Carbon Neutrality

SHORT COMMUNICATION

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Trends in carbon capture technologies: a bibliometric analysis

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Abstract

Climate change is an ever-present issue, which has a vast variety of potential solutions, one of which being carbon capture. This paper aims to use bibliometric analysis techniques to find trends in carbon capture within the technologies of adsorption, absorption, membranes, and hybrid technologies. The Web of Science core collection database performed bibliometric searches, with the 'Bibliometrix' plug-in for R software, performing the bibliometric analysis. Bibliometric data spanned across 1997–2020 and the investigation found that adsorption technologies dominated this period in terms of citations and articles, with hybrid technologies being the least produced but rising in scientific productivity and citations. The Analysis found China and the United States of America to be the dominant producers of articles, with global collaboration being central to carbon capture. The 'International Journal of Greenhouse Gas Control' ranked as the top producer of articles however, the 'ACS Applied Materials & Interfaces' was the leading journal in terms of H-index.

Keywords: Carbon capture, Bibliometric analysis, Absorption, Adsorption, Membranes, Hybrid carbon capture

1 Introduction

Natural disasters such as hurricanes, algal outbreaks, wildfires, droughts, and floods have become the norm devastating millions of people every year. Changes in our climate cause these events [23]. Year on year record-breaking storms, record-breaking temperatures, and extreme weather events cause devastating damage [22, 35, 37, 47]. These events are not random acts of nature, and we know the cause to be climate change, global warming. Climate change is an ever-increasing concern for current and future generations. Global temperatures have been on the rise since the industrial revolution. Below Fig. 1 shows the average yearly rise in global surface temperature since 1880 and, as shown in this graph, there has been an alarming increase in temperatures since 1980.

These temperatures are rising because of the greenhouse effect [18]. The greenhouse effect occurs when molecules of Greenhouse Gases (GHGs) such as methane and carbon dioxide (CO_2) absorb infrared (IR) radiation emitted by the Earth's surface. The IR radiation originates from the sun and should bounce off the Earth and exit our atmosphere, returning to the voids of space. But, when these GHGs absorb the IR radiation, it becomes trapped in our atmosphere and redirects back to the Earth's surface, causing a net heating effect. Our current society and economy relies on burning fossil fuels, burning these fuels creates CO_2 and is thus a cause of climate change [11, 20].

Governmental policies often drive research focus. One such example is the Paris Agreement, which aims to limit global temperature rise to 2.0 °C above pre-industrial times with the aim to limit temperature rise to 1.5 °C [49] This Paris Agreement led to scientific research aiming to solve our climate crisis. Researchers have developed solutions to this global crisis [6]. One such solution is carbon capture [40]. Carbon capture involves the removal of CO_2 from the atmosphere or preventing it from entering the atmosphere. Carbon capture methods may be natural, or technological, with the goal of minimizing the negative effects of climate change [13, 40, 44].

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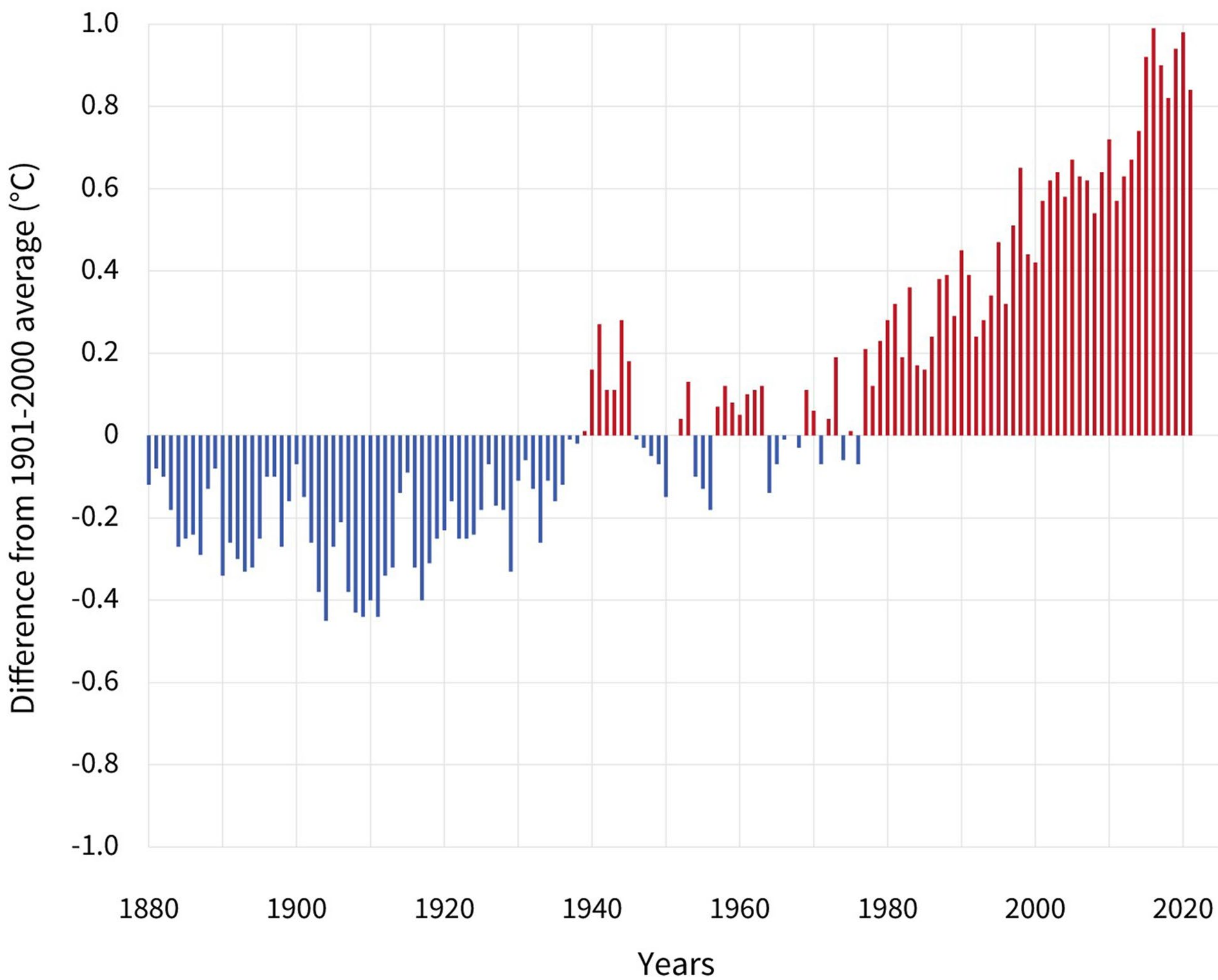

Fig. 1 Average temperature rise since 1880 [33]

Technological carbon capture comprises three groups: pre-combustion, post-combustion, and Direct Air Capture (DAC). Pre combustion technologies refer to systems which change the feed conditions of industrial combustion systems to either limit CO_2 emissions or increase the purity of CO_2 exiting, allowing the exhaust gas to go straight to storage with close to pure CO_2 [48]. Post-combustion technologies focus on purifying CO_2 exiting industrial based exhaust systems [53]. DAC technologies aim to remove CO_2 from the atmosphere and do not rely on a combustion process [45].

The most common technologies used in these groups of carbon capture include absorption, adsorption, membranes, or hybrid processes, which combine two or more technologies [44]. Oxyfuel combustion and cryogenic distillation are other categories of carbon capture technologies. However, these are energy intensive processes and are not the most practical for industrial use [40]. Oxyfuel combustion is a process which fuels combust with pure oxygen instead of air to limit the quantity of CO_2 produced in the combustion process [55]. This process requires copious quantities of oxygen, which can be energy intensive to produce. Cryogenic distillation as a process cools the feed gas mixture to low temperatures and raises it to high pressures, using phase changes to separate CO_2 from other gases. Researchers recommend cryogenic distillation for high CO_2 concentrations [15].

Membrane technologies use porous or nonporous materials to separate gas flow into two streams, referred to as the permeate (stream that permeates through the membrane) and the retentate (stream that does not permeate through the membrane), one CO_2 rich and the other Nitrogen (N_2) rich [41]. Membranes have several transport methods depending on molecule interactions with the membrane and operating conditions. These transport methods include simple diffusion, active diffusion, and active transport [10, 30]. Membranes have the potential ability to do DAC [8] and have shown exceptional performance in post-combustion processes [21, 30]. Modifications to membranes such as adding amine functional groups can lead to an increase in the capture performance of the membrane [2, 19, 46].

Carbon capture by adsorption is a process in which CO_2 adsorbs onto solid sorbents and a change in operating conditions (temperature or pressure) desorbs the CO_2 from the adsorbent. Adsorption is the adhesion of atoms, ions, or molecules onto the surface of another material. These atoms, ions, or molecules remove from the surface that they adhered to, via a change in conditions, such as pressure or temperature [42]. The atoms, ions, or molecules that adsorb onto the surface are adsorbates and the surface on which they adhere are the adsorbents. Adsorbents come from a variety of materials and each poses benefits and downsides [31]. Silica is a common adsorbent material and, like membranes, adsorbents can undergo functionalization to increase their carbon capture performance [3, 14, 50].

Absorption is the most common carbon capture technology. Carbon capture via absorption is a two-step process involving an absorber and a stripper. CO_2 absorbs to liquid solvents in the absorber, creating a CO_2 rich stream which flows to the stripper where the CO_2 desorbs using heat, creating a CO_2 lean solvent stream (recycled back to absorber) and a pure CO_2 gas stream [38]. Absorbents come in a variety of forms with various characteristics desired for effective absorbents such as good reactivity and absorptivity with CO_2, great stability below elevated thermal and fixed chemical exposure, moderate vapour pressure, suitable renewability, low environmental impact, and cost effectiveness [40].

Hybrid capture involves two or more technologies to capture CO_2. These hybrid systems need to increase the capture efficiency and capacity compared to a singular capture system because of the increased complexity of the systems. Hybrid systems are less researched compared to other technologies, as they need two developed carbon capture technologies. Adsorption and membrane processes can work in a hybrid system, such as [29, 54]. Idryma Technologias Kai Erevnas [27] have shown a large-scale hybrid technology project and the potential they have.

A Bibliometric analysis is an effective method to find trends in specific research fields [32, 39, 52]. This paper aims to use bibliometric analysis techniques to show trends and current areas of interest in carbon capture. This paper is based on bibliometric data from searches performed on the Web of Sciences, thus is not a complete representation of current trends (articles may not be on that system). Naseer et al. [36] and Omoregbe false [39] conducted similar reviews. These reviews focused on carbon capture as a whole [36] and a comparison between pre-combustion, post-combustion, and oxyfuel combustion [39]. The aim of this analysis is to outline the trends within popular capture technologies.

This paper aims to identify if specific technologies are changing in popularity from the Web of Sciences bibliometric data. This paper does not distinguish between pre-combustion or post-combustion technologies as the

Table 1 Search criteria

Technology	Search
Absorption	(KP = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND KP = ("absorption" OR "absorbent" OR "absorb")) OR (TI = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND TI = ("absorption" OR "absorbent" OR "absorb")) OR (AK = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND AK = ("absorption" OR "absorbent" OR "absorb"))
Adsorption	(KP = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND KP = ("adsorption" OR "adsorbent" OR "adsorb")) OR (TI = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND TI = ("adsorption" OR "adsorbent" OR "adsorb")) OR (AK = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND AK = ("adsorption" OR "adsorbent" OR "adsorb"))
Membrane	(KP = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND KP = ("membrane")) OR (TI = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND TI = ("membrane")) OR (AK = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND AK = ("membrane"))
Hybrid Processes	(KP = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND KP = (("hybrid") OR (("absorption" OR "absorbent" OR "absorb") AND ("membrane")) OR (("absorption" OR "absorbent" OR "absorb") AND ("adsorption" OR "adsorbent" OR "adsorb")) OR (("adsorption" OR "adsorbent" OR "adsorb") AND ("membrane")))) OR (TI = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND TI = (("hybrid") OR (("absorption" OR "absorbent" OR "absorb") AND ("membrane")) OR (("absorption" OR "absorbent" OR "absorb") AND ("adsorption" OR "adsorbent" OR "adsorb")) OR (("adsorption" OR "adsorbent" OR "adsorb") AND ("membrane")))) OR (AK = ("carbon capture" OR "CO2 capture" OR "carbon-capture" OR "CO2-capture") AND AK = (("hybrid") OR (("absorption" OR "absorbent" OR "absorb") AND ("membrane")) OR (("absorption" OR "absorbent" OR "absorb") AND ("adsorption" OR "adsorbent" OR "adsorb")) OR (("adsorption" OR "adsorbent" OR "adsorb") AND ("membrane"))))

technologies (pre or post combustion) themselves are not the focus of this quantitative based paper.

