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Bibliometric Analysis of Carbon Capture and Storage (CCS) Research: Evolution, Impact, and Future Directions

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Abstract: This bibliometric analysis offers an in-depth examination of the research trajectory concerning carbon capture and storage (CCS), as documented in Scopus-indexed publications from 1998 to 2024. A marked increase in scholarly output has been observed, reflecting the growing academic and practical interest in CCS technologies as critical tools for mitigating climate change. The analysis identifies significant growth periods following key global climate agreements and technological advancements, underscoring the academic community's engagement in developing and implementing solutions to reduce emissions. Additionally, periodic fluctuations in publication trends have been detected, which may indicate shifts in funding priorities, research focus, and the advent of competing technologies. The notable peak in 2024 suggests that CCS research has potentially reached a pivotal stage of maturity or has been revitalized in response to recent environmental policies or global events. This analysis emphasizes the need for future research to delve deeper into the evolution of CCS technologies, their integration with renewable energy strategies, and the role of policy and economic factors in shaping the CCS research landscape. Such inquiries are deemed essential for guiding global CCS research and policymaking toward effective and sustainable climate action.

Keywords: Climate change mitigation; Research trajectory; Carbon capture and storage (CCS) technologies; Sustainable climate action; CCS research maturity

1. Introduction

As the challenge of climate change intensifies, the role of CCS transitions from a mere technological option to an essential requirement (Ganeshan et al., 2023; Roy et al., 2023). The relentless increase in global emissions underscores the urgency for viable approaches to diminish CO_2 levels in the atmosphere (Cecilia et al., 2023; Daud & Muthiyah, 2023; Eyitayo et al., 2024). CCS stands out as a crucial tool in this endeavor, offering the ability to substantially capture carbon dioxide emissions, mainly from industrial activities, and sequester them underground (Fan et al., 2023a; Wei et al., 2023). This capacity positions CCS as a critical player in global climate mitigation efforts, amplifying the need for extensive research in this area to new heights (Paltsev et al., 2021; Sunaryo et al., 2023).

Within this framework, our study employs a bibliometric methodology to delve into and comprehend the expansive scope of CCS-related research. Far from being a mere scholarly pursuit, this analysis is a vital step towards fully leveraging the capabilities of CCS technologies. It aims to chart the current research territory, pinpointing key trends, lacunae, and seminal works, thus charting a course for future research and development in CCS (Şenyapar, 2023).

The importance of research into CCS is underscored by its wide-ranging impact. It presents a pathway to achieve notable reductions in greenhouse gas emissions, especially in sectors with limited alternative reduction methods. Additionally, CCS plays a significant role in promoting sustainable energy practices by enabling cleaner fossil fuel usage as part of the transition towards renewable energy sources (Fontenelle et al., 2023; Tsvetkova & Middleton, 2023; Zantye et al., 2022). Moreover, the role of CCS is critical in realizing the net-zero emission targets established by various nations, thereby becoming a cornerstone in international climate policies and initiatives (Donnison et al., 2023; Fan et al., 2023b; Hayashi et al., 2023). Research on CCS has been conducted in the form of bibliometric analysis, but the data used was limited to the Web of Science. This study, however, explores data from Scopus.

Moreover, through an extensive bibliometric analysis, this study aims to shed light on the aspects of CCS research that warrant further inquiry and funding. These insights are crucial for a spectrum of stakeholders, including researchers, policymakers, and industry leaders (Khoirunisa et al., 2023). They guide the allocation of resources, policy development, and technological advancements, all directed toward enhancing the efficiency and scalability of CCS implementations.

Ultimately, this research underscores the critical importance of CCS studies in the context of the current climate crisis. By offering an in-depth overview and future-oriented recommendations derived from bibliometric insights, the study aspires to stimulate and steer forthcoming innovations and strategies in CCS, thereby contributing substantially to the global effort in combating climate change.

This study has advanced our understanding of CCS technology with critical theoretical contributions. Through a thorough bibliometric examination of papers indexed by Scopus between 1998 and 2024, the study provides insightful information about the development and expansion of CCS research. The impact of international climate agreements and technology developments on CCS scholarly output is among the significant patterns that this analysis highlights. It draws attention to how scholarly interest has changed in reaction to new developments in environmental policy and technology, which has helped advance our theoretical knowledge of integrating CCS technologies into plans for mitigating climate change.

The findings advance scholarly understanding by charting the course of CCS research, pinpointing moments of great concentration, and revealing the dynamics of funding and research goals. This thorough summary clarifies how policy changes, technology breakthroughs, and scholarly studies in CCS interact. The paper offers a theoretical framework for comprehending the broader implications of CCS on sustainability and climate action by elucidating these relationships. These contributions close gaps in the literature and lay the groundwork for future studies that will examine how to integrate CCS with renewable energy methods and how economic and policy issues impact technology advancement.

Recognizing the study's limitations, such as potential biases in publication data and excluding non-Scopus indexed sources, and suggesting areas for further investigation will provide a more nuanced understanding and guide effective and sustainable climate action.

