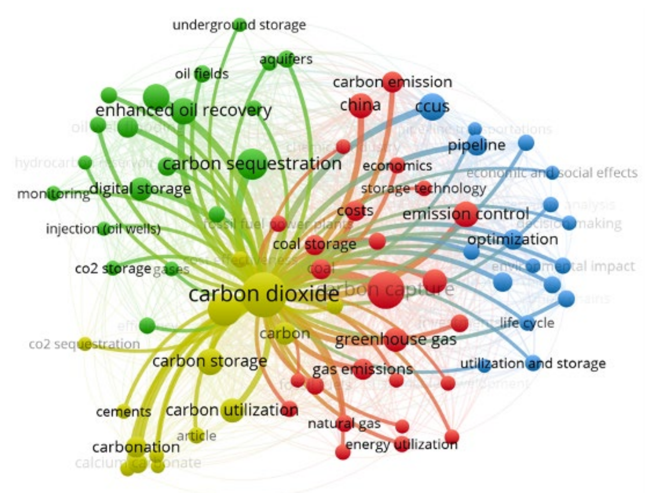


Table 2. *Network visualization keywords in each cluster*

<table>
<tr><th>Cluster</th><th colspan="2">Visualization</th></tr>
<tr><td>1</td><td>
</td><td>In cluster 1, "carbon capture" is the keyword that has the largest node size of 76 links with other keywords, and the total link strength of 875. This technology aims to reduce carbon emissions produced from power plants and industries driven by fossil fuels, thereby promoting clean energy transition (Orlov et al., 2022). A report of clean energy transition through the application of CCUS has mentioned Norway as one of the European countries expanding the project of CO_2 capture facilities executed by Norcem (cement factory) and Fortum Oslo Varme (waste-to-energy plant) as well as a large facilities of CO_2 storage in the North Sea established by a group of oil and gas companies. This project, which is known as Longship CCS project, aims to accelerate the capacity of CO_2 transport and storage at the maximum of 5 Mt/year (IEA, 2020).</td></tr>
<tr><td>2</td><td>
</td><td>In cluster 2, "carbon sequestration" has the largest node size, 74 links with other keywords and the total link strength of 560. This serves as an efficient and environmentally friendly approach by incorporating carbon dioxide emissions that have been captured into the soil in an organic matter form (Orlov et al., 2022). Even though soil carbon sequestration has been widely applied, analyzing a suitable management system and method to enhance its storage effect is still an important matter to be deepened (Hinge et al., 2020). Sanchez et al. (2018) weighed the potential of geologic sequestration for perpetual storage of CO_2 in saline aquifers, benefited by two corn-based ethanol companies in USA. The first company included the CCUS project established in Decatur, USA, to capture 1 $MtCO_2$/year which then sequestrated in the Mt. Simon sandstone, USA. Another company named Red Trail Energy had a plan to sequester 180,000 t CO_2/year in the Broom Creek Formation, North Dakota.</td></tr>
</table>

<table>
<tr><th>Cluster</th><th>Visualization</th></tr>
<tr><td>3</td><td>


In cluster 3, “CCUS” has the largest node size, 61 links with other keywords, and the total link strength of 318. CCUS is a technology that plays an important role in reducing carbon emissions in the energy sector so that net-zero emissions can be achieved by eliminating and balancing carbon emissions that are difficult to reduce or avoid. The role of CCUS is proven to be able to eliminate carbon emissions from the energy sector fall to zero by 2070 worldwide in the IEA Sustainable development scenario (IEA, 2020). It has a huge potential as a solution to generate low carbon heat and power, decarbonize industry and reduce CO_2 emissions in the atmosphere (Regufe et al., 2021). CO_2 enhanced oil recovery (CO_2- EOR) method as the technological basis to develop CCUS relies on the CO_2 injection and sequestration to be captured in geologic formation. China, the United States and Canada were the pioneers in the development of CO_2- EOR as this technology has the ability to mitigate CO_2 emission as well as proliferate the production of domestic crude oil, which then followed by some countries such as Brazil, Norway, Trinidad, Turkey, Saudi Arabia and the United Arab Emirates (Hill et al., 2020).</td></tr>
<tr><td>4</td><td>


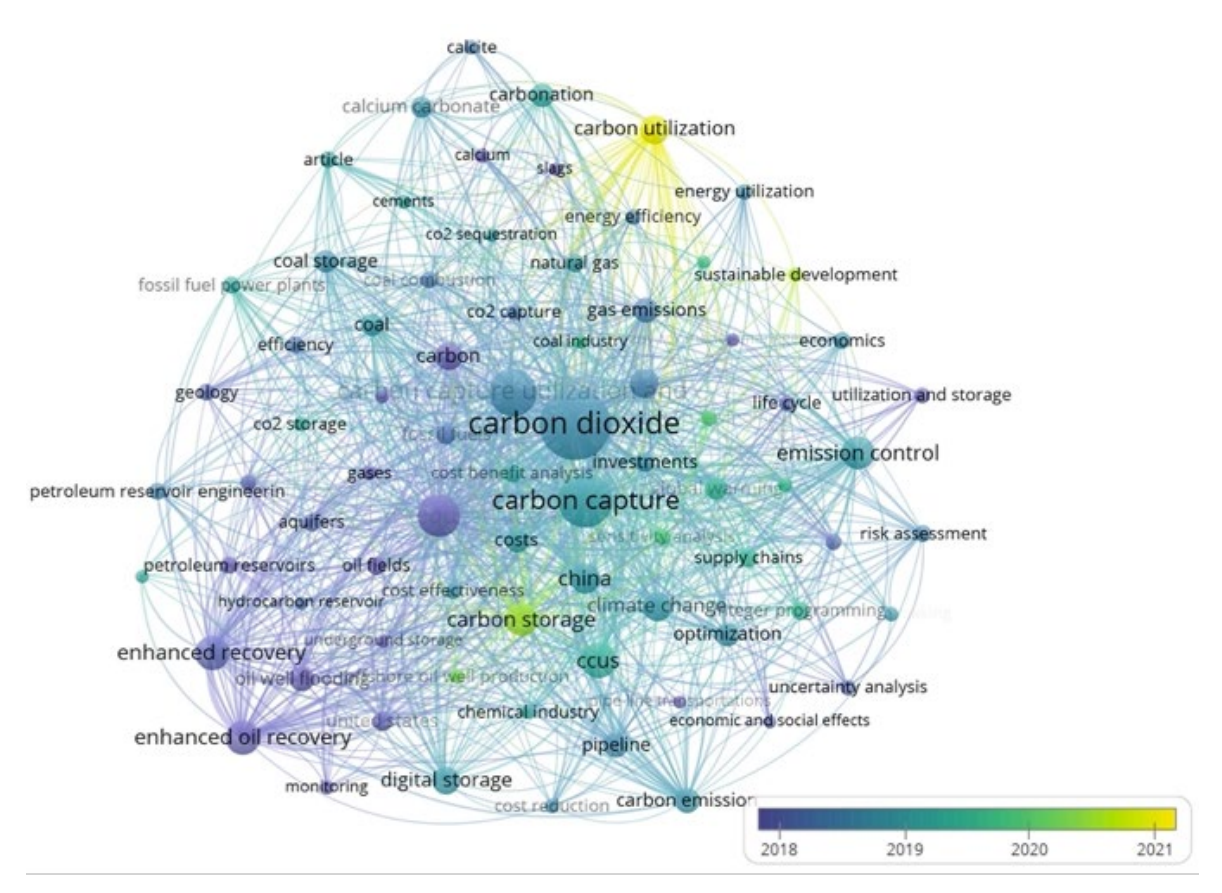
In cluster 4, “carbon dioxide” has the largest node size, 77 links with other keywords, and a total link strength of 1325. This is one of the most critical anthropogenic greenhouse gases due to being abundant and persistent in the atmosphere for a long time (Ali et al., 2020). Recently, the demand of energy has been soaring up; however, the energy supplies are dominated by fossil fuel power plants that generate CO_2 emission. In order to generate a net zero CO_2 emission path as a form of sustainable energy, CCUS technology has to create a synergy with the technology of renewable energy, hydrogen, and electrification. Notably, CCUS technology has been commenced since the era of processed natural gas, which are now challenged by the need to develop a modern global technology of CCUS that consist of 3 methods namely pre-combustion, post-combustion and oxy-combustion (Hill et al., 2020).</td></tr>
</table>

Carbon dioxide had the highest occurrence at 27.53% amongst the top 10 value of co-occurrence, although the number of citations for the publications with the keyword of “climate change” was higher than the number of citations for the publications with the keyword “carbon dioxide”. This result was in line with the research conducted by Awolesi et al. (2019), which generated 38 publications related to the keyword of “carbon dioxide”.

According to Awolesi et al. (2019), the highest publication appointed to the low carbon emission research occurred in 2012, within the 2011–2018 period. Meanwhile, Bergamschi (2019) mentioned that the publications of research on carbon capture technology increased gradually from 1998 to 2018 to reach 1,020 documents. Up to 3,800 citations were obtained in the research from 1998 to 2018, and they continued to increase along with the publications even though there were fluctuations. This indicates that the research topics regarding carbon capture, utilization and storage are in annual demand. The International Journal of Greenhouse Gas Control has the highest number of publications, namely 27 documents and 480 citations (Khosroabadi et al., 2021). *Fig. 4* is an overview of the top 10 journals based on the highest publications and citations.