2 Materials and methods

Adsorption, absorption, membranes, and hybrid technologies are promising technologies for carbon capture [38, 40, 44]. This study split the bibliometric searches into these four categories (adsorption, absorption, membranes, and hybrid technologies) with a fifth, 'combined' category representing the four data sets combined. Overall trends in carbon capture are the goal of this combined category.

The 'Web of Sciences' search engine performed this analysis, using the 'Web of Science Core Collection'. Table 1 shows the different searches performed by the advance search feature with analysis limited to 'articles' and 'proceedings papers'. The data sets have only English language documents, and searches spanned across the oldest documents within the system to 2020 while limited to 'Science Citation Index Expanded (SCI-Expanded)'. Within the searches on the web of sciences, the field tags KP, TI and AK represented 'Keyword Plus', 'Title' and 'Author Keywords'.

The logic operators 'AND' and 'OR' within the search criteria aided in focusing the searches. Parenthesis with these logic operators ensured the correct logical formulas for the searches. Quotation marks ("") within the searches ensured exact word and phrase search, to limit non-relevant results. Within the 'Hybrid Processes' technology searches, titles or keywords of the scientific papers may not contain the word 'hybrid' but could contain the words of two other technologies such as adsorption and absorption, so searches comprised these combinations as seen in Table 1. The 'combined' bibliometric data set combined the other four data sets into one.

Using data from the Web of Sciences, the Bibliometrix plug-in for R software performed the bibliometric analysis. The Biblioshiny web app associated with the Bibliometrix plug-in aided in this analysis [5].

This research aims to review each of the four categories of capture technologies and the fifth 'combined' category in terms of scientific productivity, journal sources, keywords and originating country.

The general trends analysis aims to summarize the data in terms of keyword and key phrase trends.

The scientific productivity analysis aims to uncover the scientific productivity trends within this hot topic using article outputs and citations as a measure of quantity. This analysis includes examining the scientific production (number of articles/year), cumulative citations and citations per citable years, each a factor of scientific productivity.

The journal analysis section includes an analysis of the H-index, G-index, M-index, Total Citations (TC) and Number of Publications (NP). H-index is a measure in terms of article productivity and citation impact, where there has been at least h number of articles with h number of citations [24]. G-index measures the distributive citations received, where articles rank in decreasing order of the number of citations received. The G-index is the largest number that the top g articles received (together) at least g^2 citations [12]. M-index is a measure of the H-index over the number of years since the first publication [24].

To understand the publication frequency trends, the data underwent a Lotka's law assessment. The law states that the number of authors making x contributions is a fraction of the number of authors contributing one article [34]. This law can infer the number of authors contributing x articles by knowing the number of authors contributing one article [17].

The country analysis section aims to show the top producing countries of carbon capture related scientific articles and the top collaborating countries.

3 Results and discussion

The below sections display the results from using the methods explained. Key phrases, author countries, scientific productivity, and journal sources derive the analysis. The Biblioshiny web-app from the bibliometrix R plug [5] and Microsoft Excel created visualizations of the bibliometric data.

3.1 Overview of information

Below, Table 2 displays general information from the bibliometric data in a tabular format. This table has a 'sources' row referring to the journal sources of the articles produced and thus the quantity in the 'combined' category may be less than that of the sum of the four categories. As shown in Table 2, 'Absorbent' based technologies were the first researched technologies with an article from 1997, given the bibliometric sample. The category of technology with the greatest scientific production is adsorbents. These adsorbent articles have the greatest average citations per document and average citation per year per document, shows quality and longevity within this technology research field. The category of hybrid technologies has the greatest number of Keyword Plus per Document, these systems use greater than one technology (membrane and adsorbent etc. the author refers to both technologies as keywords), and this was the expectation.

In terms of citations per document, hybrid technologies performances are good compared to the singular base technologies while considering the scope that singular

Table 2 Summary of the main information about the technologies

MAIN INFORMATION ABOUT DATA	Adsorption	Absorption	Membrane	Hybrid Processes	Combined
Timespan	2002:2020	1997:2020	2003:2020	2004:2020	1997:2020
Sources (Journals, Books, etc)	313	215	145	141	433
Documents	1877	1227	680	396	4180
Average years from publication	4.58	4.89	5.14	4.71	4.77
Average citations per documents	34.71	24.6	28.5	26.65	29.97
Average citations per year per document	5.43	3.798	4.35	4.37	4.672
References	42,743	25,827	17,528	13,942	75,300
DOCUMENT TYPES					
article	1825	1159	652	377	4013
article; proceedings paper	52	68	28	19	167
DOCUMENT CONTENTS					
Keywords Plus (ID)	3125	2038	1501	1222	5084
Author's Keywords (DE)	3142	2493	1612	1047	6216
Keywords Plus per Document	1.66	1.66	2.21	3.09	1.22
AUTHORS					
Authors	4941	3091	1897	1327	8409
Author Appearances	9086	5452	3109	1765	19,412
Authors of single-authored documents	13	17	10	11	33
Authors of multi-authored documents	4928	3074	1887	1316	8376
AUTHORS COLLABORATION					
Single-authored documents	16	23	12	13	64
Documents per Author	0.38	0.38	0.36	0.30	0.50
Authors per Document	2.63	2.52	2.79	3.35	2.01
Co-Authors per Documents	4.84	4.44	4.57	4.46	4.64
Collaboration Index	2.65	2.55	2.82	3.44	2.03

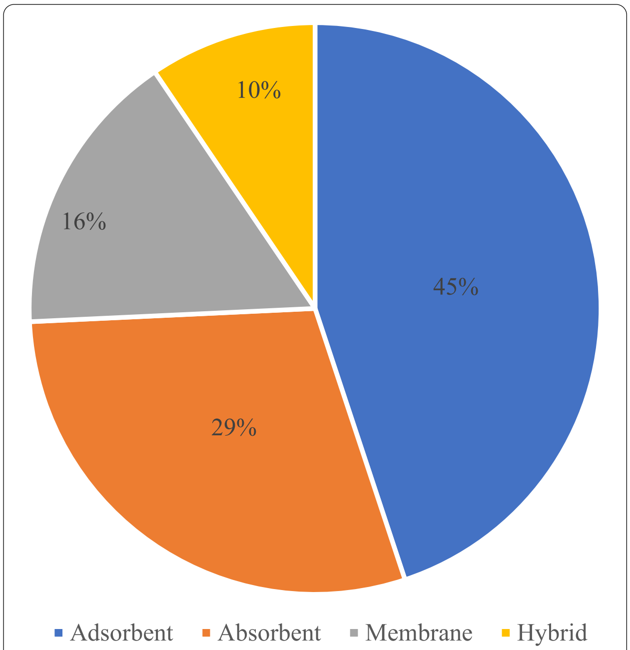

Fig. 2 Articles by technology

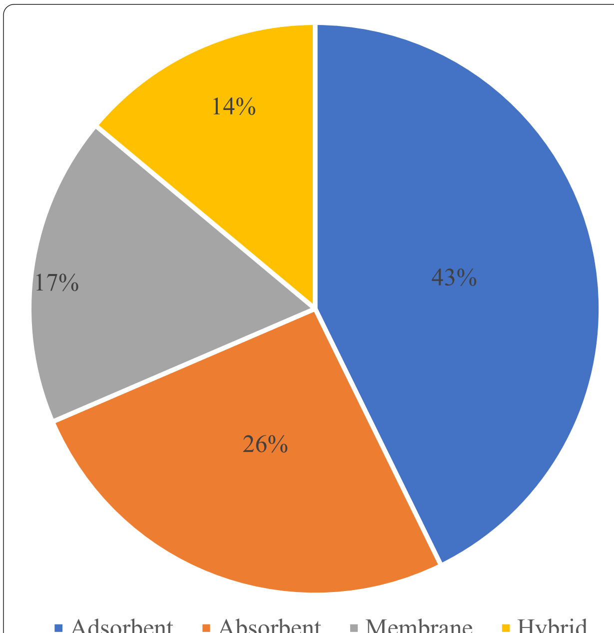

Fig. 3 Citations by technology

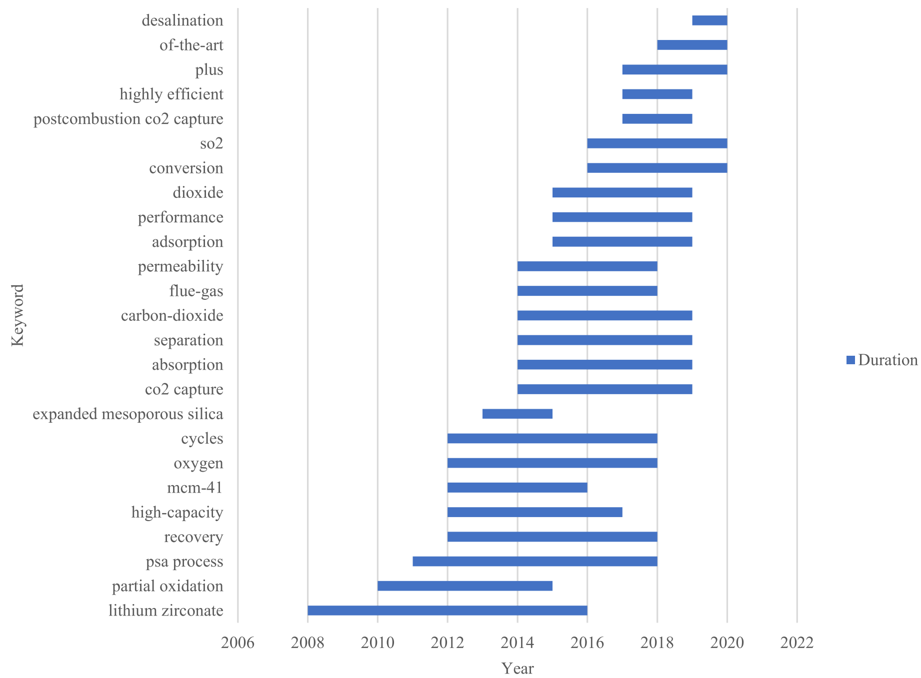

Fig. 4 Keyword trend (keyword plus)

technology articles have for other disciplines (referenced because of similar system set up, or materials used). Articles may reference articles of the same category within the data, the small number of hybrid technology articles, limits this impact for this category. Hybrid technologies having two or more technologies lead to references of both singular technologies increasing their citations.

Figures 2 and 3 display the articles and citations by technology in a pie chart format. These figures show that both hybrid and membrane technologies have a larger share of citations than articles (as percentages) suggesting that these technologies publish more relevant material.

Table 2 shows that hybrid technologies rank the highest in the collaboration index (calculated by the total authors of multi-authored articles divided by the total multi authored articles), highlighting the cooperation within this category of technology. They have the lowest rank in documents per author, which shows that an array of researchers study this specific category of technology.

3.2 General trends

This paper examined the trends in key terms results from the 'combined' data set. Below Fig. 4 displays a basic graphic of key term trends spanning from 2008 to 2020. The criteria for this graphic involved the top key terms each year, with at least five occurrences spanning multiple years (two or more) (25 results, with 2008 being the first year that terms met the criteria, spanning back to 1997). This search returns top key terms spanning consecutive years.