2. Methodology

This investigation adopted a structured approach centered on bibliometric analysis, referencing methodologies outlined in previous scholarly works (Apriantoro et al., 2023). Data was collected via a Boolean search methodology, targeting the Scopus database from 1998 to 2024. Analytical tools employed in this process included R and Rstudio for statistical analysis, VOSViewer for network mapping, and Microsoft Excel for data organization and analysis. The research was segmented into three strategic phases (Apriantoro et al., 2024a).

The preliminary phase involved a thorough review of the literature (Apriantoro et al., 2024b). This step was pivotal for two reasons: firstly, it ensured the inclusion of relevant bibliometric studies within the scope of the research, and secondly, it aided in identifying key terms and defining the research boundaries.

In the subsequent stage, the research employed a specific query: "coupled with an English language restriction. This query was implemented using Boolean logic in the Scopus database, leading to a collection of 2120 documents. This phase focused on pinpointing specific intersections of topics relevant to the study's aims.

The final stage of the study involved an in-depth analysis of the selected documents. Utilizing Rstudio, the team conducted a quantitative examination to identify trends such as the yearly distribution of documents, journal frequencies, authorship trends, institutional affiliations, geographical contributions, and subject areas. Network analysis and visualization were performed using VOSViewer, supplemented by Microsoft Excel for additional data handling. This comprehensive methodological approach allowed for a nuanced understanding of the bibliometric landscape within the chosen research area (Ariona et al., 2023).

Scopus was selected for this study because it provides a comprehensive overview of the literature across a wide range of academic disciplines. Its user-friendly interface facilitates efficient data collection, while its comprehensive metadata, encompassing citation data, abstracts, and keywords, greatly enhances bibliometric analysis. Furthermore, Scopus's widespread global usage offers diverse research perspectives, and its standardized institutional name simplifies the examination of productivity and collaboration networks. Its seamless integration with VOSviewer and other tools makes Scopus an advantageous choice for this type of research, as it improves the mapping and visualization of bibliometric data (Baas et al., 2020).

A graphical representation of the entire research methodology, encapsulating data collection and analysis procedures, is provided in Figure 1. This visualization offers an explicit and detailed account of the methodological framework employed in this study.