The number of publications and citations on the topic of carbon capture technologies reached 4,532 and 166 with an average citation per publication of 553. This study showed the number of 17.78 as the average citation per publication. *Fig. 11* shows the visualization of all keywords based on the publication year of 2018–2021. The difference of node color indicates the year of publication; hence, a lighter color implies the

Fig. 11. *Overlay visualization co-occurrence (all keywords)*

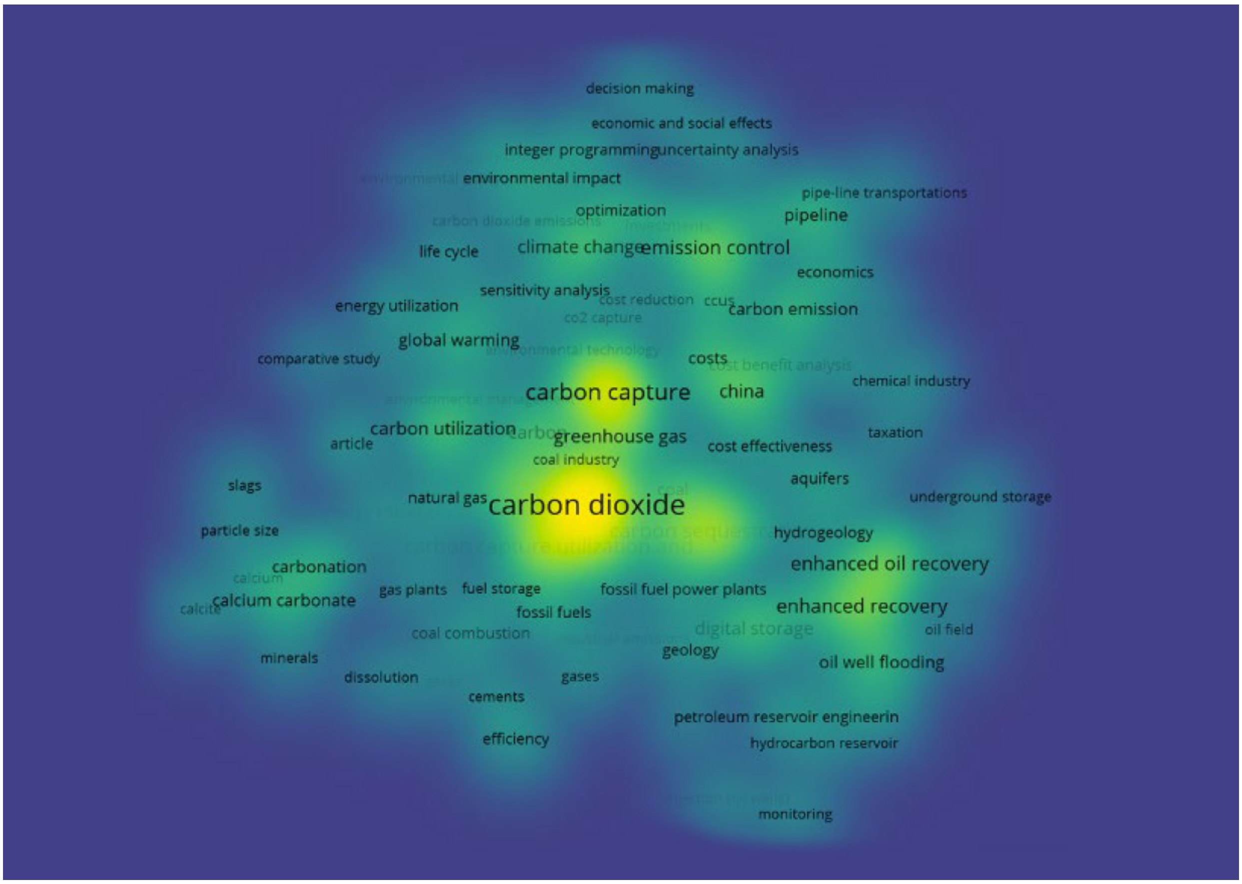


latest publication. The keyword "carbon dioxide" was widely investigated around 2018. "Carbon utilization" appeared around 2021 with 37 occurrences, total link strength of 259 and 62 linkages between keywords. This explains that the research related to carbon utilization was not largely conducted before 2021.

According to Ampah et al. (2021), the bibliometric research should be executed in a way that can strengthen the targeted discipline field through some approaches, namely (1) providing a comprehensive knowledge of the research area; (2) identifying research gaps; (3) highlighting the results of study for future studies. A number of journals identified through Vos Viewer have recognized the existence of CCUS incentive policies and regulations applied for some countries such as China (Zhang et al., 2013), United Kingdom (Leonzio et al., 2020), Hong Kong (Zhang et al., 2021) and United Arab Emirates (Al-Saleh et al., 2012). However, there is a lack of studies addressing the policies and regulations released by ISO standards and international regulation boards to inform on the property rights of the selected sites and accountability for stored $CO_2$with respect to the period of ownership and financial matters.

In addition, the density visualization of index keywords (*Fig. 12*) showed some keywords in the areas of hazy colors (e.g., green-blue color) that interpreted the research gaps in the literature that need to be identified, such as: "environmental impacts", which can be correlated to the analysis of environmental impacts for CO_2 leakage during transportation; "cost reduction", which relates to the knowledge of the reduced cost of capture, transport and storage capacity processes; and "carbonation" to be related to the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future,

Fig. 12. *Density visualization co-occurrence (index keywords)*



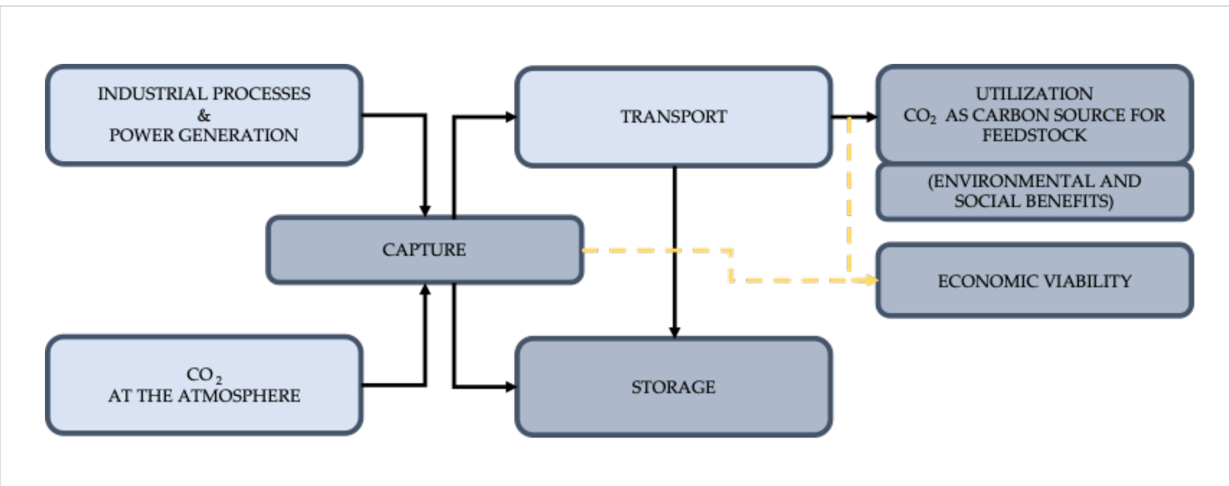
since the existing conventional method of carbonation still requires labor force and are cost-intensive (Simonson et al., 2020). Furthermore, the advanced carbonation method will contribute to the economic viability of carbon utilization, which can be achieved through the use of synthesized rare earth elements at the stage of the treatment process of mineral carbonation for accelerating the economic value of steel slags (Baciocchi and Costa, 2021).

CCUS technology is referred to as sustainable if the economic performance of the preferred method can be achieved without generating additional environmental negative impacts. Thus, CCUS, as one of the climate change mitigation technologies that may achieve the carbon emission reduction target, needs to provide economic, social, and environmental benefits as shown in *Fig. 13* (Assche and Comprenolle, 2022). In addition, the technology of CCU offers the area of social and environmental benefits to be investigated beyond its current initial stage and limited scope of research (Cosbey, 2009). Mitigation and adaptation are important in reducing carbon emissions and are an integrated approach to climate action and development. The integrated approach includes assessment, goal setting, identification, financing and implementation as well as monitoring, evaluation and learning (Jeffrey and Anika, 2022).

Conclusions

CCUS is proven as one of the ultimate technologies for mitigating climate change by capturing carbon emissions produced by industries, which are then being stored at 700 m below the sea level. Bibliometric analysis was used to examine the research trends such as CCUS by identifying keyword networks, authors, organizations, countries, growth trends in terms of the number of publications and citations by publishers and source titles in the period 2012–2022. The results of this study, derived from 296 documents of the Scopus database, showed the increase of publications concerning CCUS related keywords by 2,766.6% within the period of 2012–2022. Based on this study, the most productive country in conducting investigations on CCUS was China, empowered by Zhang X as the most prolific writer affiliated with China University of Petroleum. However, the organization that published the highest number of research on CCUS was National Taiwan University. On the basis of the publication and citation, this study found International Journal of Greenhouse Gas Control as the most productive journal that was published by Elsevier Ltd., that is widely known as a competent publisher of the highest number of publications and citations for research publications. Based on the co-occurrence analysis of index

Fig. 13. *The inclusion of environmental, social and economic impacts into a simplification of the CCUS process to illustrate a sustainable CCUS pathway*



keywords, the research gaps are identified in the literature, such as the analysis of environmental impacts for CO_2 leakage during transportation, the knowledge of the reduced cost of capture, transport and storage capacity processes as well as the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future since the existing conventional method of carbonation still requires labor force and is cost-intensive. This study identified the potential further research for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach. Hence, the importance of CCUS technology for CO_2 sequestration is clearly identified through this study, which is beneficial for the development of CCUS research, particularly to contribute to clean energy transition.