Noteworthy phrases seen within this analysis includes 'absorption', 'permeability', 'adsorption', 'expanded mesoporous silica', 'mcm-41' (mesoporous silica), 'high capacity', 'psa process', 'lithium zirconate', these phrases are indicators of the trends in carbon capture research. 'Lithium zirconate' is the key term that kept the described criteria for the longest duration, lithium zirconate is a common material used is absorption carbon capture process [26]. 'psa process' being a Pressure Swig Adsorption (PSA), a common adsorption method used to capture CO_2 [42]. Permeability here suggests a trend in membranes, as permeability is a membrane performance indicator [10]. The way the bibliometric analyses software works makes this graphic not completely exact. Take 'expanded mesoporous silica', mesoporous silica is a well-researched material for carbon capture technologies [14]. But, because of the way the software works, it picked up 'expanded mesoporous silica' as a key term which seen in Fig. 4 is not as popular. 'mcm-41', another silica which can undergo modifications to increase capture performance as shown by [56]. 'of-the-art' trending from 2018 to 2020 suggests novel technologies being researched, as this would have likely been with state-of-the-art, implying novelty and

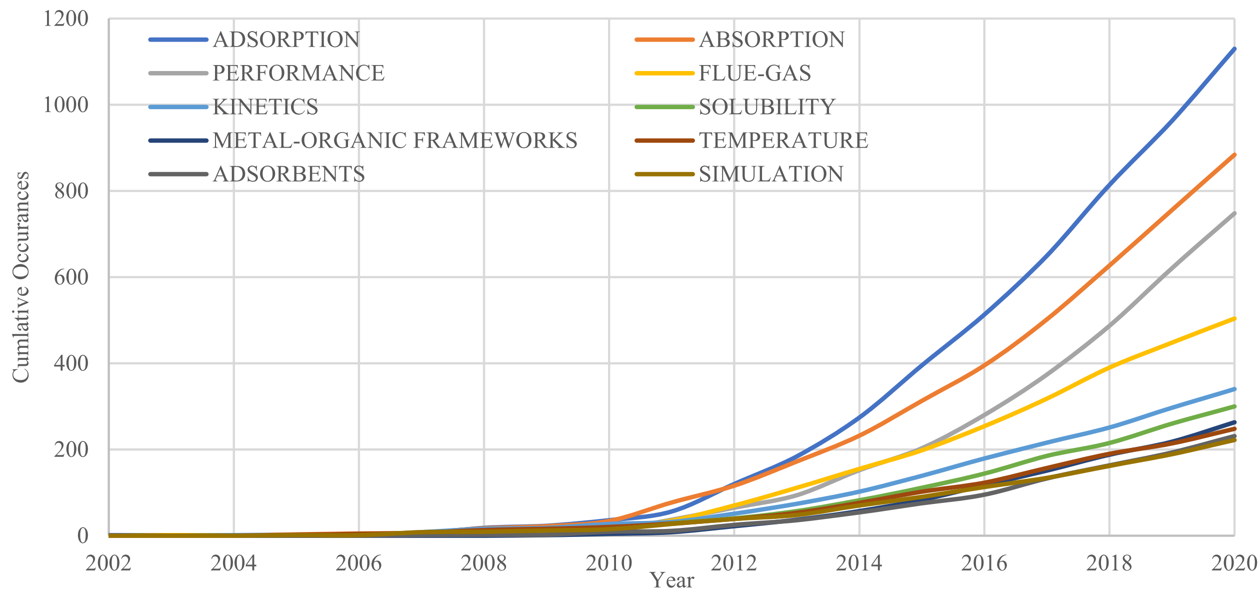

Fig. 5 Keyword growth trend

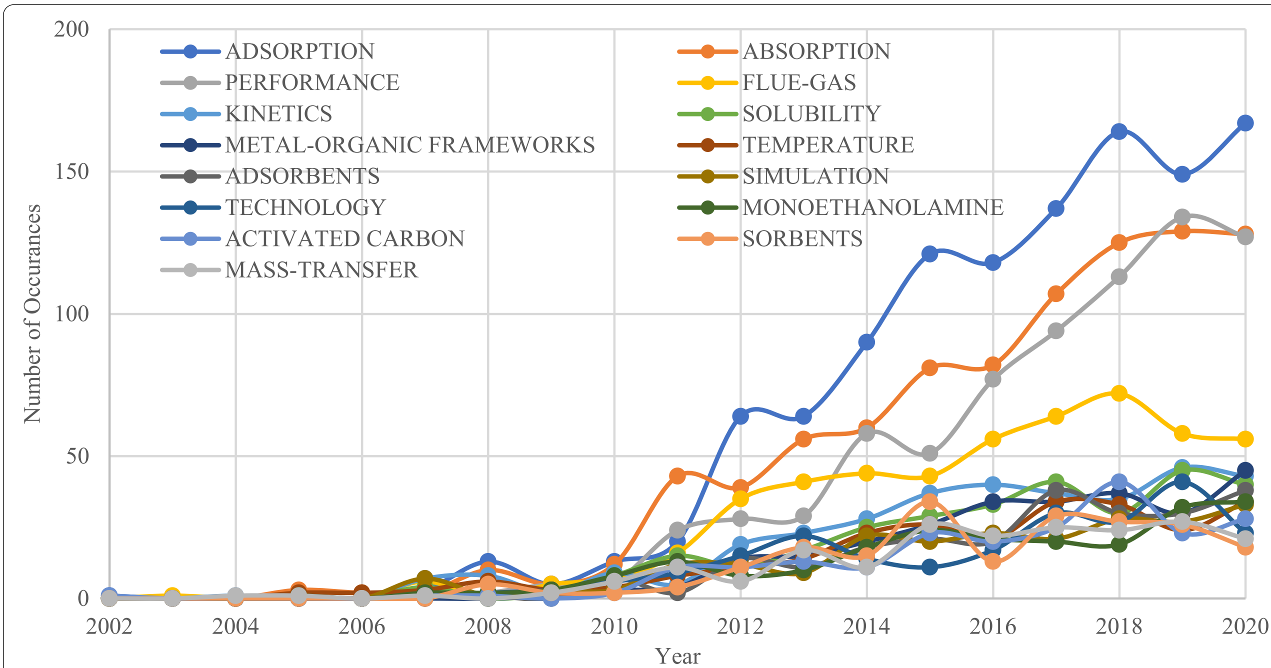

Fig. 6 Phrase trend

newness. Trends of ‘cycles’ from 2012 to 2018 hints at adsorption processes trending as ‘cycles’ are a crucial part of swing adsorption systems [43].

To get a more in-depth understanding of keyword trends, this study analyzed trends of the top twenty keywords, omitting the following ‘CO2 CAPTURE’, ‘SEPARATION’, ‘CARBON-DIOXIDE’, ‘CAPTURE’, ‘CARBON-DIOXIDE CAPTURE’, ‘REMOVAL’, ‘GAS’, ‘STORAGE’, ‘CO2’ and ‘DIOXIDE’. These keywords omitted as they are common across each technology category

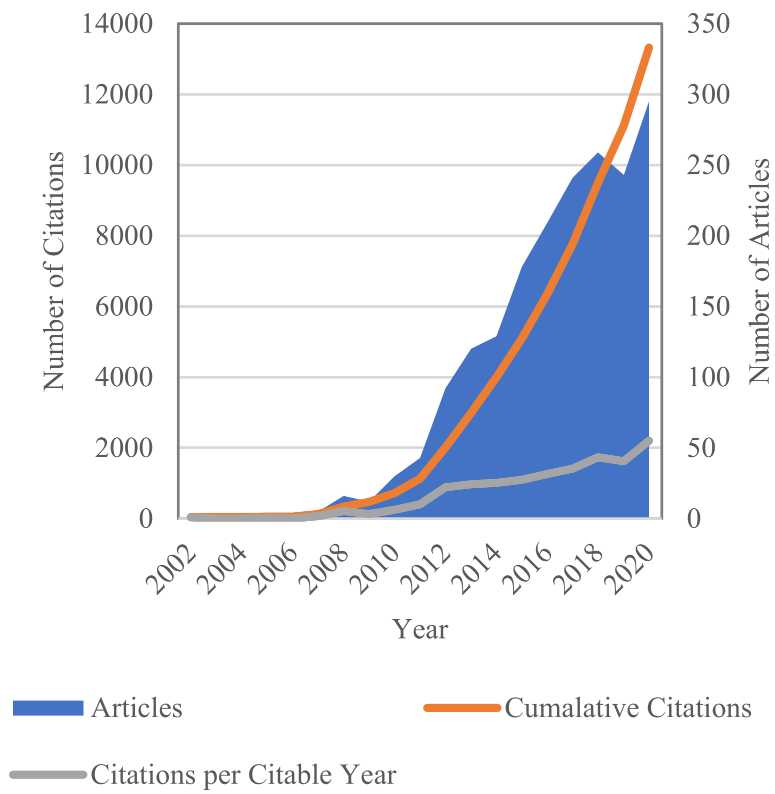

Fig. 7 Adsorbent, productivity and citations

as the top results. This data created two graphics, Fig. 5 which shows the cumulative growth of these keywords and Fig. 6, the actual number of occurrences of the key terms each year.

Figure 5 shows the most trending terms from the keyword plus section of the bibliometric data to be 'ADSORPTION', 'ABSORPTION', 'PERFORMANCE' and 'FLUE-GAS'. 'PERFORMANCE' being a trending word showing that articles focused on the operational performance of carbon capture equipment, i.e., performance of the equipment used, or increasing performance in various carbon capture technologies, i.e., performance comparison articles or statements such as 'increased performance', 'performance improvement'. Conversely, it could indicate competitiveness in the field, leaving one to believe in a performance standard researchers aim to achieve.

slight dip followed by a two-year growth in popularity which if this trend is to continue then 2021 could be a popular year for adsorption-based carbon capture articles. There were no other key trends identified in Figs. 5 and 6. The graphs represent this sample with no guarantee that trends will continue.

3.3 Scientific productivity

The bibliometric data underwent scientific productivity examinations. Each data set underwent individual examination and as a collective group too as shown in (Figs. 7, 8, 9, 10, and 11). These graphs include scientific production (Number of Articles/year.), cumulative citations (the sum of the citations per citable year accumulated up to the year in question) and citations per citable year (see eq. 1).

$$Citations\ per\ Citable\ Year = \frac{(Mean\ total\ Citations\ per\ Article) * (Number\ of\ Articles)}{Citable\ Years} \quad (1)$$

Figure 6 below shows a plateau in 'absorption' occurrences since 2018. 'adsorption' follows a trend of a

As seen from Figs. 7, 8, 9 and 10, there has been a steady increase in article production and cumulative citations