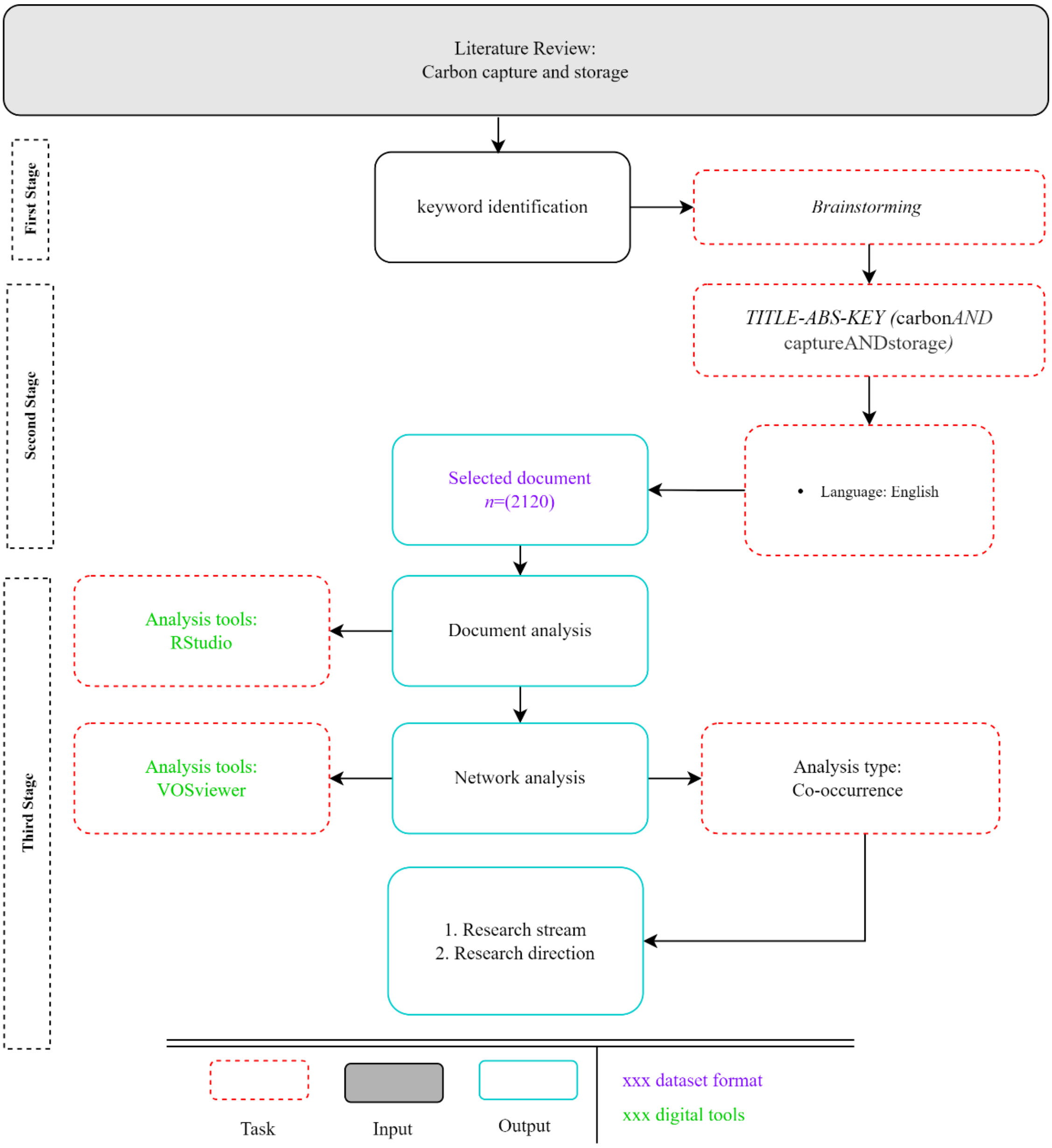

Figure 1. Research procedure
Note: This figure was prepared by the authors

3. Results

Figure 2 illustrates the upward trend in the number of carbon capture articles indexed by Scopus from 1998 to 2024. This graph offers valuable information regarding the increasing scholarly attention towards carbon capture. The upward trend depicted in the graph signifies a rising level of consciousness and immediacy among researchers concerning climate change, as well as the quest for efficient remedies to reduce carbon dioxide emissions. The notable surge in publications, especially post-2013, could be attributed to reactions toward international climate agreements, CCS technology advancements, and legislative efforts promoting research and development in this field.

A noteworthy aspect of these data for further investigation is the presence of yearly oscillations, which may suggest fluctuations in funding, shifts in research objectives, or the advent of novel technologies supplanting interest in carbon capture. A surge in 2024 may suggest that this subject has attained a specific degree of advancement in the scientific literature or has garnered notable focus due to climate change-related events or new energy legislation.

It is crucial to analyze the context and content of these publications to gain insight into future research. This analysis will provide significant information about the direction of research trends, the areas that are receiving the most focus, and any remaining research gaps that need to be addressed. Research could concentrate on prominent carbon capture technologies (Cachola et al., 2023), effective implementation on an industrial level (Wilberforce et al., 2021), or policy analysis promoting CCS adoption (Aune et al., 2022). Conducting a more thorough analysis of the relationship between global events and trends in publications could assist in determining the primary factors contributing to the expansion of this body of literature. This analysis could also offer suggestions to stakeholders on developing successful strategies to promote research on carbon capture.

Figure 3 shows that the United States and the United Kingdom demonstrate leadership in the number of publications, indicating a highly developed research ecosystem supported by robust government policies, substantial financing, and extensive international collaboration. Conversely, China's robust stance demonstrates the nation's dedication to tackling environmental concerns and underscores the significance of scientific inquiry in mitigating climate change.

India's notable scientific accomplishments highlight the necessity of including developing nations more extensively in the worldwide discussion on carbon storage. This indicates the requirement for more comprehensive international cooperation to ease the sharing of knowledge and resources. An examination of publications from these countries can provide valuable information about their research goals, which may include technology development, sustainable legislation, or new carbon storage programs.