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Thalia

by J Maria Utha

Submission date: 12-Apr-2023 09:56AM (UTC+0700)
Submission ID: 2062163996
File name: Thalia.pdf (2.49M)
Word count: 8425
Character count: 45857

EREM 79/1

Journal of Environmental Research, Engineering and Management
Vol. 79 / No. 1 / 2023
pp. 37–55
DOI 10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

Received 2022/10 | Accepted after revision 2023/02

https://doi.org/10.5755/j01.erem.79.1.32424

Research Development on Carbon Capture, Utilization and Storage as a Climate Change Mitigation Technology

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The continuous growth of energy consumption leads to the increase of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). Carbon capture, utilization and storage (CCUS), which consists of carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), is a technology that aims to capture CO_2. Therefore, this study evaluates and provides an overview of CCUS in the period 2012–2022, by using a bibliometric analysis to obtain a complete perspective and reference on CCUS. The data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into the Scopus database, and 296 documents were generated. Other software used included Open Refine, VOS viewer and Tableau to describe publication and citation trends, co-authorship, and co-occurrence. CCUS research trend increased by 2,766.6% from 2012 to 2022. The most productive country in investigating CCUS was China, and Zhang X. was the most prolific writer. The organization that published the highest number of research on the topic was the National Taiwan University. The publications and citations were dominated by the International Journal of Greenhouse Gas Control that was published by Elsevier Ltd., which also issues a number of significant publications and receives the highest number of citations.

Keywords: bibliometric analysis, carbon emission, carbon capture, carbon capture utilization, carbon capture storage.

Introduction

The increase of greenhouse gas (GHG) emissions has become a global climate issue that profoundly raises the world's attention due to the impact of climate change. The Intergovernmental Panel on Climate Change (IPCC) launched a Special Report on Global Warming of 1.50 °C, which contains various impacts created on human health, food security and ecosystems. This impact can be anticipated through the attempt of limiting the temperature rise by 1.50 °C above the average temperature prior to industrial era. Total GHG emissions in 2018 reached 55.3 gigatons of CO_2 equivalent. Consequently, hydro-meteorological disasters may occur due to extreme weather that changes the length of dry and rainy season and increases the frequency and duration of droughts. Another impact of climate change is a rise in temperature and sea level (Nerem et al., 2018; Zhao et al., 2020). According to Stone et al. (2009), carbon dioxide emissions have increased by 40% since the period of the Industrial Revolution, and human activities might have greatly contributed to CO_2 release since that time. Carbon dioxide is capable of absorbing long-wave IR radiation (heat) being emitted by the earth which can make the greenhouse effect stronger, hence any increase in CO_2 emissions ultimately causes a rise in the earth's temperature.

The largest CO_2 emissions are generated from agricultural activities, energy production and energy use. Furthermore, trade, transportation, and the growing manufacturing industry add to CO_2 emissions as stated by Adom (2012), which exacerbates the ecological aspects of environment such as climate and climate change. Moreover, the tourism industry elevates carbon dioxide emissions; thereby it is important to raise the awareness of global warming and climate change into the practice of business as usual (Balogh and Jambor, 2017). In order to abate the global warming, reducing the levels of carbon dioxide (CO_2) emissions from exhaust gases produced by industrial activities has to be promptly undertaken since the levels of carbon dioxide (CO_2) emissions have continued to increase from year to year (Rinanti et al., 2014). Global warming has an impact on all living things and nature such as rising sea levels, climate anomalies and natural disasters (Fachrul et al., 2019; Rinanti et al., 2013).

By 2100, the level of atmospheric CO_2 emissions is estimated to reach around 800 ppm and the earth's surface temperature tends to rise by 4 °C (Wang and Oko, 2017). According to The Summary for Policymakers of the IPCC Working Group III report, Climate Change 2022: Mitigation of Climate Change, 195 countries in the world have agreed to limit GHG emissions. A conference held in Paris from 30 November to 12 December 2015 propagated the Paris Agreement to the United Nations Framework Convention on Climate Change. Furthermore, the treaty aims to mitigate the climate change towards a low-carbon, resilient and sustainable future and ensures that global temperature elevations keep well below 2 °C (Wang and Oko, 2017). Carbon capture, utilization and storage (CCUS) comprises carbon capture and storage (CCS) as well as carbon capture and utilization (CCU), both of which aim to capture CO_2 that is being released into the air. The difference between these two technologies lies mainly in the fact that, in CCS, CO_2 emissions are captured and injected into underground storage areas, while in CCU, the CO_2 is converted into commercial products. Based on Zaemi and Rohmana (2021), CCUS's goal is to capture 85% of CO_2 that is released from power plants and industries and the resulting emissions are to be transported into 700 meters depth below sea level through pipes.

Based on IPCC (2022), CCS is the most feasible/accessible technology to reduce emissions from carbon-intensive industries and power generation; however, the mitigation costs tend to reach 138% without CCS technology. This technology is applied for the downstream phase of CCS pathways, by capturing carbon emissions to be stored and utilized for other production processes (Prayitno et al., 2021). Meanwhile, Reiner (2016) has found that CCS technology is employed for climate mitigation and expected to decrease the GHG emissions by 32% until 2050. This target can be justified by the research done by Akbar et al. (2021) that CCS technology captures 85–95% of the CO_2 produced by an industry. Besides of that CCS technology is also

able to reduce carbon emissions with an accuracy level of 95% when applied in a waste-to-energy plant.

The Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCC) has summoned all countries in the world to commit to implementing actions to keep average global temperature below 2 °C and to continue with efforts for suppressing the increase to 1.5 °C. Afterward, targets for each country's commitment were created, where the Paris Agreement set a target to reduce GHG emissions, which is called the Nationally Determined Contribution (NDC). The achievement of GHG emission reductions is verified to ensure that the calculation process complies with the principles that have been recognized as transparent, accurate, consistent, comprehensive, and comparable (TACCC) at the national and international level. This mechanism works through the improvement of scrutinizing and disclosure for lowering the GHG emissions level to encourage the countries for acquiring the climate incentive. The report of TACCC will be beneficial for stakeholders to set a number of measureable goals for climate change mitigation that includes the efforts for reducing emission, resilience enhancement and for allocating financial resources (Weikmans et al., 2019).

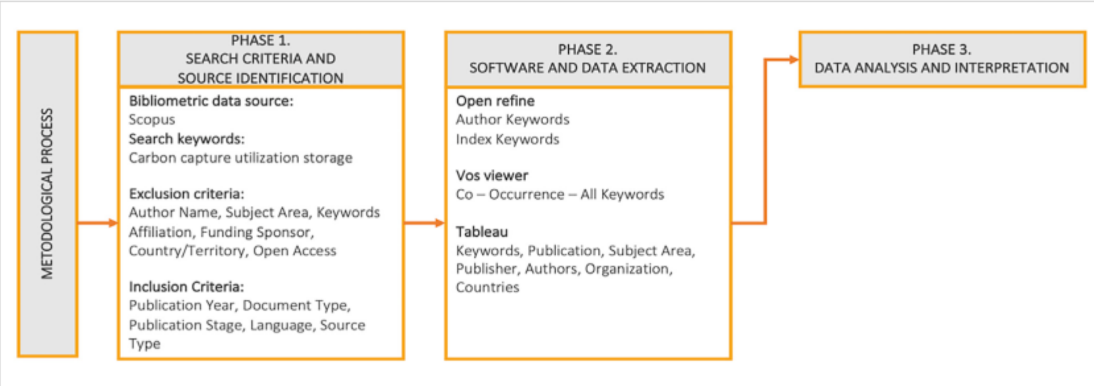
However, the technology of CCUS has not been widely applied, although data and references collection on the technology is largely available. Moreover, the implementation cost of CCUS varies greatly in the fields of electricity and industry (Adisaputro and Saputra, 2017). According to Zaemi and Rohmana (2021), the challenges of developing CCUS are to determine the location of infrastructure and the environment to be used as CO_2 storage areas plus the high required costs. Owing to the significant topic of the IPCC Agenda 2030 on greenhouse gases, CCUS remains to be an interesting global issue to be investigated as a climate change mitigation technology although many studies of greenhouse gases have been extensively conducted. In addition, a number of research works have investigated the application of CCUS technology in some countries, such as the United States (Alphen et al., 2010), China (Jiang and Ashworth, 2020), ASEAN countries (Kimura et al., 2020) and the United Kingdom (Gough et al., 2020). This review, therefore, offers the trend of research development in the field of CCUS to show the acceleration of technology used to apply the CCUS methods for industrialization in some countries within the year of 2012–2022.

The significant objective of this research is to evaluate the growing trend of investigation on CCUS from 2012–2022, as well as to determine the distribution and productivity of research by authors, organizations, and countries, plus the distribution of research work on subject areas and publishers through the following research questions namely: (1) How do the CCUS technologies provide a solution for reducing the carbon emission of industries around the world?; (2) What are the CCUS technologies that most frequently applied for the industry within 2012–2022?; (3) Who are the most prolific authors followed by the most productive countries and organizations?; (4) What are the potential areas of interest in the research development of CCUS technologies? Therefore, the bibliometric analysis which aims to find the research gaps for further exploration on the topic of carbon capture, utilization and storage, was conducted by using the Scopus database. This article divides its systematics of writing into the following parts, namely the introduction, methods, results and discussion, conclusion and references list.

Methods

According to Chen et al. (2015), Singh and Borthakur (2018), a bibliometric analysis is an effective method of analyzing research progress and quantitative trends in publications on a particular topic, by providing an overview of literature contribution both nationally and internationally (Zhang et al., 2020; Zyoud et al., 2022). Sweileh (2022) explains that any bibliometric study uses a statistic approach to identify growth patterns and development of publications as well as collaborative patterns among authors, institutions, and countries. Moreover, bibliometrics identify the research gaps through analyzing the research niche offered by the publication database, which is useful to provide the basis for conducting further research (Singh and Borthakur, 2018; Zhang et al., 2020). The method is divided into three phases, namely data mining, extraction and analysis, as presented in *Fig. 1*.