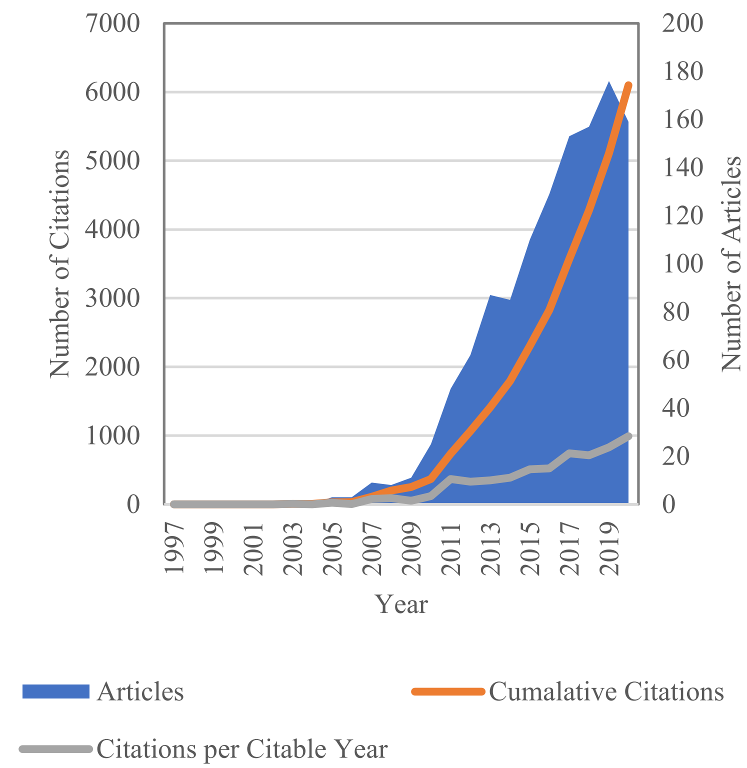

Fig. 8 Absorbent, productivity and citations

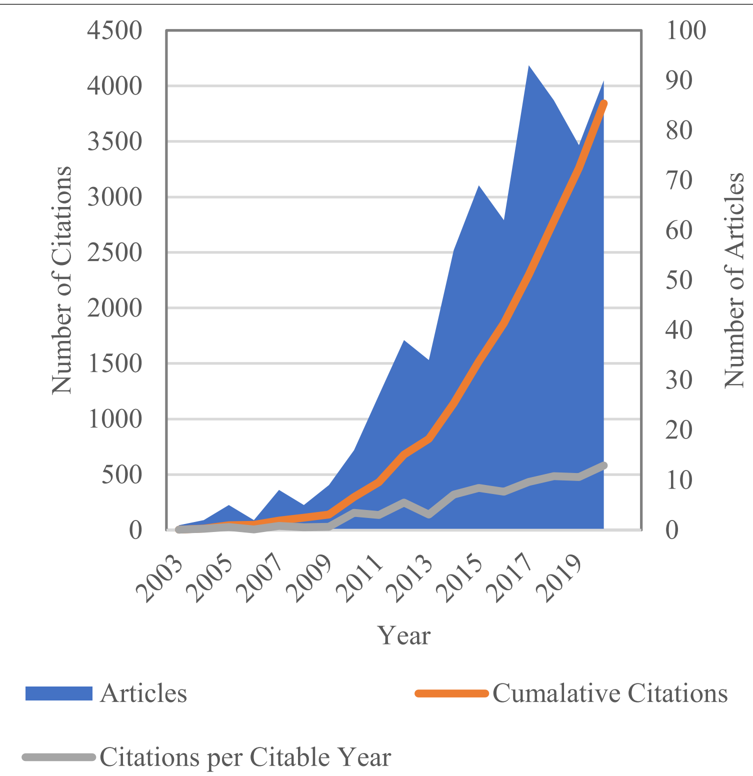

Fig. 9 Membrane, productivity and citations

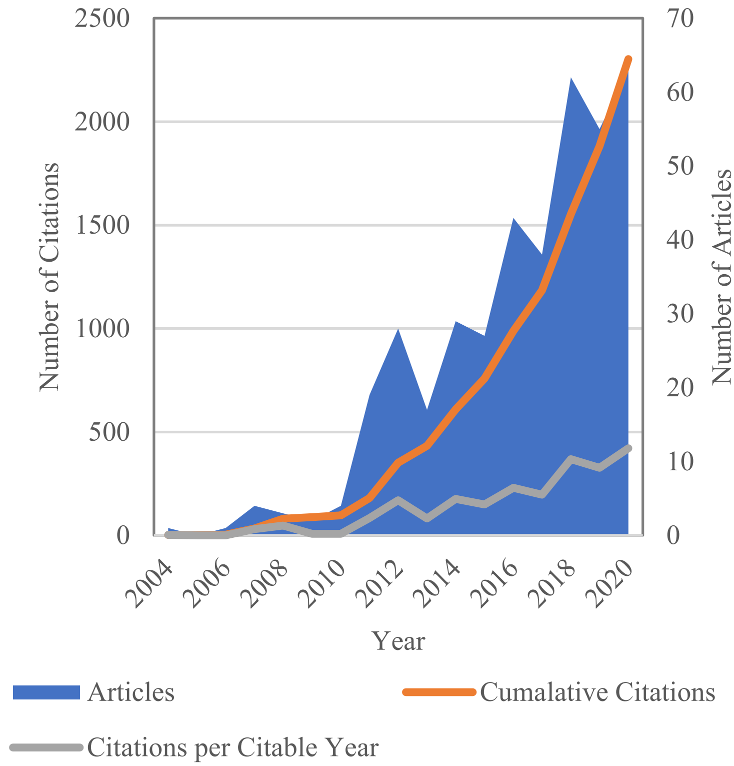

Fig. 10 Hybrid, productivity and citations

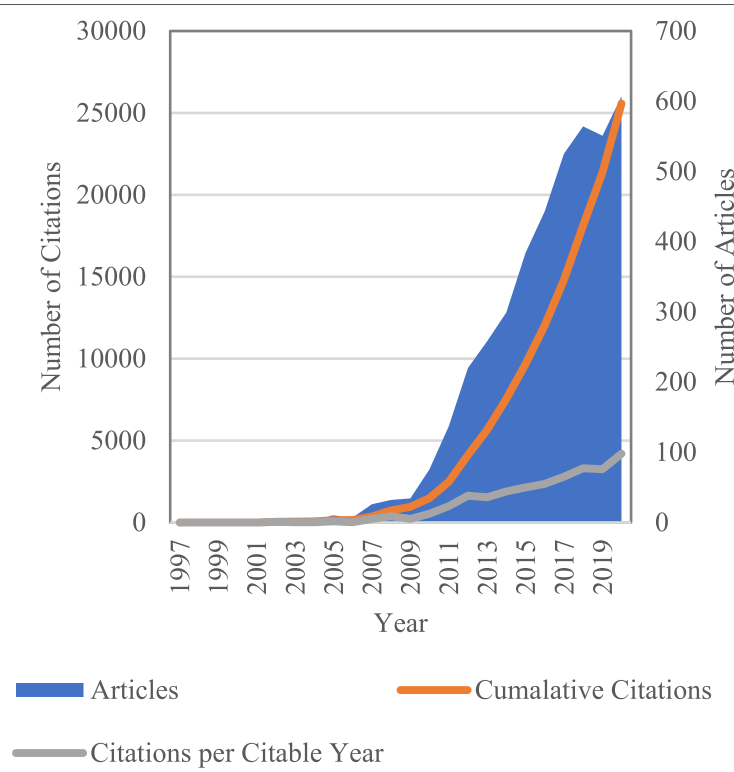

Fig. 11 Combined, productivity and citations

per year in each category of carbon capture technology investigated. Figure 11, a graphical representation of the combined bibliometric data set confirms this trend. The figures show that carbon capture research is on the rise.

As seen from the above figures, adsorbent technologies (Fig. 7) have the highest productivity rates of the selected technologies with hybrid (Fig. 10) and membrane (Fig. 9) technologies being lowest and second lowest, suggesting these are under published areas. This is a quantitative analysis, one can draw no conclusion whether these are under published areas because they are upcoming technologies or whether they are not showing promise. Hybrid technologies' scientific production may be low because of the processes including two or more technologies. Citations show the same trend, with adsorption showing the highest quantities of citations largely because of the quantity of articles produced, again with membrane and hybrid ranking lowest.

These figures show that interest in the areas of adsorption (Fig. 7) and hybrid technologies (Fig. 10) are on the rise with the increase in the quantity of citations per citable year (grey line on the graphs). They have positive trend lines in terms of citations per citable year, which suggests production of quality work interesting other researchers. While the main source of citations for these documents may be other articles on carbon capture, the possibility that other sources cited these articles is present, e.g. articles considering alternative uses of the capture system materials, or the same process used in a different application.

Table 3 Top three journal sources for each category

Journal Source	Sources	Number of Articles
Adsorption	CHEMICAL ENGINEERING JOURNAL	113
	INDUSTRIAL \& ENGINEERING CHEMISTRY RESEARCH	101
	MICROPOROUS AND MESOPOROUS MATERIALS	65
Absorption	INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL	194
	APPLIED ENERGY	71
	INDUSTRIAL \& ENGINEERING CHEMISTRY RESEARCH	71
Membranes	JOURNAL OF MEMBRANE SCIENCE	129
	INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL	54
	SEPARATION AND PURIFICATION TECHNOLOGY	42
Hybrid Processes	INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL	22
	APPLIED ENERGY	20
	ENERGY	18

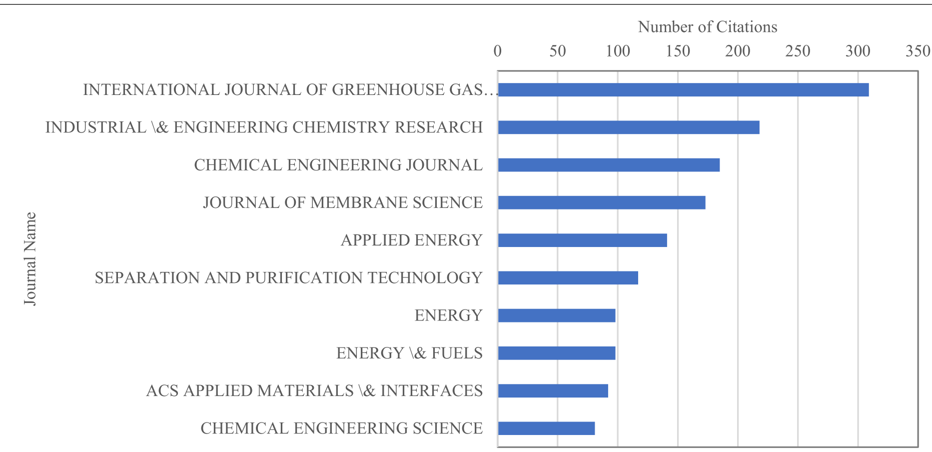

Fig. 12 Combined, no articles produced based on journal sources

Table 4 Journal index rankings, base technologies

	Journal Source	H_index	G_index	M_index	TC	NP
Adsorption	ACS APPLIED MATERIALS \& INTERFACES	27	51	2.70	2706	60
	ADSORPTION-JOURNAL OF THE INTERNATIONAL ADSORPTION SOCIETY	16	36	1.14	1334	49
	AICHE JOURNAL	16	22	1.07	932	22
Absorption	APPLIED ENERGY	29	43	2.64	2135	71
	APPLIED THERMAL ENGINEERING	11	17	1.10	290	17
	ACS SUSTAINABLE CHEMISTRY \& ENGINEERING	8	12	1.60	177	12
Membrane	ACS APPLIED MATERIALS \& INTERFACES	11	15	1.10	482	15
	APPLIED ENERGY	10	14	0.91	535	14
	AICHE JOURNAL	7	11	0.47	207	11
Hybrid Technologies	APPLIED ENERGY	13	20	1.30	620	20
	ACS APPLIED MATERIALS \& INTERFACES	8	10	0.80	313	10
	APPLIED THERMAL ENGINEERING	5	6	0.31	111	6

Table 5 Combined, journal source indices

Journal Source	H_index	G_index	M_index	TC	NP
ACS APPLIED MATERIALS \& INTERFACES	31	58	3.1	3689	92
ADSORPTION-JOURNAL OF THE INTERNATIONAL ADSORPTION SOCIETY	17	36	1.21	1371	52
ACS SUSTAINABLE CHEMISTRY \& ENGINEERING	17	26	2.43	813	43
ADVANCED FUNCTIONAL MATERIALS	9	10	0.82	618	10
ACS OMEGA	7	13	1.17	179	13

3.4 Journal analysis

This paper analyzed journal sources to find the top producing journals of the articles within the bibliometric data. The top-ranking journals may aid in understanding the focus of the published articles, by using the themes of the journals, i.e., material production or process optimization, etc. Table 3 shows the top three journal sources of the individual technologies in a tabular format, with the combined category in a graphical format in Fig. 12.

As seen from Fig. 12 (combined basis) the journal with the most publications is the 'International Journal of Greenhouse Gas Control' [28]) a peer-reviewed journal that has one of its focuses areas as Carbon Capture, Transport, and Storage, this suggests a vast array of topics discussed within these articles. The second most researched journal, 'Industrial and Engineering Chemistry Research' [25] has an emphasis on experimental and computational/theoretical papers but has a particular interest in papers that have a mix of both, which suggests that many articles submitted here may include scale-up/simulation processes along with experimental data. The 'Chemical Engineering Journal' [9] completes the top three which again is an engineering paper which focus on environmental engineering and novel materials, this journal could have produced articles based on new materials or on engineering solutions to improve developed technologies.