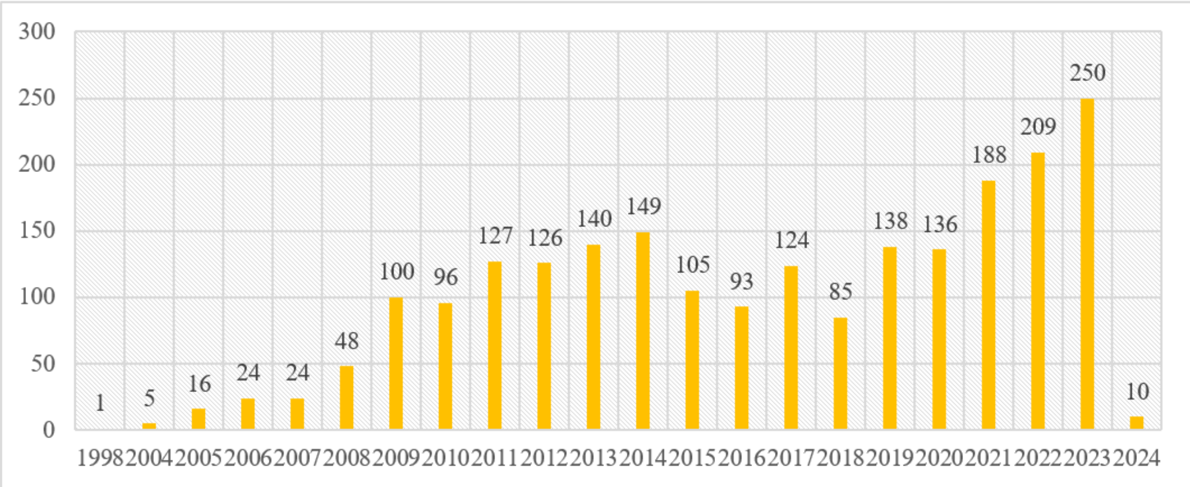

Figure 2. Publication by year
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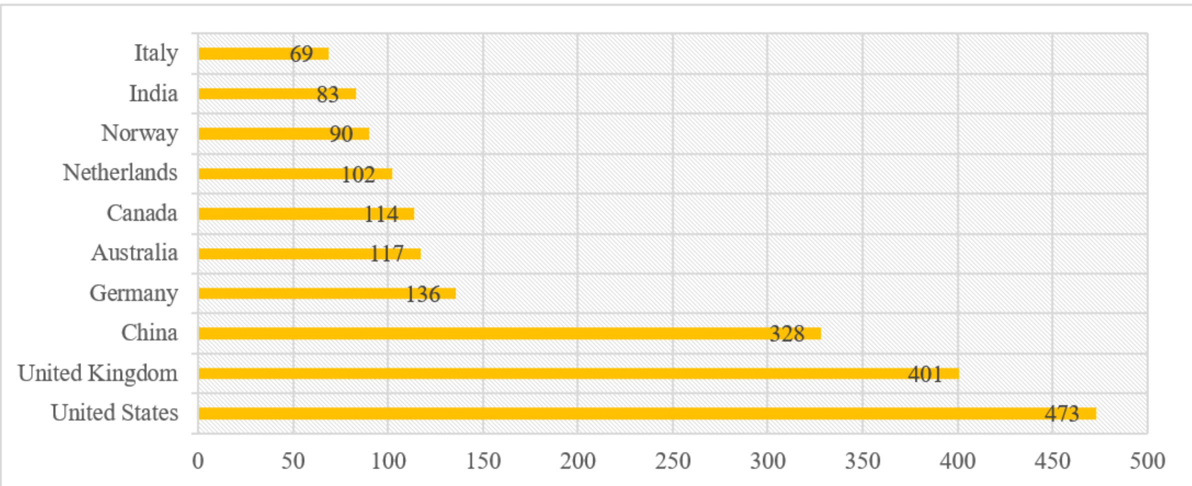

Figure 3. Publication by country
Note: This figure was prepared by the authors

By examining countries with a comparatively lower publication count, like Italy, we can discern areas of research that have yet to be well explored and discover possible avenues for development. This indicates potential for interdisciplinary and transnational research endeavors that can enhance global research capability. Moreover, by doing historical trend analysis, one can gain insights into the evolving dynamics of research and identify future research requirements. This can facilitate the formulation of strategies to foster successful policy-making and industrial innovation (Beck, 2020).

Establishing a connection between this study and world policy and economics, particularly in terms of implementation and socioeconomic consequences, will guarantee that the research not only adds to the academic body of knowledge but also brings about tangible changes that promote the reduction of emissions and sustainable development (Karayannis et al., 2014). This initiative aims to foster convergence between scientific research and global interests to accomplish international climate objectives effectively.

It is crucial to analyze the context and content of these publications to gain insight into future research. This analysis will provide significant information about the direction of research trends, the areas that are receiving the most focus, and any remaining research gaps that need to be addressed. Research could concentrate on prominent carbon capture technologies, effective implementation on an industrial level, or policy analysis promoting CCS adoption. Conducting a more thorough analysis of the relationship between global events and trends in publications could assist in determining the primary factors contributing to the expansion of this body of literature. This analysis could also offer suggestions to stakeholders on developing successful strategies to promote research on carbon capture.

Figure 4 shows publications by affiliation. Imperial College London is the top institution in the number of publications, with the Chinese Academy of Sciences and the University of Edinburgh closely behind. The inclusion of institutes from various nations illustrates the geographical heterogeneity in carbon storage research, underscoring its global significance as a topic of study.

Imperial College London, the institution with the most published works, benefits from a robust research framework, significant financial resources, and global partnerships, contributing to its leadership position in this area. The Chinese Academy of Sciences, serving as China's premier research institution, exemplifies the nation's dedication to environmental-focused scientific and technological research, aligning with its objective of mitigating emissions and spearheading advancements in sustainable technologies.