Fig. 1. *Study method diagram*



Search criteria and source identification

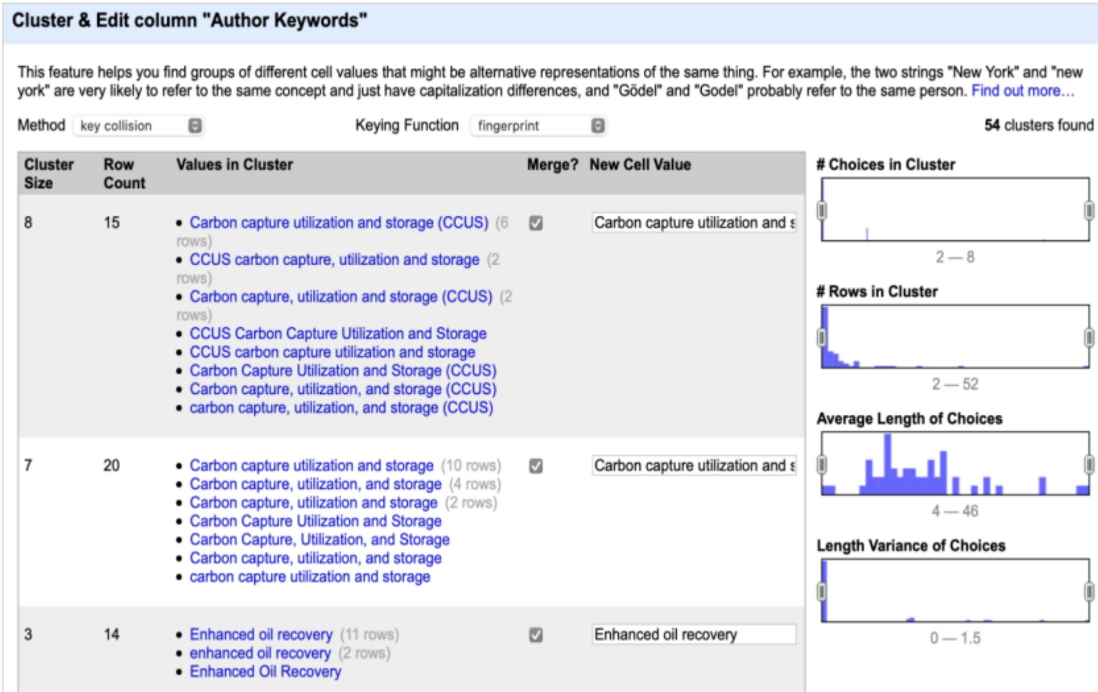
In phase I, data search was carried out on January 20, 2022, by inputting the keyword "carbon capture utilization storage" into Scopus database. Owing to the nature of Scopus as the world's leading literature database published by Elsevier and known to have the highest number of citations (Herawati et al., 2022; Borthakur and Govind, 2017), the Scopus database fits into the expected outcomes of this study. Then, filtering was done with the year of publication, document type, publication stage, language, and source type to obtain more significant results. The data were mined from 2012 to 2022 by limiting the type of article document, final publication stage, journal source type and the English language used. After filtering, 296 available documents were generated and the search results were exported in the CSV format with citation information, bibliographical information, abstract, and keywords. Files exported from the Scopus database were fed into the Open Refine software to reduce inconsistent and repetitive keywords in the mined data.

Software and data extraction

The data obtained from the Scopus database was further extracted and processed by using Open Refine, Vos Viewer and Tableau Public software. The data were fed into Open Refine to reduce several keywords with different spellings but same meaning and to establish the keywords in an exact writing format for avoidance of repetition. Open Refine is able to clean the data from one format to another, overcomes inconsistencies in data sets and divides data into more detailed parts, in an automatic or manual attempt (NIH, 2022).

Fig. 2 shows repeated keywords, namely "Carbon Capture Utilization and Storage (CCUS)", "CCUS carbon capture, utilization and storage", "Carbon capture, utilization and storage (CCUS)", "CCUS Carbon Capture Utilization and Storage", "CCUS Carbon Capture Utilization and Storage", "Carbon Capture Utilization and Storage (CCUS)", "Carbon capture, utilization and Storage (CCUS)" and "carbon capture, utilization, and storage (CCUS)". Some of these have the same meaning but different spellings, hence they are reduced to one format of the keyword, i.e., "Carbon Capture Utilization and Storage (CCUS)". The reduced keywords generated through Open Refine were then fed into the VOS Viewer software, which presents and visualizes specific information about bibliometric chart maps for easier analysis of the relationships or networks about a research topic (Athar et al., 2019). Open Refine enables the author to select the preferred data set, thus the results contained a list of useful data that removes redundant keywords. It means that carbon capture utilization and storage (CCUS) has been tested as the natural result of removing data with redundant keywords. In addition, CCUS is the representative value of other related values (Bergamschi, 2019), to generate a more extensive subject field such as Carbon Capture and Carbon Storage, Carbon Capture Strategies and Carbon Storage Sustainable.

Fig. 2. *Extract data using Open Refine*



The software provides data visualization based on co-authorship, co-occurrence, citation, bibliometric coupling, and co-citation. In this study, co-occurrence of all keywords (author and index keywords) as well as co-authorship (authors) based on network and overlay visualization were used particularly. In co-occurrence analysis, all keywords were chosen as the selected unit with a full counting method. Based on the 296 documents from Scopus, 3,298 keywords were obtained. Once the minimum number of occurrences was set at eight, 78 thresholds were generated, indicating that 78 keywords were repeated eight times in the 3,298 keywords.

Even though the keywords were tidied up in Open Refine, some redundant keywords still appeared that had the same meaning as CO_2 and carbon dioxide. These were employed as a writing format using Thesaurus note, which were then imported into VOS Viewer. In co-authorship analysis, the applied unit analysis referred to authors with the full counting method. The total number of authors in the 296 Scopus-generated documents was 1,011. After setting the minimum number of an author's documents at three, the threshold obtained was 76 authors. Tableau software was used to simplify complex data in the form of interactive graphic visualizations, for easy analysis and understanding (Akhtar et al., 2020). Akhtar et al. (2017) and Murray (2013) stated that Tableau is the most powerful and flexible analytical platform for providing data information and managing their rows into various visualization types.

Data analysis and interpretation

296 research publications were processed by using Open Refine, VOS Viewer and Tableau software regarding publication and citation trends; co-authorship and co-occurrence were analyzed and interpreted, then comparative analysis was conducted within the aforementioned research publications.

The method should consist of research design, subject characteristics, data collection process and data analysis. If necessary, it should raise ethical issues

particularly when dealing with human participants. Appropriate statistical methods should be used, although the biological mechanism should be emphasized. The statistical model, classes, blocks, and experimental units must be designated. Consultation with a statistician is recommended to prevent any incorrect or inadequate statistical methods.

Results and Discussion

Global distribution of publication and citation trend (2012–2022)

One of the objectives mentioned in this article is the determination of global research distribution in 2012–2022. The trends of publications and citations in those years are presented in *Fig. 3*. The total number of publications obtained from Scopus regarding "Carbon Capture Utilization and Storage" was 296. This figure increases significantly from 3 publications in 2012 to 83 publications in 2021. The number of publications and citations in 2021 are inversely related. In 2022, the total number of published documents and citations seemed to decrease because the data were collected in January, hence they did not represent 2022 as a whole. From 2012 to 2015, the increase of published documents and citations was directly proportional, but in 2016, the number of citations increased. The highest citations occurred in 2016; however, the number decreased by 72% after 2016.

Research on carbon capture, utilization and storage (CCUS) has been issued from several journals and publishers including Elsevier Ltd., MDPI AG, Frontiers Media S.A., Italian Association of Chemical Engineering – AIDIC, and Blackwell Publisher Ltd, which are the top 5. Elsevier Ltd. has the highest number of publications and 1,322 citations of 97 documents, as well as journals reaching 28. Furthermore, its top 5 journals with the number of publications and citations respectively are Journal of 1) Greenhouse Gas Control (36.76%; 24.93%), 2) Cleaner Production (17.65%; 7.01%), 3) Applied Energy (17.65%; 38.40%), 4) Energy (16.18%; 13.28%), and 5) CO_2 Utilization (11.76%; 16.38%). Based on the results, 138 journals published articles on carbon capture, utilization and storage with up to 3,947 received citations.

Co-authorship analysis

This co-authorship analysis indicates the relationship between authors, countries and organizations, represented in a network diagram containing nodes and lines classified in different clusters. The clusters of nodes and lines are being distinguished by colors, while the size of nodes shows the weight and repetition of keywords. In addition, the distance from one node to another illustrates the strength of their relationship, and farther link between nodes means both keywords have less research (Khosroabadi et al., 2021).

Authors

The authors who conducted research on CCUS were 62, while their productivity is depicted in *Fig. 5* with the highest number of publications and citations. Zhang X is the most prolific writer in terms of the number of

Fig. 3. *Annual publication and citation spread (2012–2022)*

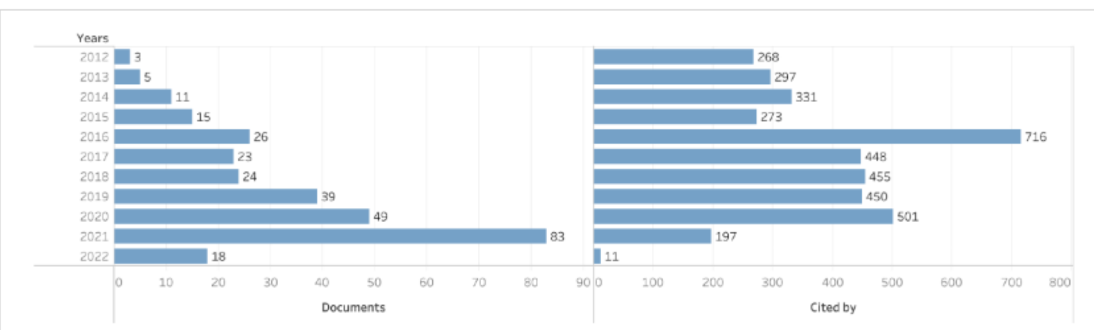


Fig. 4. *Distribution of publications and citations by journal: (a) publication and (b) citation*