Table 4 below displays the top-ranking journals in terms of their H-index, G-index, M-index, TC, and NP for each individual technology category. Table 5 displays the same information for the combined top five overall journals. As seen from Table 5 'ACS Applied Materials & Interfaces' [4] ranked first across the H-index [24], the G-index [12] and the M- [24]. This shows that articles published in this journal are high-quality and relevant articles. An M-index of one or greater shows high-quality research, and every journal in Table 5 met this criterion. The journal Applied Materials and Interfaces [4] (the top-ranking in quality indicators) ranked ninth in the quantity of articles produced, which suggests that higher quantities do not lead to the higher-quality publications. This journal is an inter-disciplinary journal focusing on new materials and interfacial processes, a possible explanation of its H-index performance as if the journal focuses on novel materials, other researchers may use the same materials in their research or may compare their own results to the results from the original author, leading to more citations. The second ranking journal, 'Adsorption Journal of the International Adsorption Society' [1]) a journal aiming to supply

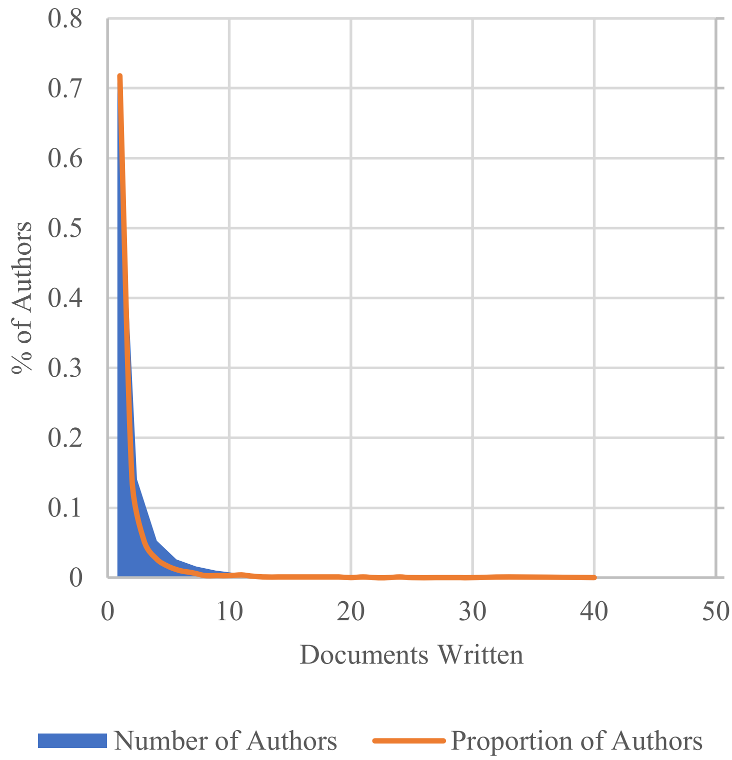