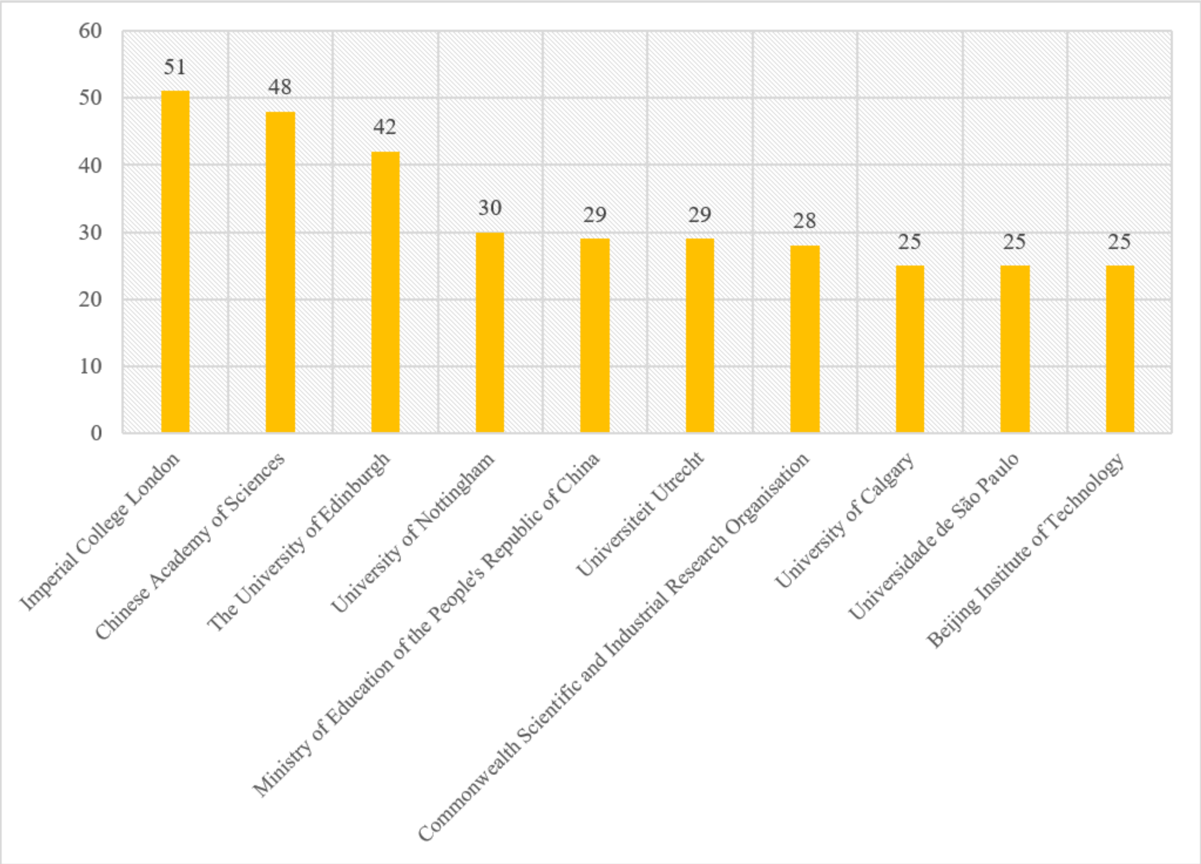

Figure 4. Publication by affiliation
Note: This figure was prepared by the authors

The University of Edinburgh, which is notable, may exemplify the robustness of research in the UK and the nation's emphasis on cultivating sustainable solutions. The involvement of the University of Nottingham and the University of Calgary highlights the significant contribution of higher education institutions in furthering research on this subject. These institutions provide resources and expertise to explore novel technologies and policy initiatives.

This analysis further highlights the significance of collaboration between different agencies. Educational institutions frequently engage in partnerships with government entities, such as the Ministry of Education of the People's Republic of China, as depicted in the graph, illustrating the harmonious relationship between official directives and scholarly investigation.

To facilitate future research, it is crucial to promote enhanced collaboration among these institutions by establishing an international consortium dedicated to carbon storage. The acceleration of innovation can be achieved by integrating expertise from diverse fields and capitalizing on the strengths of each organization.

Examining the role and contribution of each affiliate in the literature can unveil distinct areas of competence and deficiencies in current research. This would facilitate the creation of a synchronized research plan to tackle the worldwide challenges presented by climate change and the rising levels of carbon in the atmosphere (Pickard et al., 2014). To make progress, academics, government agencies, and industry must work closely together to create realistic solutions and policies that can be implemented on a large scale.

The data shown in Table 1, the bibliometric evaluation, offers a granular assessment of the scholarly influence wielded by various authors within their specific areas of expertise. Li X distinguishes itself with an unrivaled h-index of 15, indicating that a minimum of 15 works have been cited at least as many times, highlighting a significant and unwavering academic presence initiated in 2009. The g-index, standing at 21, underscores Li X's academic impact through a subset of their extensively cited publications.

Table 1. Most relevant authors

Author	H Index	G Index	M Index	TC	NP	PY Start
Li X	15	21	0,938	540	21	2009
Zhang X	14	23	1,167	741	23	2013
Cormos C-C	13	22	0,813	1111	22	2009
Tan Rr	13	18	1	539	18	2012
Wang Y	12	18	1,333	354	18	2016
Hansson A	11	12	0,688	406	12	2009
Li J	11	16	0,733	284	17	2010
Stephens Jc	11	17	0,55	504	17	2005
Fridahl M	10	13	1,25	393	13	2017
Yang Y	10	14	1,25	376	14	2017

Source: Processed data, 2024

Note:
H-index: Measures an author's impact by the number of papers with equivalent citations.
G-index: Focuses on highly-cited papers to assess impact.
M-index: Normalizes the H-index for career length.
T.C.: Total citations for all an author's papers.
N.P.: Author's total number of publications.
PY-Start: Year of the author's first publication.

Not far behind, Zhang X boasts an h-index of 14 and the most elevated g-index of 23 in this analysis, demonstrating a significant academic presence. An m-index surpassing the value of 1 denotes Zhang X's swift and ascending influence in the field since 2013, as evidenced by a remarkable total citation count of 741, indicating a prolific and impactful span of research conducted within a brief timeframe.

Cormos C-C, with a slightly lower h-index of 13 relative to Li X., nonetheless leads the dataset with the highest total citation figure of 1111. This number reflects the extensive influence and reach of Cormos C-C's work across the scholarly community, further emphasized by a g-index of 22, which points to many of their papers receiving widespread citations.