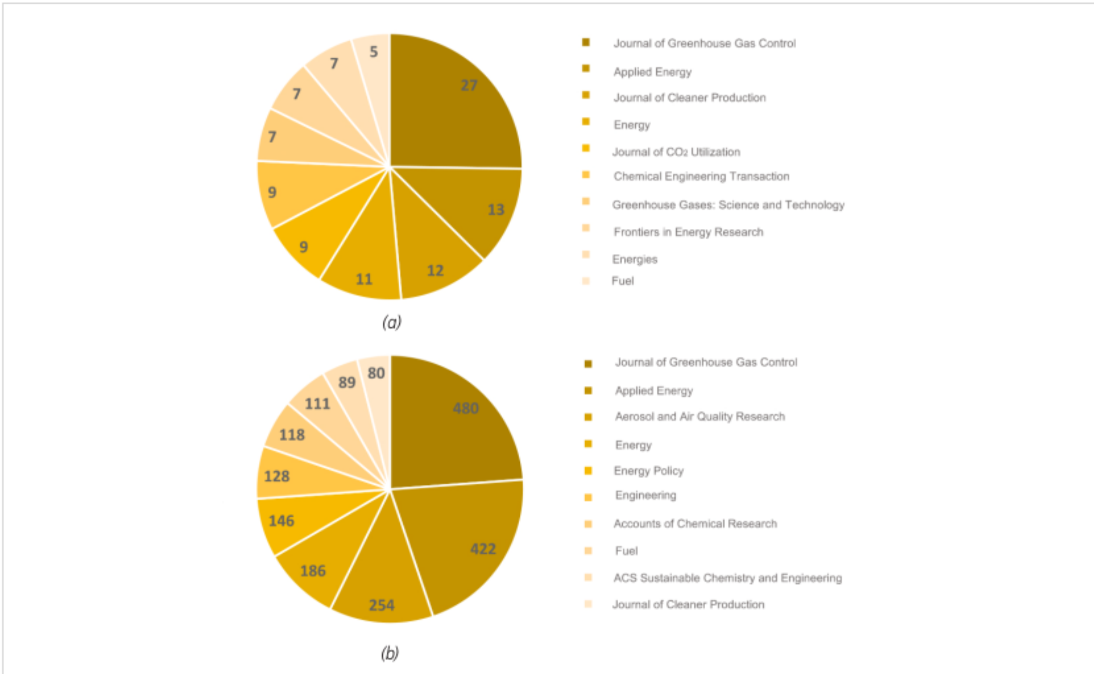
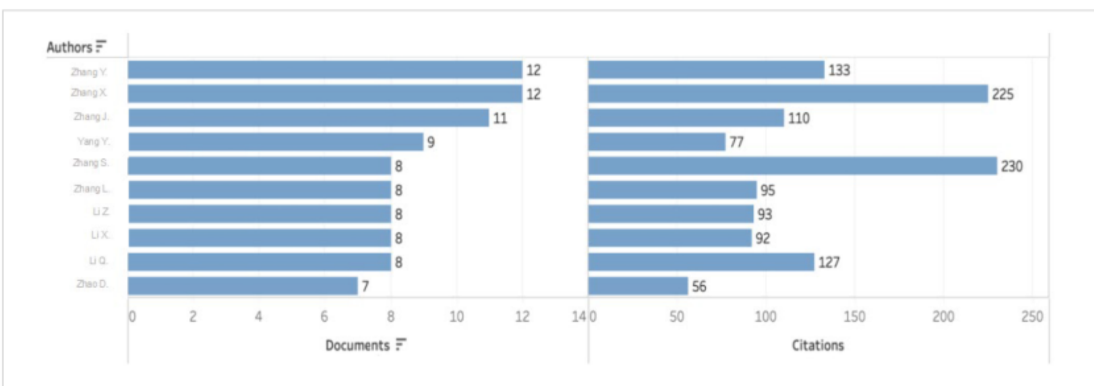
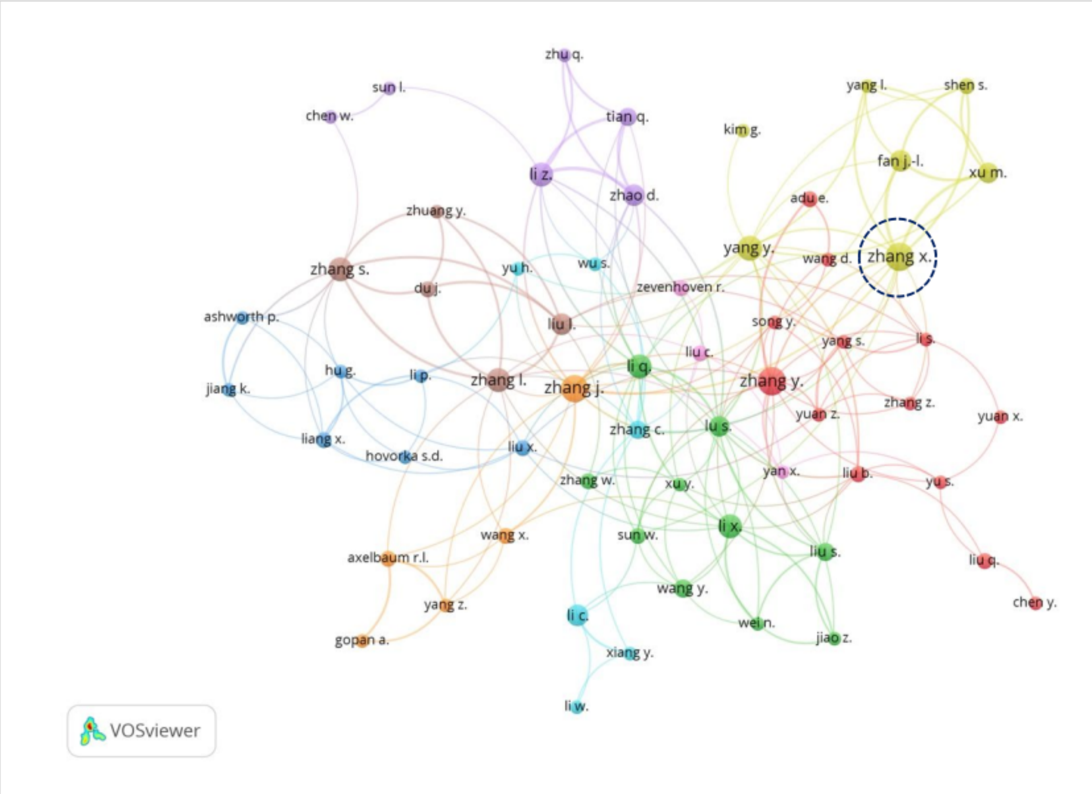


Fig. 5. *Author productivity in terms of publications and citations*



publications issued during 2012–2022, namely 12 documents that received 225 citations. These were lesser compared to Zhang S who reached 230 citations with a total of 8 documents published. The authors' relationship to one another is presented in *Fig. 6*, and in total, they are divided into 9 clusters distinguished by the nodes' color. Zhang X has the highest total link strength of 33 and several relationships with 14 authors from other clusters through an average publication in 2019. The high citations obtained from authors are influenced by their number of links, meaning that there is a high chance of receiving citations with a high link.

Fig. 6. *Co-authorship network of authors*



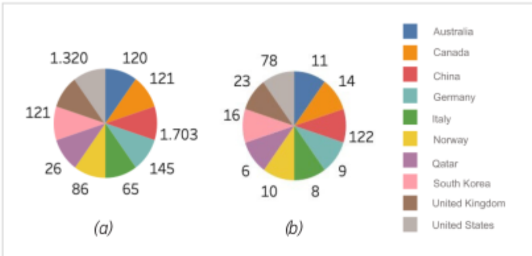
During 2012–2015, Zhang X weighed the research development of CCUS technology in China including enhanced oil recovery and onshore saline aquifer as the most dominant options for the large-scale CO_2 utilization and storage techniques for the development of a roadmap of CCUS technology in China, followed by estimating the potential of methanol through hydrogenation (CTM) and steel slag mineral carbonation and utilization (SCU) to optimize the efficiency of emission reduction, as well as the potential of CO_2 enhanced oil recovery (EOR) and CO_2 enhanced water recovery (EWR) for direct emission reduction.

Throughout the period of 2016–2018, Zhang X highlighted the scope of his research among the topic of the benefit of a vertical integration model that fits for considering the revenue of CCUS technology applied for national projects in China, especially to determine the economic benefits from enhance recovery oil (EOR) and the benefits of CO_2 EOR technology to ease the high investment cost by subsidizing the application of EOR to accelerate the CCUS development in China.

Countries

Fig. 7 shows the top 10 publications and citations based on their geographical location. The results of this study indicated China as the most productive country in conducting investigation on CCUS topics in 2012–2022, where the highest number of citations received was 43.39% and the publications reached 41.08% of the total citations amongst other 9 other countries. However, a similar study of CCUS by (Omoregbe et al., 2018) showed a contrary result, that USA generated more publications (4,416) than China, which generated only 1,876 publications.

Fig. 7. *Top 10 countries with the highest number of citations and publications: (a) citation and (b) publication*

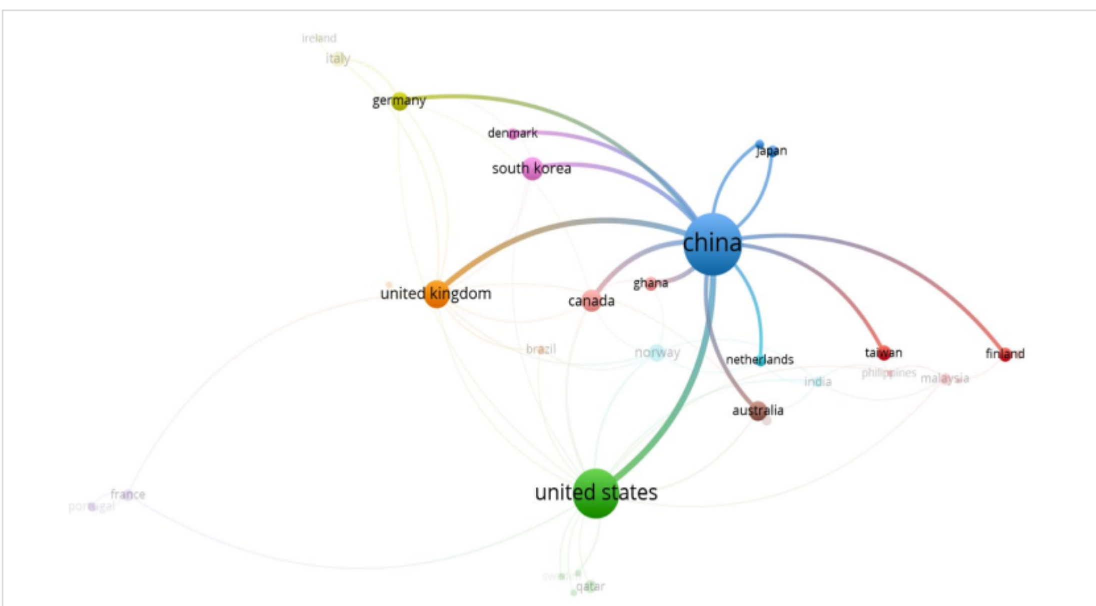


The second rank was occupied by the United States with publications and citations of 26.26% and 33.63%, respectively. As presented in *Fig. 8*, 32 countries were connected and divided into 10 clusters. The total link strength is the accumulated strength of the relationship between different items (Jiang and Ashworth, 2021). Based on countries analysis, the highest total link strength was achieved by China and the United States, namely 45 and 38. Meanwhile, the United Kingdom, Germany, South Korea, and Canada undertook a collaboration on research with China and the United States.