Fig. 13 Adsorption, Lotka's Law

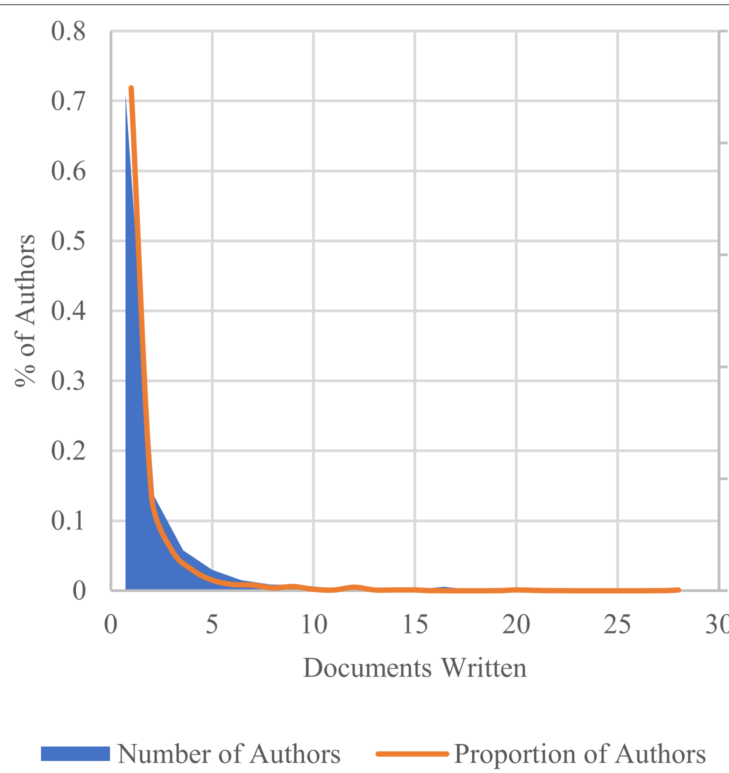

Fig. 14 Absorption, Lotkas Law

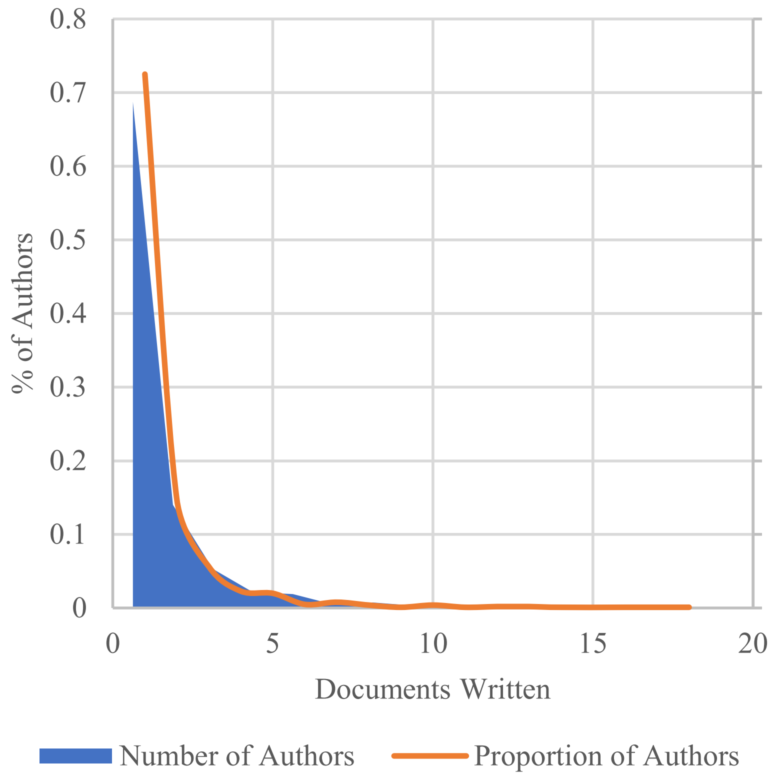

Fig. 15 Membranes, Lotkas Law

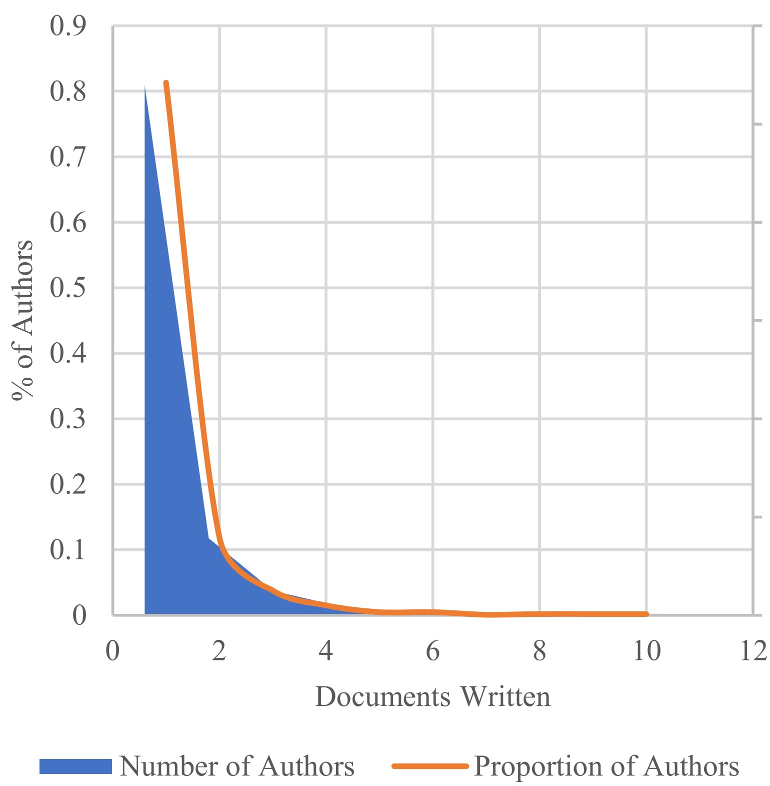

Fig. 16 Hybrid, Lotkas Law

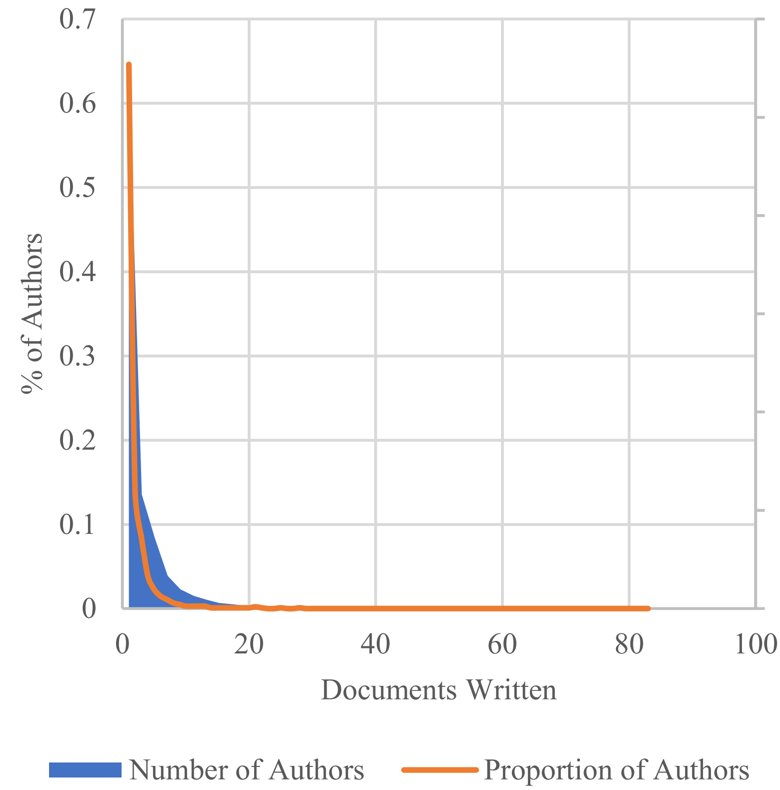

Fig. 17 Combined, Lotkas Law

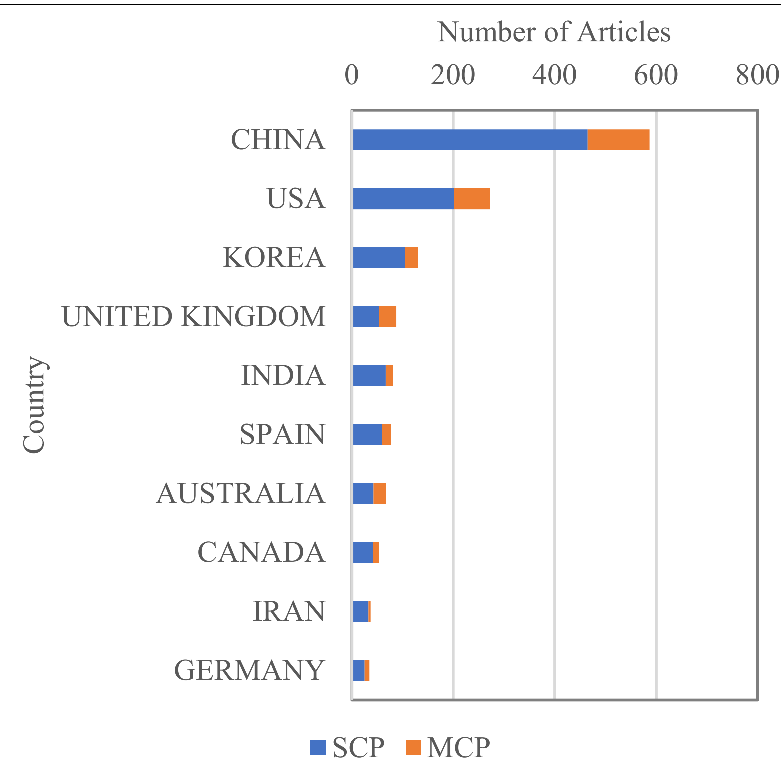

Fig. 18 Adsorbents, top contributing countries

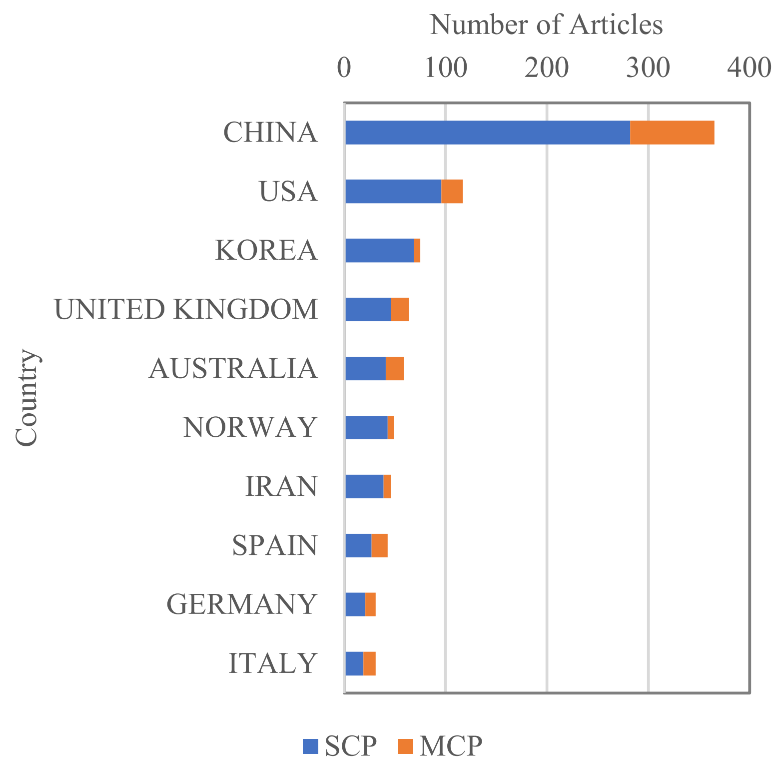

Fig. 19 Absorbent, top contributing countries

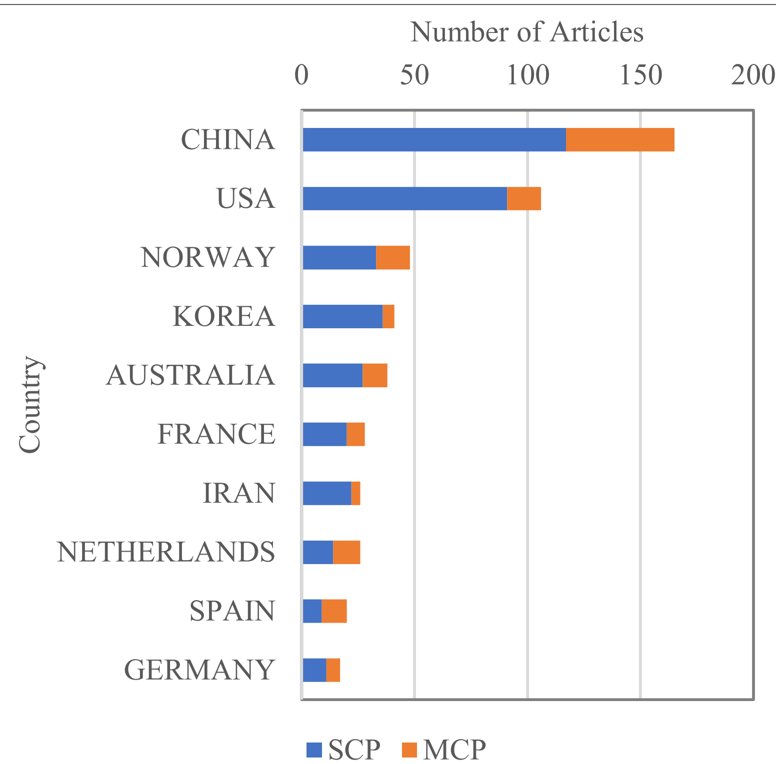

Fig. 20 Membrane, top contributing countries

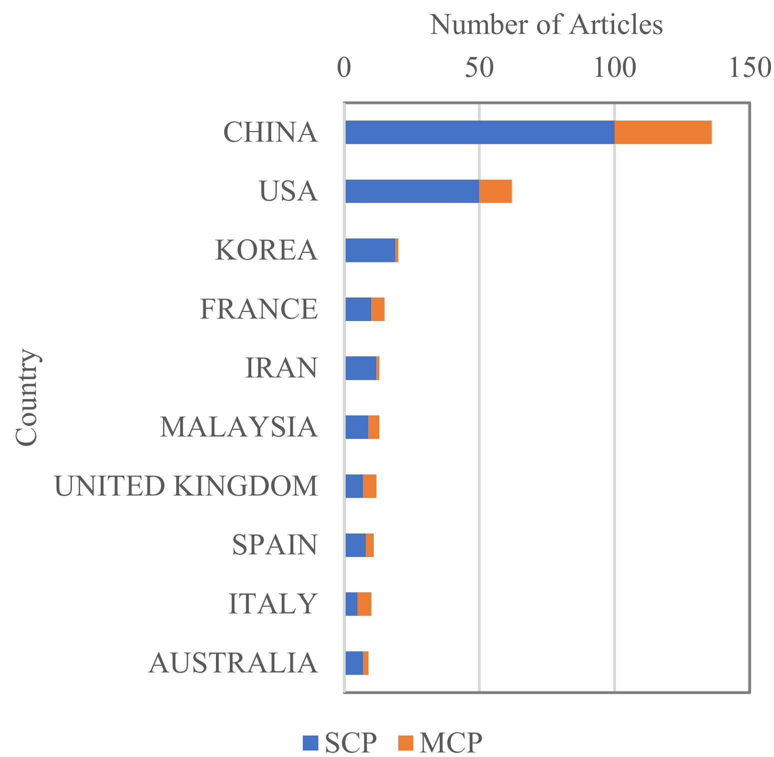

Fig. 21 Hybrid, top contributing countries

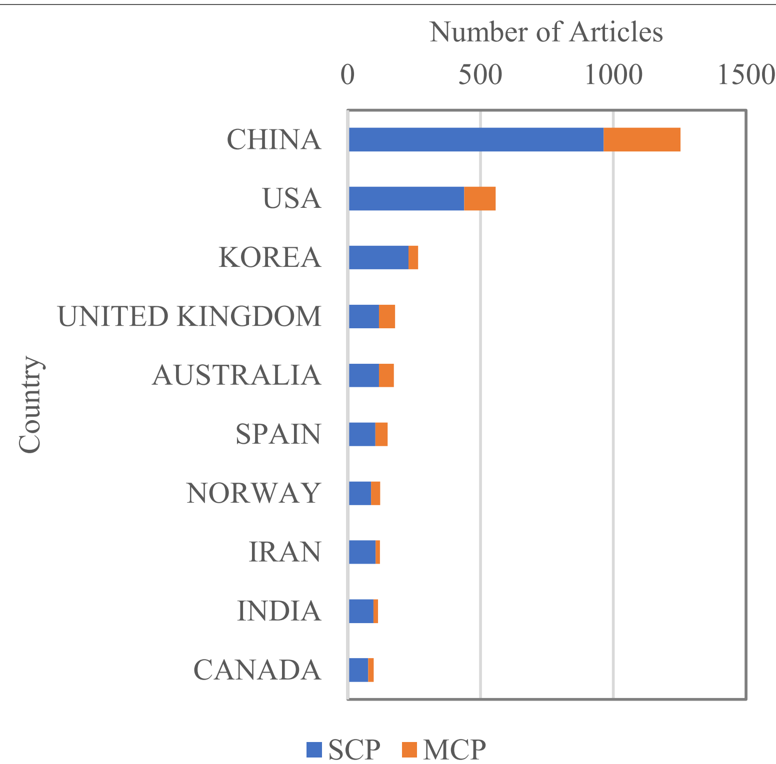

Fig. 22 Combined, top contributing countries

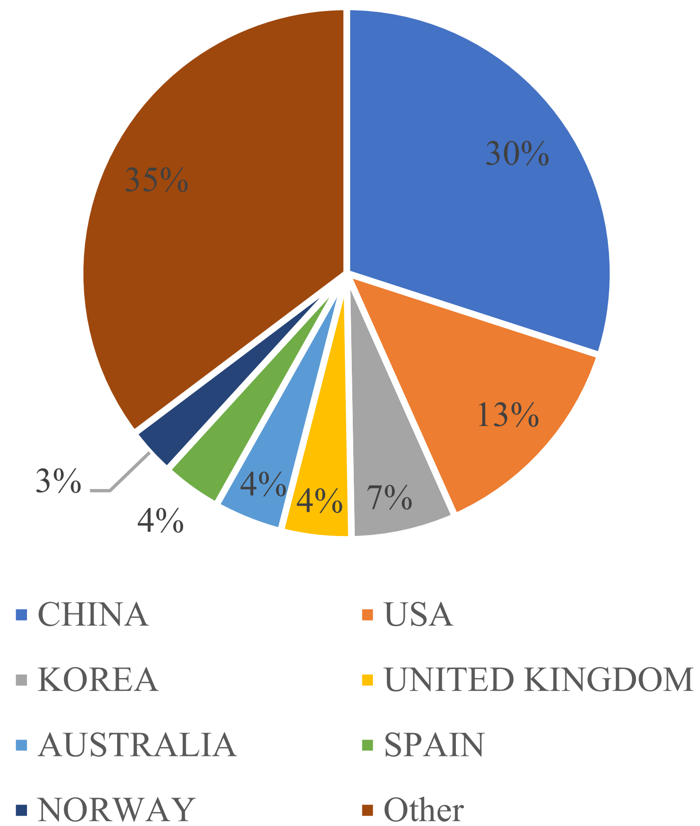

Fig. 23 Author nationality split

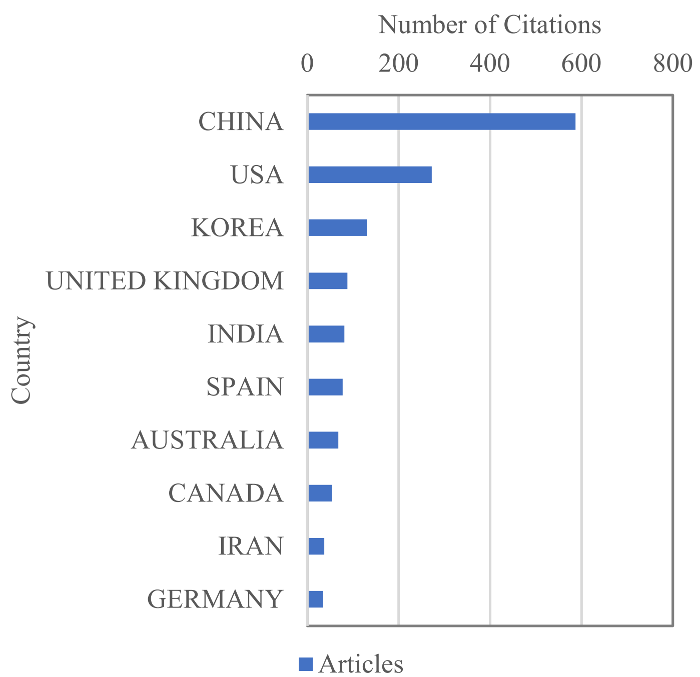

Fig. 24 Adsorbent, top cited countries

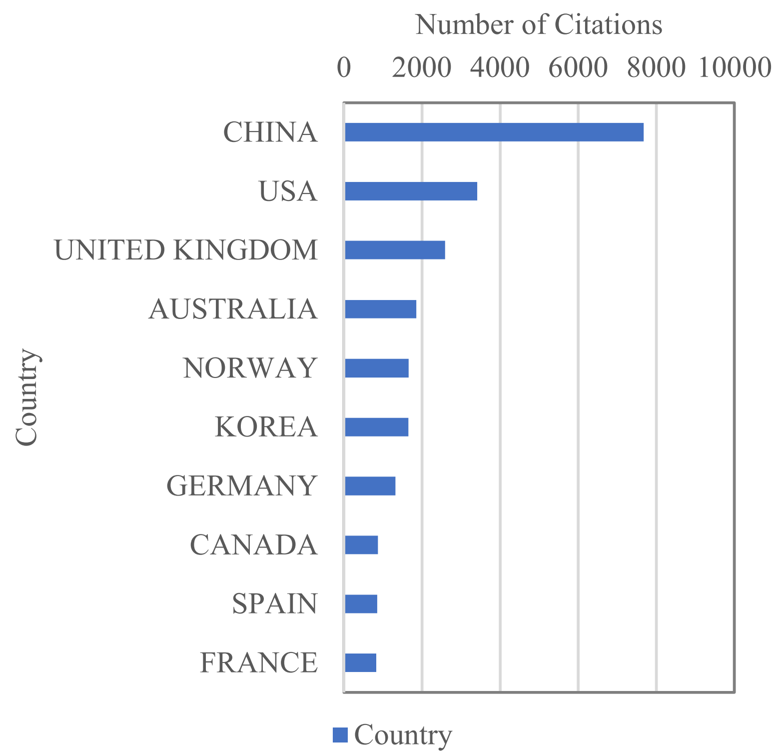

Fig. 25 Absorbent, top cited countries

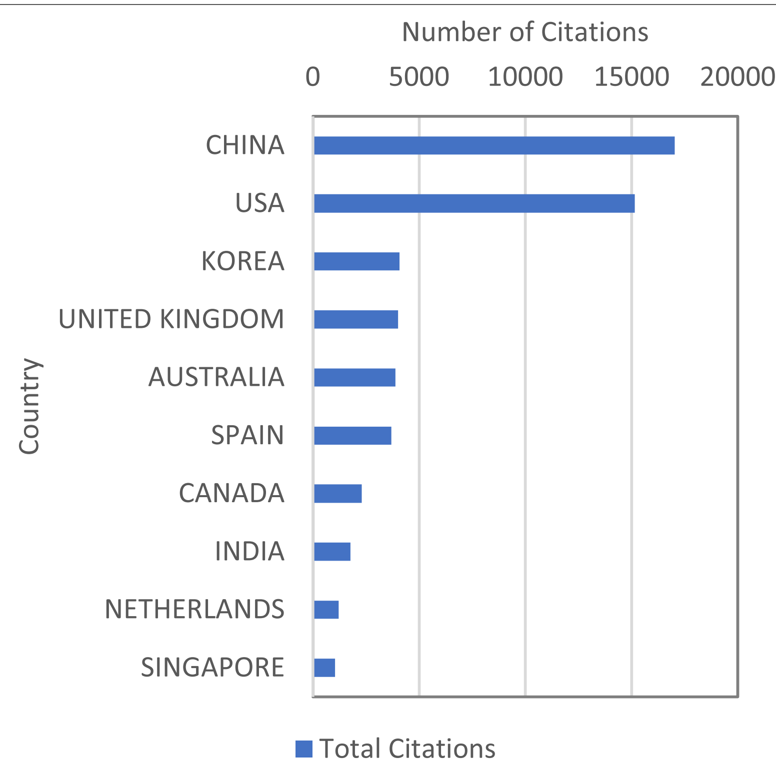

Fig. 26 Membrane, top cited countries

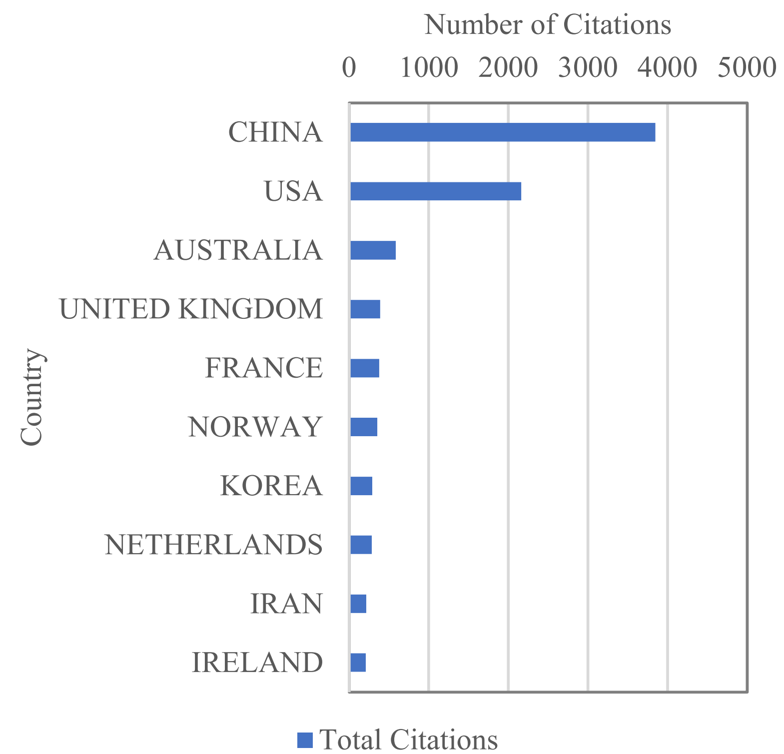

Fig. 27 Hybrid, top cited countries

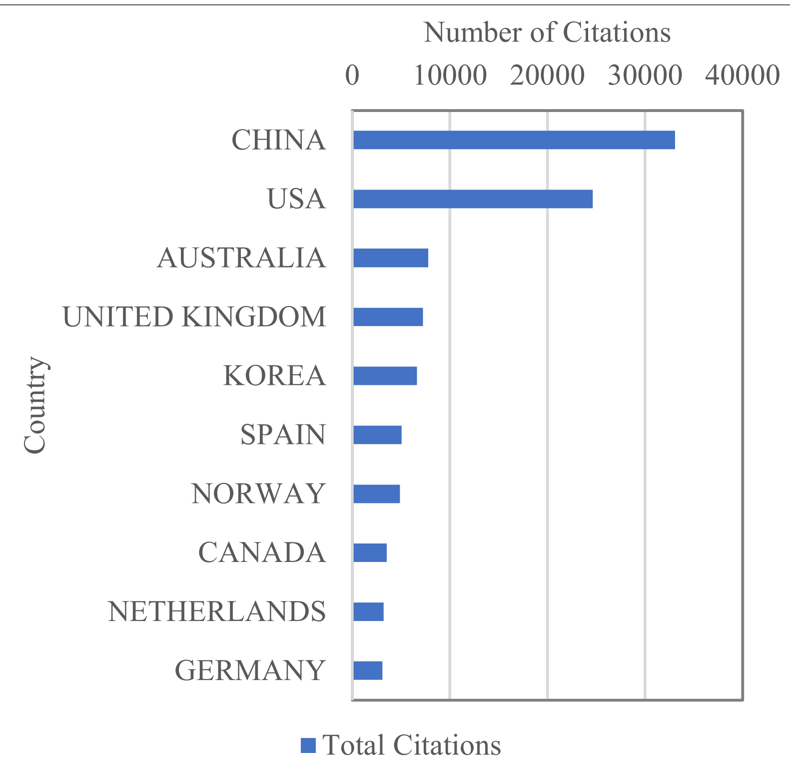

Fig. 28 Combined, top cited countries

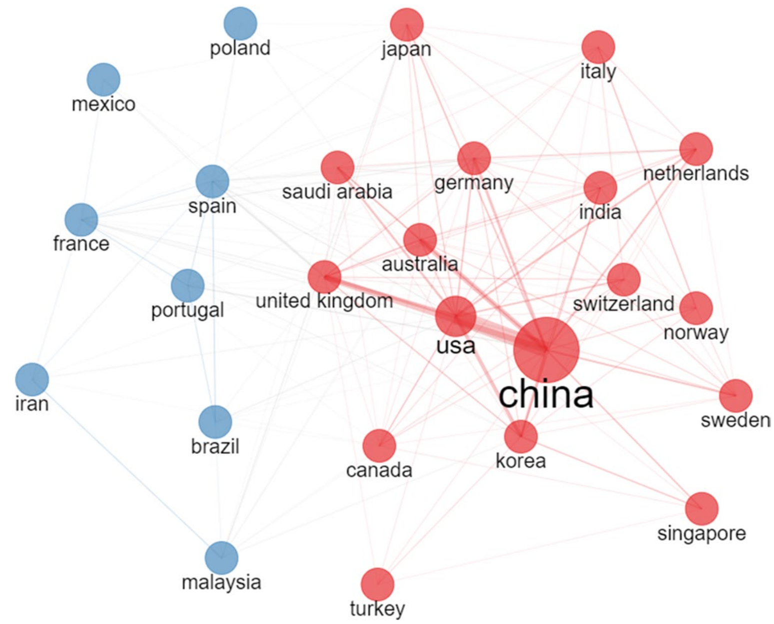

Fig. 29 Adsorption, country collaboration map

authoritative information on adsorption and allied field to scientists, engineers, and technologists. This journal ranking high suggests progress in adsorption-based carbon capture technologies and suggests that adsorption techniques yield desirable carbon capture results.

3.5 Lotka's law

Lotka's law describes the frequency of publication by authors in each field, it says that the number of authors making x contributions is a fraction of the number of authors contributing one article [34]. Figures 13, 14, 15, and 16 graphically show the Lotkas law assessment for each individual technology. Figure 17, the combined bibliometric data set follows Lotka's Law. This implies that the publications follow the expected trend in author publication frequency.

3.6 Country analysis

Analysis of the bibliometric data found the top contributing countries to each category of technology. Figures 18, 19, 20, 21, and 22 displays graphs of this data.

Figure 22 depicts the top ten producing countries, and it shows that China is the biggest contributor of articles on both Single Country Publications (SCP) and Multi Country Publications (MCP). China has been the top producer for each subcategory of technologies too (adsorbent, absorbent, membrane, and Hybrid). As seen