Tan Rr exhibits an m-index of 1, revealing a notable and enduring impact in the field since 2012. Possessing an h-index comparable to Cormos C-C and a total citation figure akin to that of Li X, Tan Rr's research output has demonstrated a consistent resonance in the academic sphere.

Wang Y is noted for its superior m-index of 1.333, the highest among the group, hinting at a rapid and significant ascent in academic stature since 2016. Despite more modest h-index and g-index values, Wang Y's elevated m-index suggests a swiftly growing acknowledgment within the academic community.

The other researchers in the group, including Hansson A, Li J, Stephens Jc, Fridahl M, and Yang Y, have made substantial contributions within their respective research disciplines. Notably, Fridahl M and Yang Y demonstrate high m-indices despite entering the publication arena more recently in 2017, suggesting their fast track to becoming influential figures in their fields.

In sum, the bibliometric data reveals a lively and evolving academic terrain where scholars such as Li X and Zhang X have cemented considerable academic stature, while individuals like Wang Y, Fridahl M, and Yang Y are swiftly carving out their significant research niches. The aggregated citation counts testify to the collective impact of their scholarly endeavors. At the same time, the h- and g-indices offer a glimpse into the scope and depth of their academic reach. When viewed collectively, these indicators present a multi-layered view of the authors' impact, showcasing a spectrum from established authority to rising prominence within the academic landscape.

The dataset highlights a compelling local-versus-global academic impact pattern among various scholarly documents. Table 2 shows the most globally cited documents. The work of Ploetz (2009) stands out with a staggering 6600% local-to-global citation ratio, indicating that while the document has been cited extensively within a localized or specialized community, it has garnered little attention on the global stage. This disparity could imply that the document's content is particularly relevant to a specific demographic or regional interest or could reflect a community's concentrated research focus.

Table 2. Most global site document

Document	Local Citations	Global Citations	LC/GC Ratio (%)
Ploetz (2009)	132	2	6.600,00
Cremer (2009)	132	7	1.885,71
Rackley (2009)	132	164	80,49
Meadowcroft & Langhelle (2009)	45	26	173,08
Underschultz et al. (2016)	37	5	740,00
Schwendig (2010)	30	5	600,00
Forbes et al. (2010)	30	3	1.000,00
Gibbins & Chalmers (2008)	21	686	3,06
Glessner & Young (2008)	21	3	700,00
Markusson et al. (2012)	12	26	46,15

Source: Processed data, 2024

Cremer (2009) piece shares this trend of high local engagement with a local-to-global citation ratio of 1885.71%, suggesting that it, too, has a specialized impact within a specific scholarly enclave. Although also highly cited locally, Rackley (2009) the publication shows a more evenly distributed recognition with an 80.49% ratio, indicating the document has a significant presence in the broader global academic discourse. Meadowcroft & Langhelle (2009) while having fewer local citations, work maintains a high local-to-global citation percentage of 173.08%, again suggesting focused local interest. Conversely, Gibbins & Chalmers (2008) despite a lower number of local citations, the document demonstrates extensive global reach and influence, evidenced by a lower local-to-global citation ratio of 3.06%.

The 2016 document by Underschultz et al. (2016) and the 2010 work by Schwendig (2010) both show high local-to-global citation ratios, at 740% and 600%, respectively, which may indicate these authors are cited frequently within a specific field or locale soon after publication, awaiting wider global acknowledgment.

Notably, Forbes et al. (2010) work and Glessner & Young (2008) publication also exhibits a high local-to-global citation ratio, suggesting that these documents, while not extensively cited globally, hold substantial value within a targeted academic or regional context. Finally, Markusson et al. (2012) the document has a more moderate local-to-global citation ratio of 46.15%, which could suggest a balanced distribution of academic influence both locally and globally, or it could reflect a transitional stage where the document is beginning to gain broader recognition.

The thematic map in Figure 5 categorizes various climate science and carbon management research topics based on their centrality (relevance) and density (degree of development).

In the upper right quadrant labeled "Motor Themes," we find terms such as "carbon sequestration," "climate change," and "carbon capture and storage." These are established core topics within the field, possessing high development and centrality. This suggests that they are well-researched areas that continue to drive the field forward and are integral to the academic discourse on climate action (Humpenöder et al., 2014).

Conversely, the lower right quadrant contains "Basic Themes," which include "carbon capture," "carbon dioxide," and "greenhouse gases." Despite their foundational role in the field, these themes are marked by high centrality but lower development, indicating that while they are universally recognized as crucial, they may have reached a point of maturity where significant new developments are less frequent (Yasemi et al., 2023).

On the upper left, we find "Niche Themes" like "article," "priority journal," and "greenhouse effect." These topics are characterized by high development but lower centrality. This positioning suggests that while there is a concentration of research and development in these areas, they might be highly specialized or currently of interest to a smaller segment of the research community.