After the meeting of G8 in 2005, these above-mentioned countries were included into a pledge in Hokkaido for strengthening the climate change mitigation (Cosbey, 2009). Recently, Germany and United Kingdom reached the relative high rank for their international policy for climate change mitigation among other G20 countries, followed by the United States and China for their international level of climate negotiations performance. Meanwhile, the Republic of Korea (South Korea) and China received an appreciation amongst other G20 countries for their national climate policy. However, Canada showed the least willingness to improve their climate change mitigation performance due to political interest (Cosbey, 2009).

These remarkable achievements of respective countries were delineated from their Nationally Determined Contribution (NDC) for short-term that affects long-term goals, such as 55% of decarbonization goal belonging to Germany, 40% national reduction target of greenhouse gas emission in United Kingdom, and 25–28% reduction in greenhouse gas emission for the United States (Falduto and Rocha, 2020).

Fig. 8. *Co-authorship network of countries*



Organizations

In this study, the 296 publications were distributed across 687 organizations. This shows that this research was carried out from a diverse number of organizations including companies and mostly from universities. The top 10 organizations with the highest number of citations are shown in *Table 1*. The number of citations obtained from top 10 organizations with the highest citations was 1,553, belonging to the United States (47.39%), Taiwan (30.26%), and China (22.34%). However, the organizations with the highest citations were National Taiwan University and Taipei Medical University with citations of 235 each, while the lowest citations came from Amaren Corp United State (206).

Table 1. *Top 10 organizations with the highest citations*

Organization	Total Citation (%)
Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan	15.13%
Department of Biochemistry, Taipei Medical University, Taipei, Taiwan	15.13%
Indiana Geological Survey, Indiana University, Bloomington, United State	11.14%
Exxonmobil Upstream Company, Houston, United State	11.14%
Department of Geological Sciences, Indiana University, Bloomington, United State	11.14%
Laboratory of Low Carbon Energy, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of thermal Engineering, Tsinghua University, Beijing, China	7.60%
Key Laboratory for Green Chemical Technology of Ministry of Education, Collaborative Innovation Center of Chemical Science and Engineering, School of Chemical Engineering and Technology, Tianjin University, China	7.15%
Department of Chemistry, University of North Carolina at Chapel Hill, United State	7.15%

National Taiwan University secured its most productive position in CCUS publication due to the efforts for weighing the importance of earth science, life science and social science which transformed into multi-disciplinary programs providing solutions particularly for climate change issues implemented in a number of climate change research and carbon capture practices as well as sustainable development related case studies and seminars (NTU, 2018). Meanwhile, Taipei Medical University put its remarkable efforts for CCUS related research topics such as carbonation, slags and steel making that plays a significant role into carbon capture, assigned under Department of Bio-chemistry.

Co-occurrence analysis

In this research, the keywords collected from 296 documents were 3,298. After setting the minimum number of occurrences at eight, 78 thresholds were generated. This shows that 78 keywords were repeated eight times in the 3,298 keywords. The co-occurrence visualization for all keywords is presented in *Fig. 9*, which is divided into four clusters marked with different colors: the first is red, second is green, third is blue, and fourth is yellow. Each cluster has one keyword with the highest total link strength. According to *Table 2*, cluster 1 is “carbon capture”, 2 is “carbon sequestration”, 3 is “CCUS” and 4 is “carbon dioxide”.

The sphere shaped icons are called nodes and they have relationships with one another which indicate the relationships of different keywords. The node size shows the weight and repetition of a keyword, hence a larger size means that the keyword is more frequently used than the keyword of smaller nodes. The distance from one node to another illustrates the strength of their relationship, and the farther link between nodes means that both keywords have less research (Jiang and Ashworth, 2021). The keyword “carbon dioxide” contained in cluster 4 had the highest occurrence of 212, total link strength of 135 and up to 77 linkages compared to other keywords. Meanwhile, “slags” had the lowest occurrence which is 8, total strength of 46, and 19 linkages between keywords. The positions of the top 10 keywords with occurrences and citation scores are depicted in *Fig. 10*.

Fig. 9. *Network of co-occurrence (all keywords)*

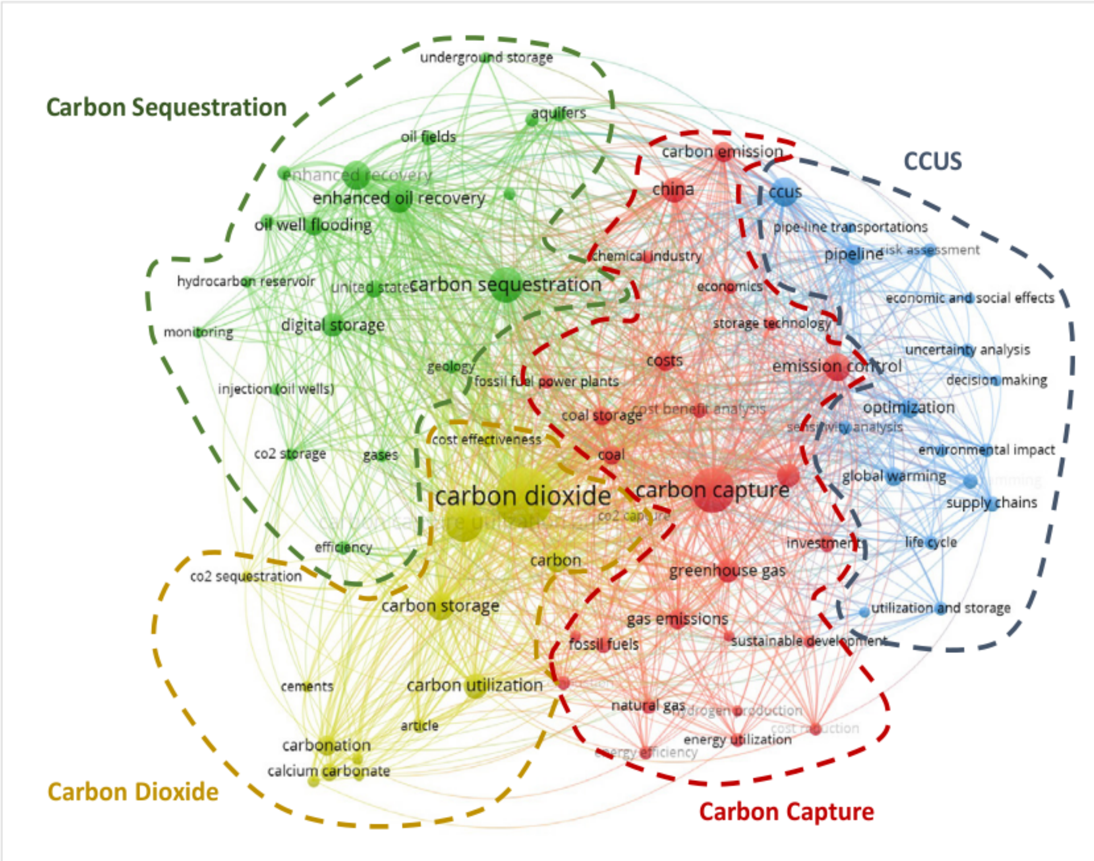


Fig. 10. *Top 10 keywords based on the number of occurrences and citations*

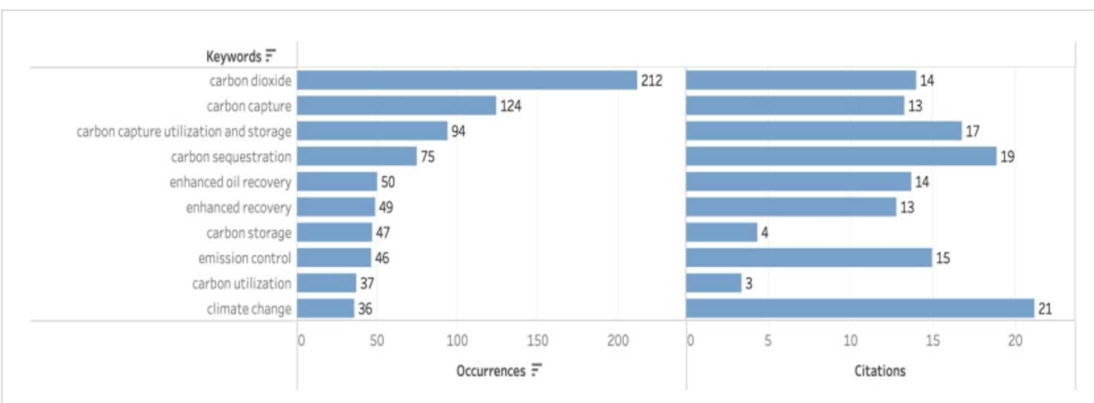
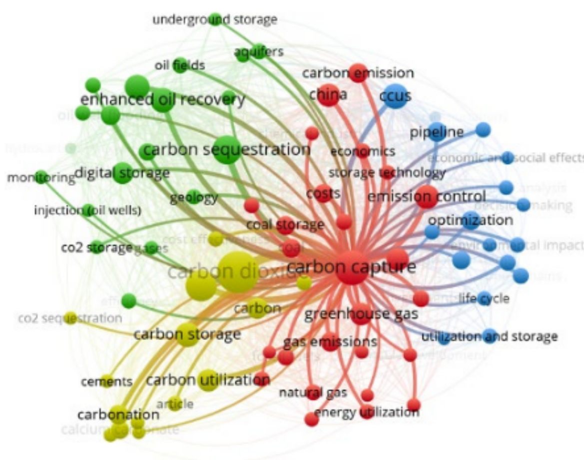
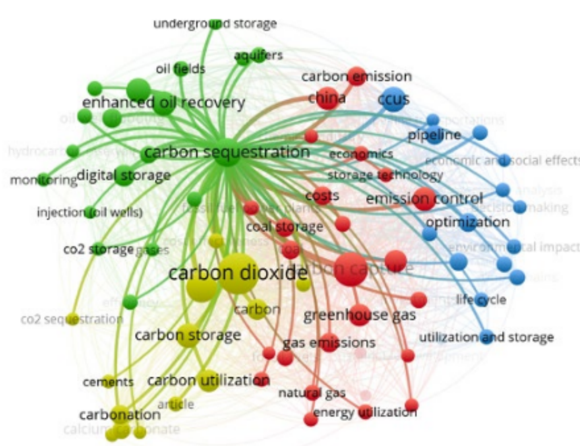


Table 2. *Network visualization keywords in each cluster*

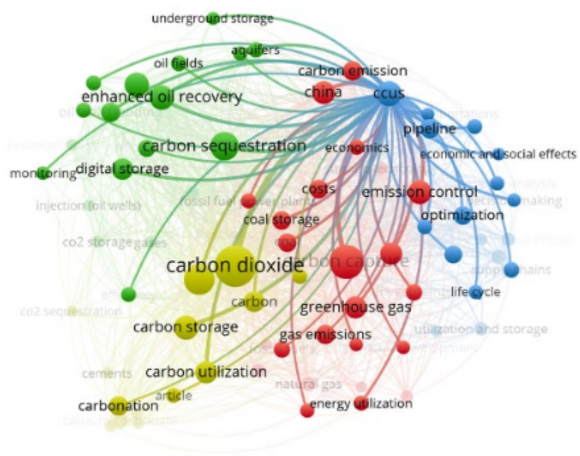
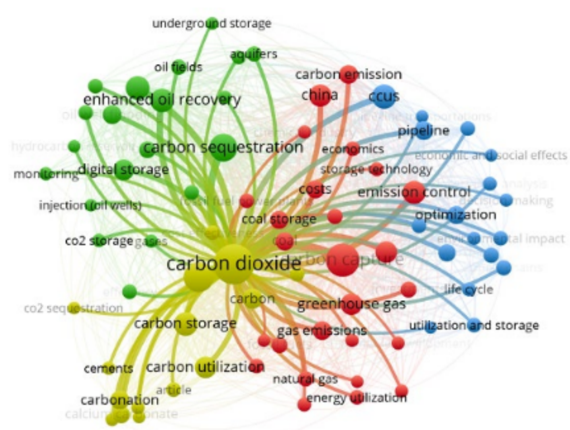
<table>
<tr><th>Cluster</th><th colspan="2">Visualization</th></tr>
<tr><td>1</td><td>



</td><td>In cluster 1, "carbon capture" is the keyword that has the largest node size of 76 links with other keywords, and the total link strength of 875. This technology aims to reduce carbon emissions produced from power plants and industries driven by fossil fuels, thereby promoting clean energy transition (Orlov et al., 2022). A report of clean energy transition through the application of CCUS has mentioned Norway as one of the European countries expanding the project of CO_2 capture facilities executed by Norcem (cement factory) and Fortum Oslo Varme (waste-to-energy plant) as well as a large facilities of CO_2 storage in the North Sea established by a group of oil and gas companies. This project, which is known as Longship CCS project, aims to accelerate the capacity of CO_2 transport and storage at the maximum of 5 Mt/year (IEA, 2020).</td></tr>
<tr><td>2</td><td>



</td><td>In cluster 2, "carbon sequestration" has the largest node size, 74 links with other keywords and the total link strength of 560. This serves as an efficient and environmentally friendly approach by incorporating carbon dioxide emissions that have been captured into the soil in an organic matter form (Orlov et al., 2022). Even though soil carbon sequestration has been widely applied, analyzing a suitable management system and method to enhance its storage effect is still an important matter to be deepened (Hinge et al., 2020). Sanchez et al. (2018) weighed the potential of geologic sequestration for perpetual storage of CO_2 in saline aquifers, benefited by two corn-based ethanol companies in USA. The first company included the CCUS project established in Decatur, USA, to capture 1 $MtCO_2$/year which then sequestrated in the Mt. Simon sandstone, USA. Another company named Red Trail Energy had a plan to sequester 180,000 t CO_2/year in the Broom Creek Formation, North Dakota.</td></tr>
</table>

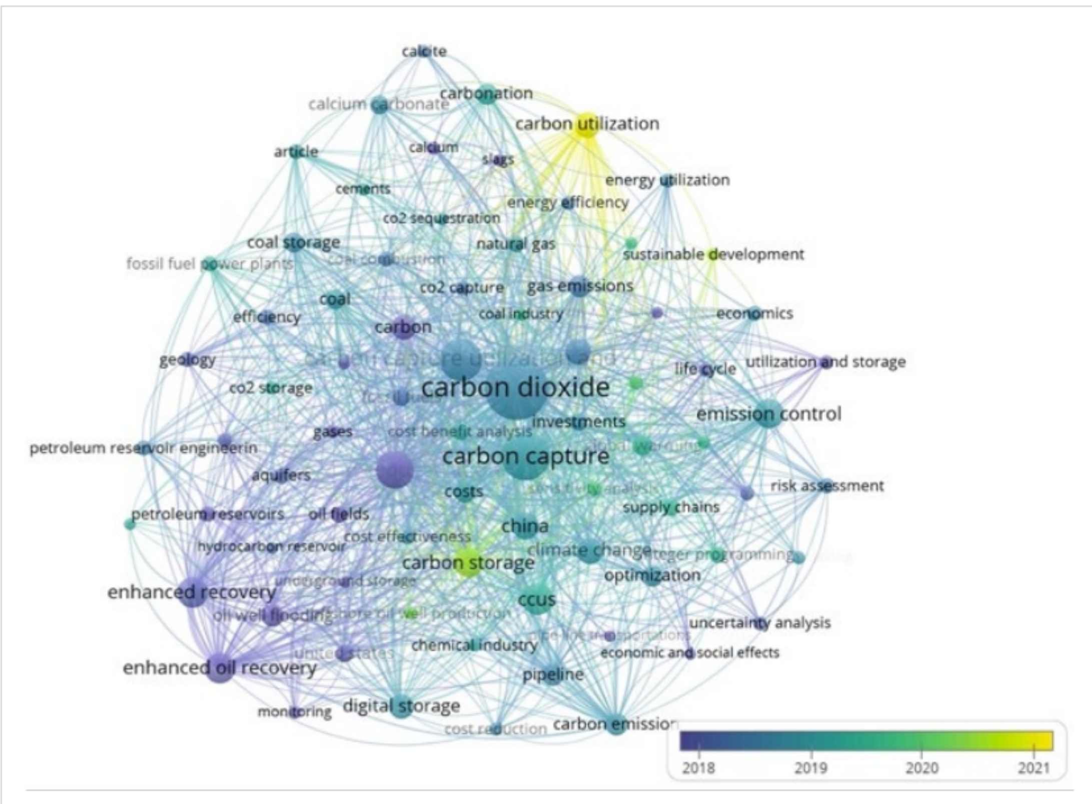
<table>
<tr><th>Cluster</th><th>Visualization</th><th></th></tr>
<tr><td>3</td><td>
</td><td>In cluster 3, "CCUS" has the largest node size, 61 links with other keywords, and the total link strength of 318. CCUS is a technology that plays an important role in reducing carbon emissions in the energy sector so that net-zero emissions can be achieved by eliminating and balancing carbon emissions that are difficult to reduce or avoid. The role of CCUS is proven to be able to eliminate carbon emissions from the energy sector fall to zero by 2070 worldwide in the IEA Sustainable development scenario (IEA, 2020). It has a huge potential as a solution to generate low carbon heat and power, decarbonize industry and reduce CO_2 emissions in the atmosphere (Regufe et al., 2021). CO_2 enhanced oil recovery (CO_2- EOR) method as the technological basis to develop CCUS relies on the CO_2 injection and sequestration to be captured in geologic formation. China, the United States and Canada were the pioneers in the development of CO_2- EOR as this technology has the ability to mitigate CO_2 emission as well as proliferate the production of domestic crude oil, which then followed by some countries such as Brazil, Norway, Trinidad, Turkey, Saudi Arabia and the United Arab Emirates (Hill et al., 2020).</td></tr>
<tr><td>4</td><td>
</td><td>In cluster 4, "carbon dioxide" has the largest node size, 77 links with other keywords, and a total link strength of 1325. This is one of the most critical anthropogenic greenhouse gases due to being abundant and persistent in the atmosphere for a long time (Ali et al., 2020). Recently, the demand of energy has been soaring up; however, the energy supplies are dominated by fossil fuel power plants that generate CO_2 emission. In order to generate a net zero CO_2 emission path as a form of sustainable energy, CCUS technology has to create a synergy with the technology of renewable energy, hydrogen, and electrification. Notably, CCUS technology has been commenced since the era of processed natural gas, which are now challenged by the need to develop a modern global technology of CCUS that consist of 3 methods namely pre-combustion, post-combustion and oxy-combustion (Hill et al., 2020).</td></tr>
</table>

Carbon dioxide had the highest occurrence at 27.53% amongst the top 10 value of co-occurrence, although the number of citations for the publications with the keyword of "climate change" was higher than the number of citations for the publications with the keyword "carbon dioxide". This result was in line with the research conducted by Awolesi et al. (2019), which generated 38 publications related to the keyword of "carbon dioxide".