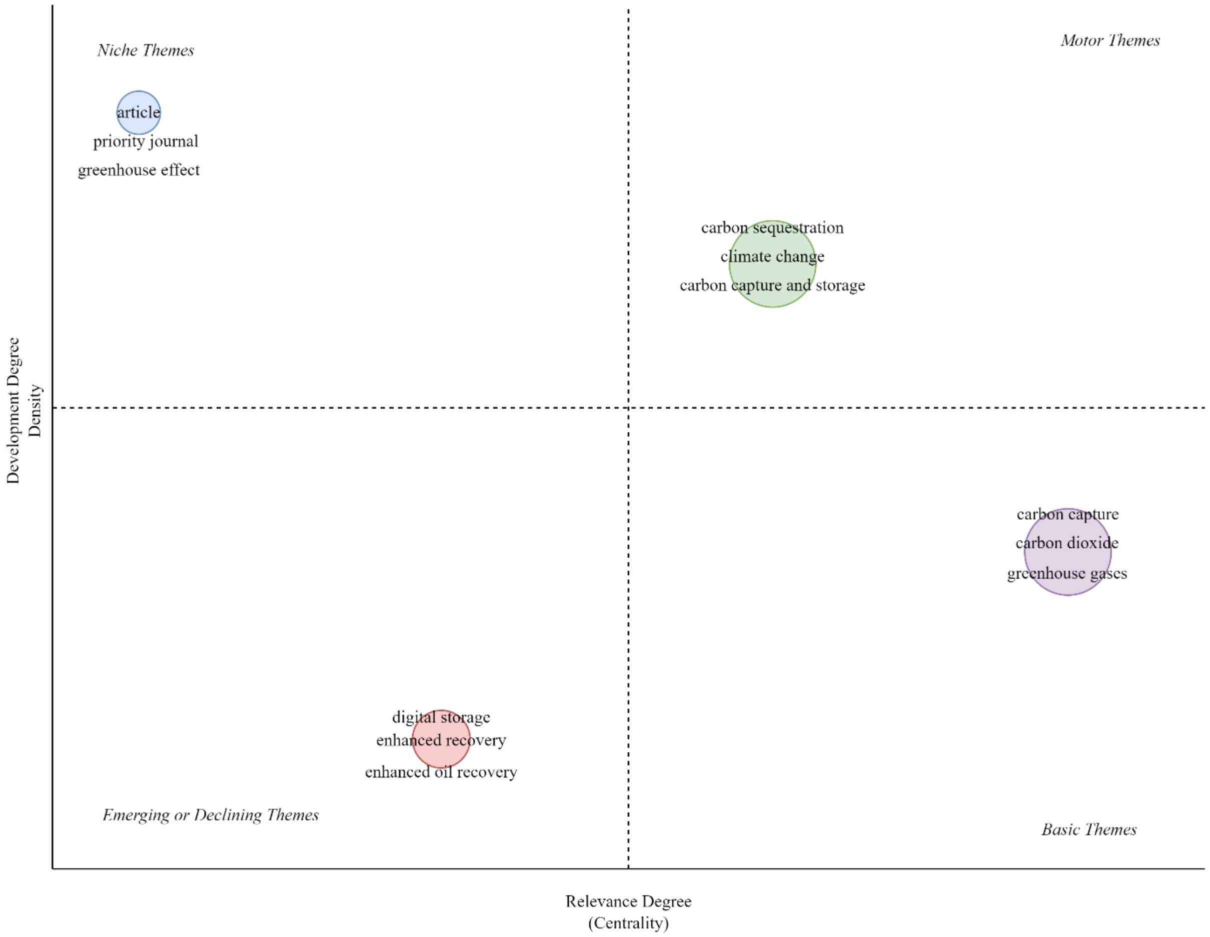

Figure 5. Thematic map

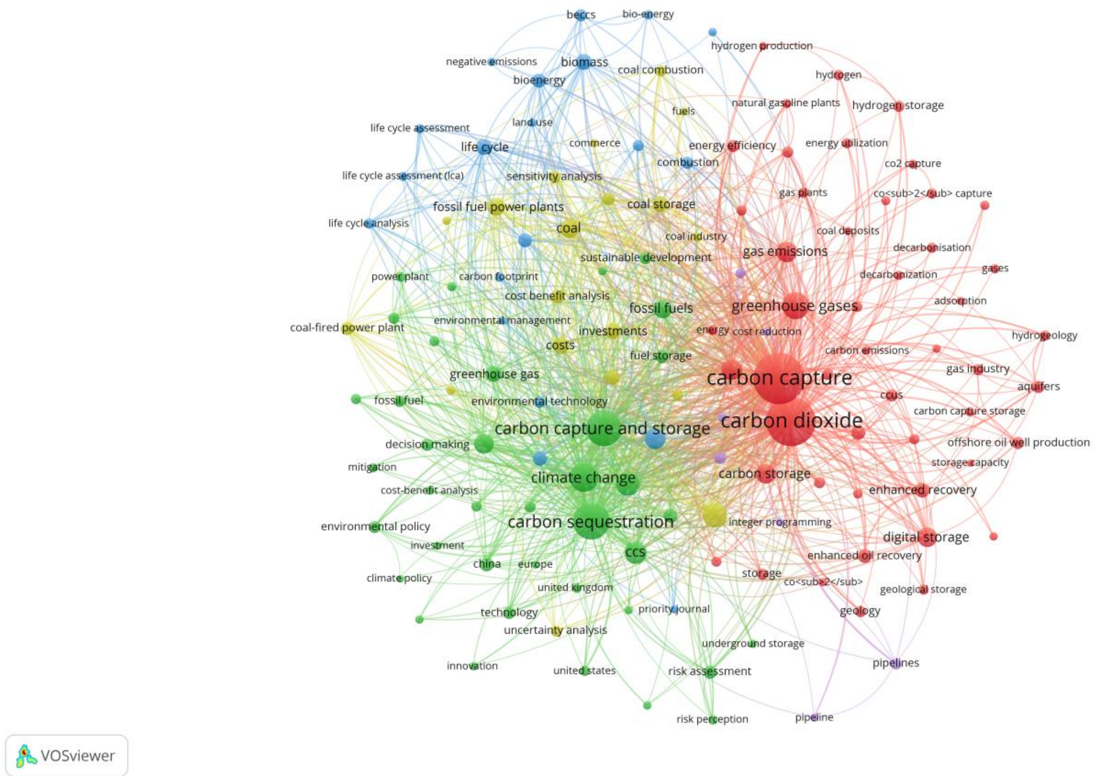

Figure 6. Co-occurrence visualization

Lastly, the "Emerging or Declining Themes" in the lower left quadrant are represented by "digital storage," "enhanced recovery," and "enhanced oil recovery." These topics have lower centrality and development, which could imply that they are either nascent areas of research that are beginning to gain traction or once significant themes that are losing prominence in current research narratives (Iskandar & Syahrial, 2022).

Overall, the thematic map indicates a dynamic research landscape where specific themes are well-established and central to ongoing discourse. In contrast, others represent either emerging areas of interest or specialized, mature, or potentially declining topics within the broader climate science and carbon management field.

The provided visualization is a bibliometric map generated using VOSviewer in Figure 6, which specifically examines the co-occurrence of keywords in scientific or technical domains. This visualization illustrates the link between the most commonly co-occurring terms in the provided dataset. The analysis unit is set to include all keywords, and the calculation method used is complete counting. The dataset contains 10,946 keywords, of which 133 have a minimum threshold of 30 occurrences.

The nodes on the map are sized based on the frequency of the keywords, while the lines' thickness and length show the level of co-occurrence or the strength of the association between the two keywords. Varying hues can signify distinct clusters or interconnected themes, implying that keywords within the same cluster frequently co-occur and may possess a shared context within the literature. The predominant emphasis seems to be on keywords such as "carbon capture," "carbon dioxide," and "greenhouse gases," suggesting that the main areas of research revolve around CCS and their influence on greenhouse gases.

Given this analysis, future research suggests examining novel approaches to boost carbon sequestration efficiency, investigating sustainable techniques for enhanced recovery, and formulating regulatory frameworks that may effectively integrate CCS with energy sources. Renewable. Furthermore, doing research that delves into a more profound comprehension of "risk assessment" and "decision-making" within environmental policy and technological investment would be beneficial (Pouran et al., 2022).