According to Awolesi et al. (2019), the highest publication appointed to the low carbon emission research occurred in 2012, within the 2011–2018 period. Meanwhile, Bergamschi (2019) mentioned that the publications of research on carbon capture technology increased gradually from 1998 to 2018 to reach 1,020 documents. Up to 3,800 citations were obtained in the research from 1998 to 2018, and they continued to increase along with the publications even though there were fluctuations. This indicates that the research topics regarding carbon capture, utilization and storage are in annual demand. The International Journal of Greenhouse Gas Control has the highest number of publications, namely 27 documents and 480 citations (Khosroabadi et al., 2021). *Fig. 4* is an overview of the top 10 journals based on the highest publications and citations.

The number of publications and citations on the topic of carbon capture technologies reached 4,532 and 166 with an average citation per publication of 553. This study showed the number of 17.78 as the average citation per publication. *Fig. 11* shows the visualization of all keywords based on the publication year of 2018–2021. The difference of node color indicates the year of publication; hence, a lighter color implies the

Fig. 11. *Overlay visualization co-occurrence (all keywords)*

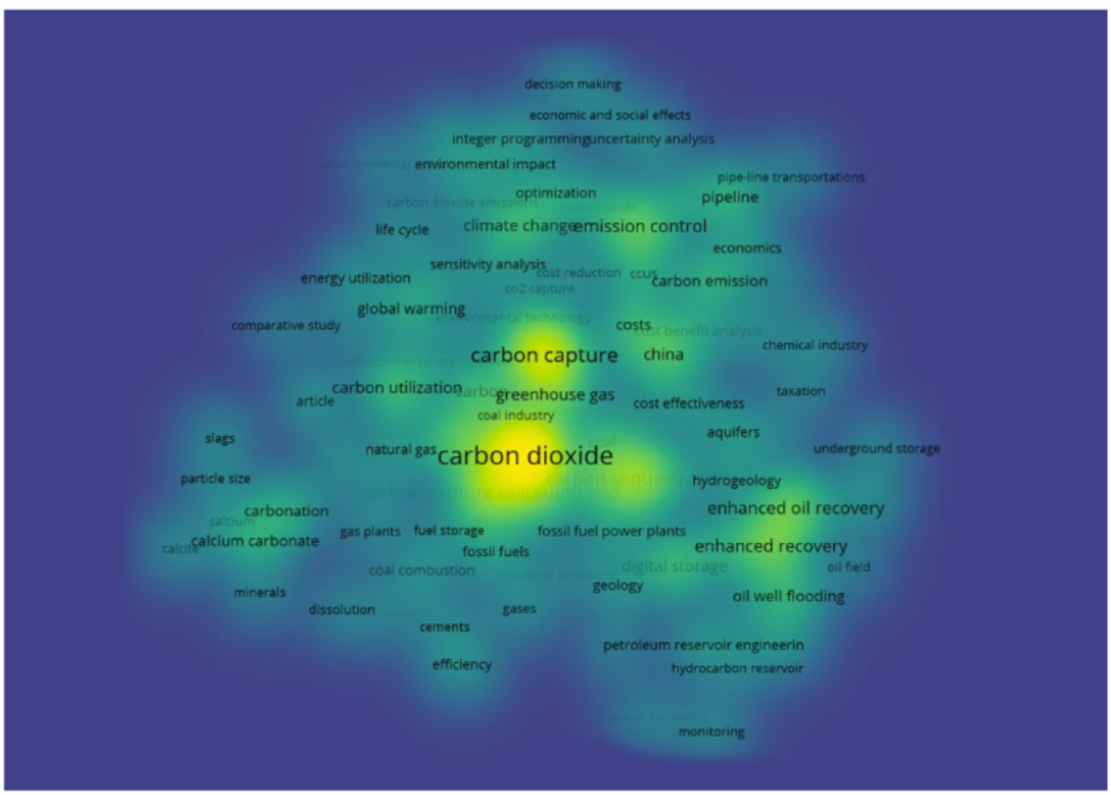


latest publication. The keyword "carbon dioxide" was widely investigated around 2018. "Carbon utilization" appeared around 2021 with 37 occurrences, total link strength of 259 and 62 linkages between keywords. This explains that the research related to carbon utilization was not largely conducted before 2021.

According to Ampah et al. (2021), the bibliometric research should be executed in a way that can strengthen the targeted discipline field through some approaches, namely (1) providing a comprehensive knowledge of the research area; (2) identifying research gaps; (3) highlighting the results of study for future studies. A number of journals identified through Vos Viewer have recognized the existence of CCUS incentive policies and regulations applied for some countries such as China (Zhang et al., 2013), United Kingdom (Leonzio et al., 2020), Hong Kong (Zhang et al., 2021) and United Arab Emirates (Al-Saleh et al., 2012). However, there is a lack of studies addressing the policies and regulations released by ISO standards and international regulation boards to inform on the property rights of the selected sites and accountability for stored CO_2 with respect to the period of ownership and financial matters.

In addition, the density visualization of index keywords (*Fig. 12*) showed some keywords in the areas of hazy colors (e.g., green-blue color) that interpreted the research gaps in the literature that need to be identified, such as: "environmental impacts", which can be correlated to the analysis of environmental impacts for CO_2 leakage during transportation; "cost reduction", which relates to the knowledge of the reduced cost of capture, transport and storage capacity processes; and "carbonation" to be related to the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future,

Fig. 12. *Density visualization co-occurrence (index keywords)*



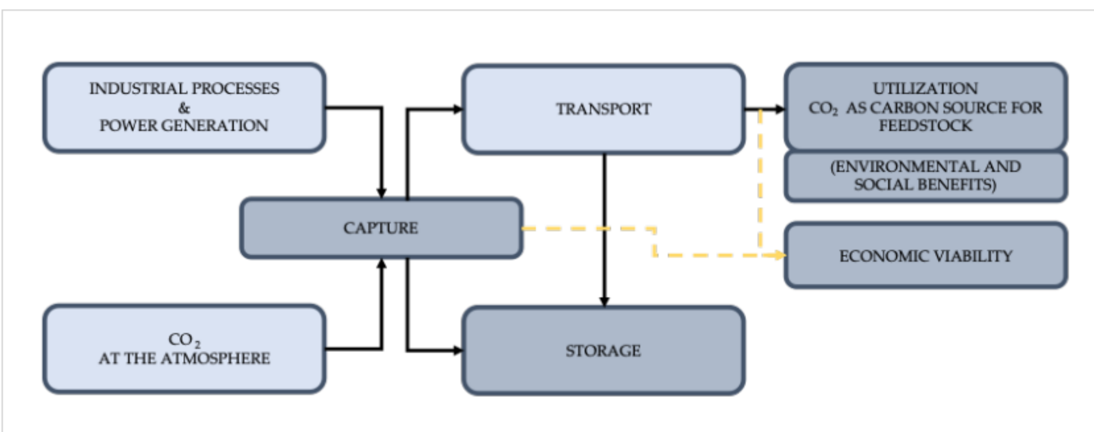
since the existing conventional method of carbonation still requires labor force and are cost-intensive (Simonson et al., 2020). Furthermore, the advanced carbonation method will contribute to the economic viability of carbon utilization, which can be achieved through the use of synthesized rare earth elements at the stage of the treatment process of mineral carbonation for accelerating the economic value of steel slags (Baciocchi and Costa, 2021).

CCUS technology is referred to as sustainable if the economic performance of the preferred method can be achieved without generating additional environmental negative impacts. Thus, CCUS, as one of the climate change mitigation technologies that may achieve the carbon emission reduction target, needs to provide economic, social, and environmental benefits as shown in *Fig. 13* (Assche and Comprenolle, 2022). In addition, the technology of CCU offers the area of social and environmental benefits to be investigated beyond its current initial stage and limited scope of research (Cosbey, 2009). Mitigation and adaptation are important in reducing carbon emissions and are an integrated approach to climate action and development. The integrated approach includes assessment, goal setting, identification, financing and implementation as well as monitoring, evaluation and learning (Jeffrey and Anika, 2022).

Conclusions

CCUS is proven as one of the ultimate technologies for mitigating climate change by capturing carbon emissions produced by industries, which are then being stored at 700 m below the sea level. Bibliometric analysis was used to examine the research trends such as CCUS by identifying keyword networks, authors, organizations, countries, growth trends in terms of the number of publications and citations by publishers and source titles in the period 2012–2022. The results of this study, derived from 296 documents of the Scopus database, showed the increase of publications concerning CCUS related keywords by 2,766.6% within the period of 2012–2022. Based on this study, the most productive country in conducting investigations on CCUS was China, empowered by Zhang X as the most prolific writer affiliated with China University of Petroleum. However, the organization that published the highest number of research on CCUS was National Taiwan University. On the basis of the publication and citation, this study found International Journal of Greenhouse Gas Control as the most productive journal that was published by Elsevier Ltd., that is widely known as a competent publisher of the highest number of publications and citations for research publications. Based on the co-occurrence analysis of index

Fig. 13. *The inclusion of environmental, social and economic impacts into a simplification of the CCUS process to illustrate a sustainable CCUS pathway*



keywords, the research gaps are identified in the literature, such as the analysis of environmental impacts for CO_2 leakage during transportation, the knowledge of the reduced cost of capture, transport and storage capacity processes as well as the need for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach for the future since the existing conventional method of carbonation still requires labor force and is cost-intensive. This study identified the potential further research for optimizing the method of carbonation for CCUS technology in a more viable and feasible approach. Hence, the importance of CCUS technology for CO_2 sequestration is clearly identified through this study, which is beneficial for the development of CCUS research, particularly to contribute to clean energy transition.

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