The study visualization reveals the presence of peripheral nodes with keywords such as "risk assessment" and "decision-making," which are less interconnected and less noticeable in comparison to primary themes like "carbon capture" or "carbon dioxide." These keywords on the study map suggest that they have yet to receive significant attention in the broader discussion on CCS. However, the "risk assessment" discussion is crucial since it helps discover and evaluate potential risks linked to CCS technologies. Likewise, "decision-making" plays a vital role in establishing the policies and strategies necessary for CCS's successful and enduring implementation.

These keywords' limited availability and relative seclusion indicate unexplored possibilities for integrating risk assessments and decision-making procedures into CCS research. This suggests the necessity for additional investigation to comprehend how these factors can impact the efficacy of CCS technology in real-world scenarios. Hence, these infrequent and less interconnected subjects bring attention to unexplored domains in the study and present opportunities for pioneering and enhancing our methods in addressing the obstacles of CCS.

4. Conclusion

The uptrend in Scopus-indexed publications on carbon capture from 1998 to 2024 highlights an intensified focus within the academic community on climate change mitigation strategies, particularly CCS. This trend reflects a response to global climate agreements, technological advancements in CCS, and supportive policy initiatives. The observed annual fluctuations suggest dynamics influenced by funding, research priorities, and emergent technologies. The peak in 2024 may indicate a mature interest or a reaction to recent climate or policy developments. Further research should delve into the content of these publications to discern the trajectory of CCS technologies, their integration with renewable energy sources, and the role of risk assessment and decision-making in CCS's technological and policy advancements. This research could ultimately guide effective strategies for future CCS initiatives and contribute to the global endeavor of sustainable development.

Policymakers should increase support and funding for CCS research, introduce financial incentives for industry to adopt the technology, and strengthen policies and regulations that support CCS. Educators should update curricula to include the latest CCS technologies, encourage interdisciplinary study, and provide hands-on training. Researchers should focus on emerging trends, analyze the impact of policies on CCS, and collaborate with the industry to understand real-world challenges while disseminating research findings to influence industry policies and practices.

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