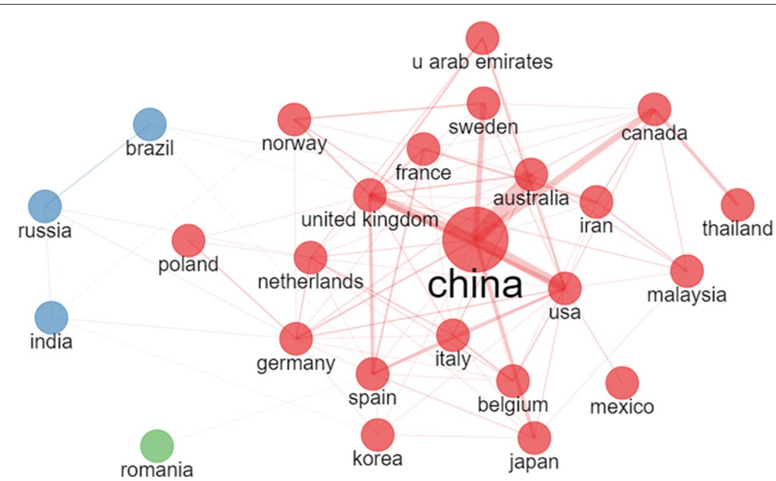

Fig. 30 Absorption, country collaboration map

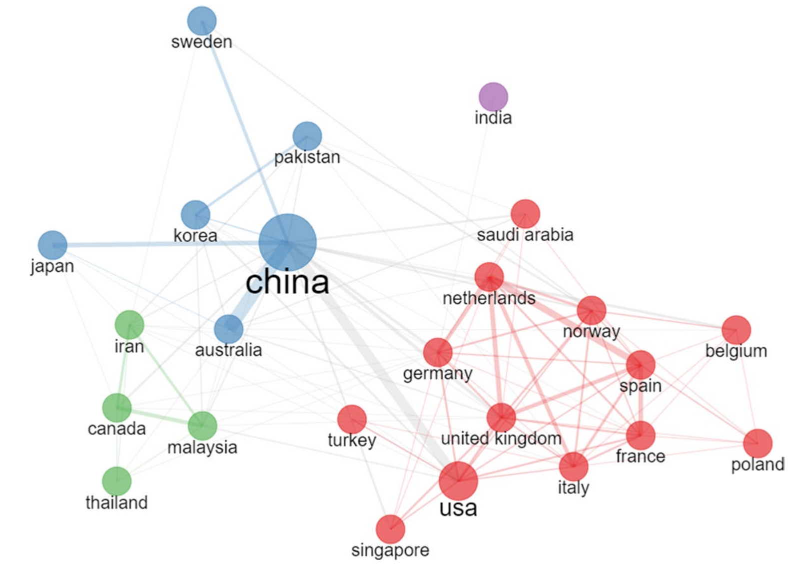

Fig. 31 Membrane, country collaboration map

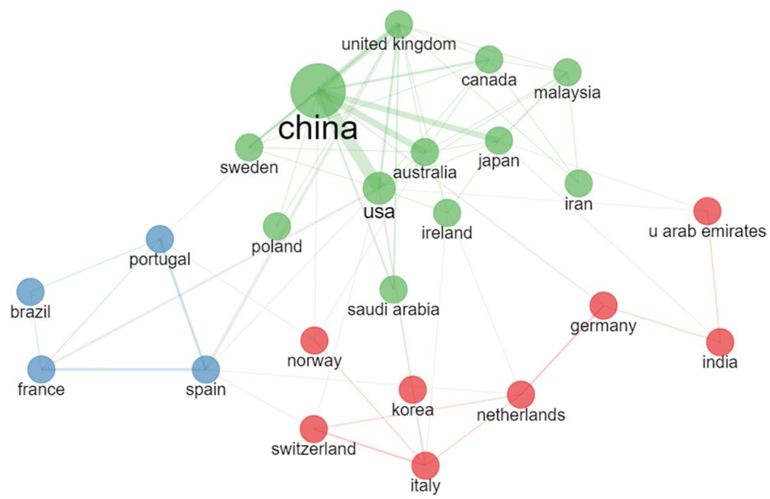

Fig. 32 Hybrid, country collaboration map

in Figs. 18, 19, 20 and 21, these statistics show China is the leading country in terms of carbon capture research. The United States of America (USA) came second in each table, with the remaining eight places in the top ten varying across various technologies. Figure 23 highlights this dominance from China, showing they account for 30% of the articles with the USA accounting for 13% leaving both combining for 43%, a sizable part.

While China and the USA both dominated production of articles, they dominated in the total number of citations received for the articles produced with China being on top with the USA second, for each technology category assessed as seen in (Figs. 24, 25, 26,27, and 28). The remaining eight out of the top tens were a mix of other countries. One interesting fact to note here is that Ireland and Singapore are the only countries that had not featured in the top ten of any productivity figures, but they made it into the top ten of the most cited membrane and hybrid countries Figs. 26 and 27, showing the quality of research stemming from these countries.

Global collaboration has a significant role in carbon capture technologies, as shown in Fig. 38. This international unity highlights the size of the issue, i.e., climate change, and it shows a global cooperation to find solutions

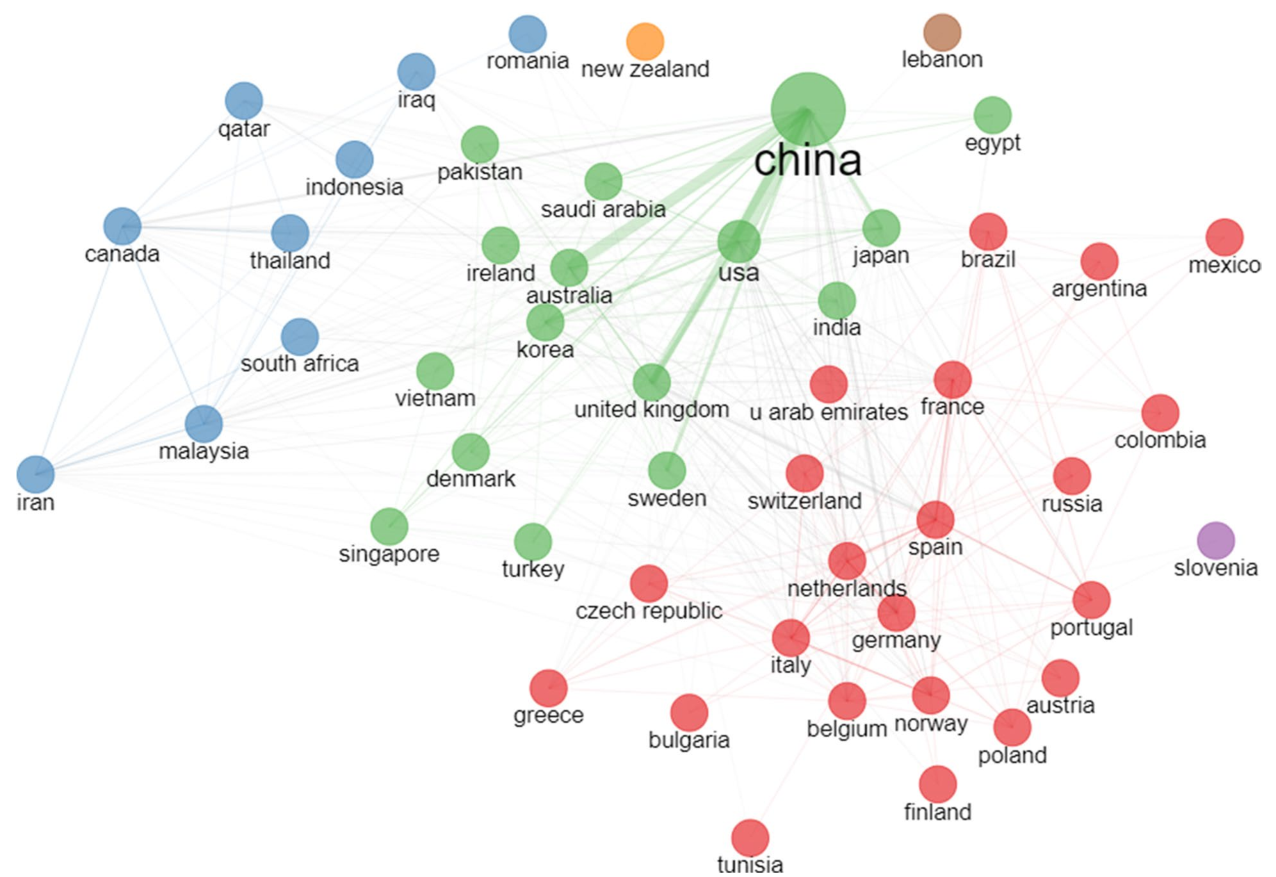

Fig. 33 Combined, country collaboration map

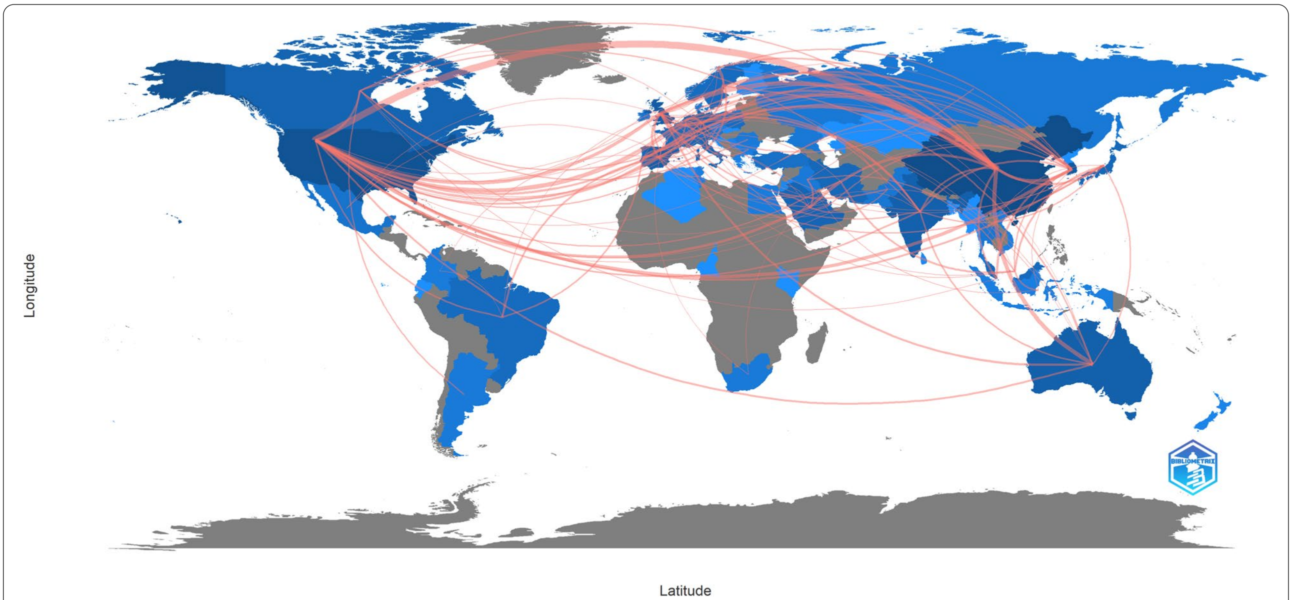

Fig. 34 Adsorbent, country collaboration map

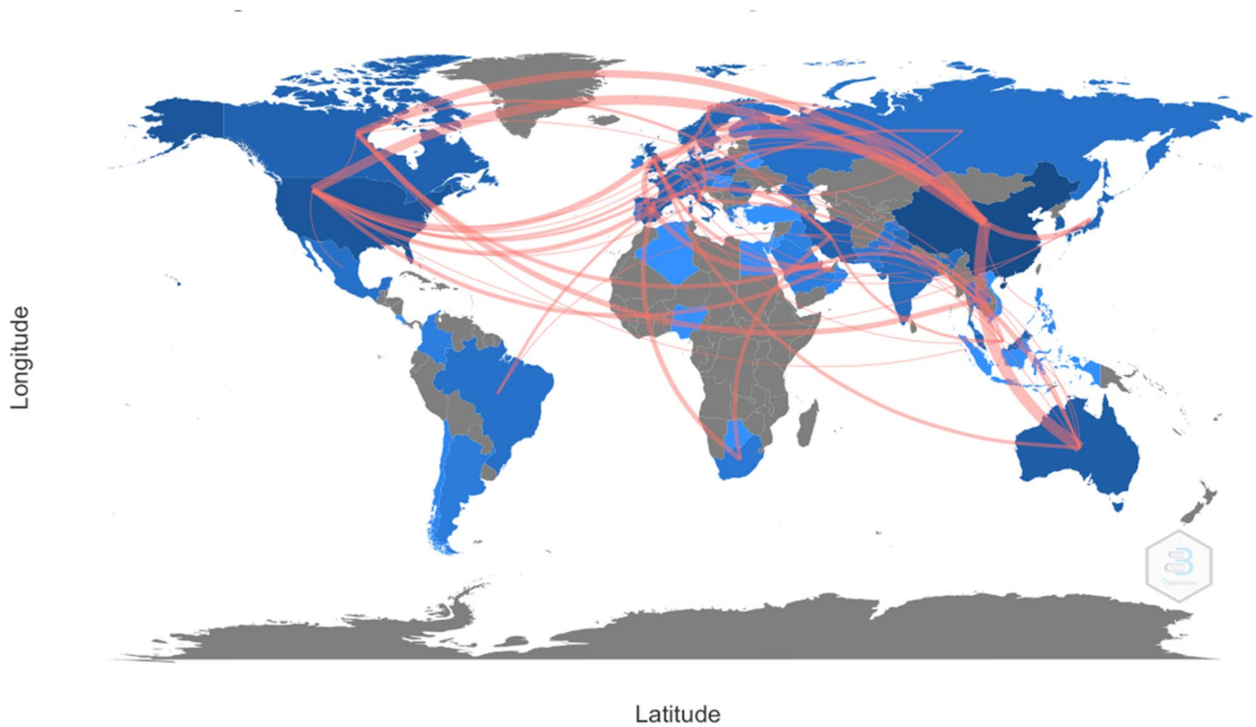

Fig. 35 Absorbent, country collaboration map

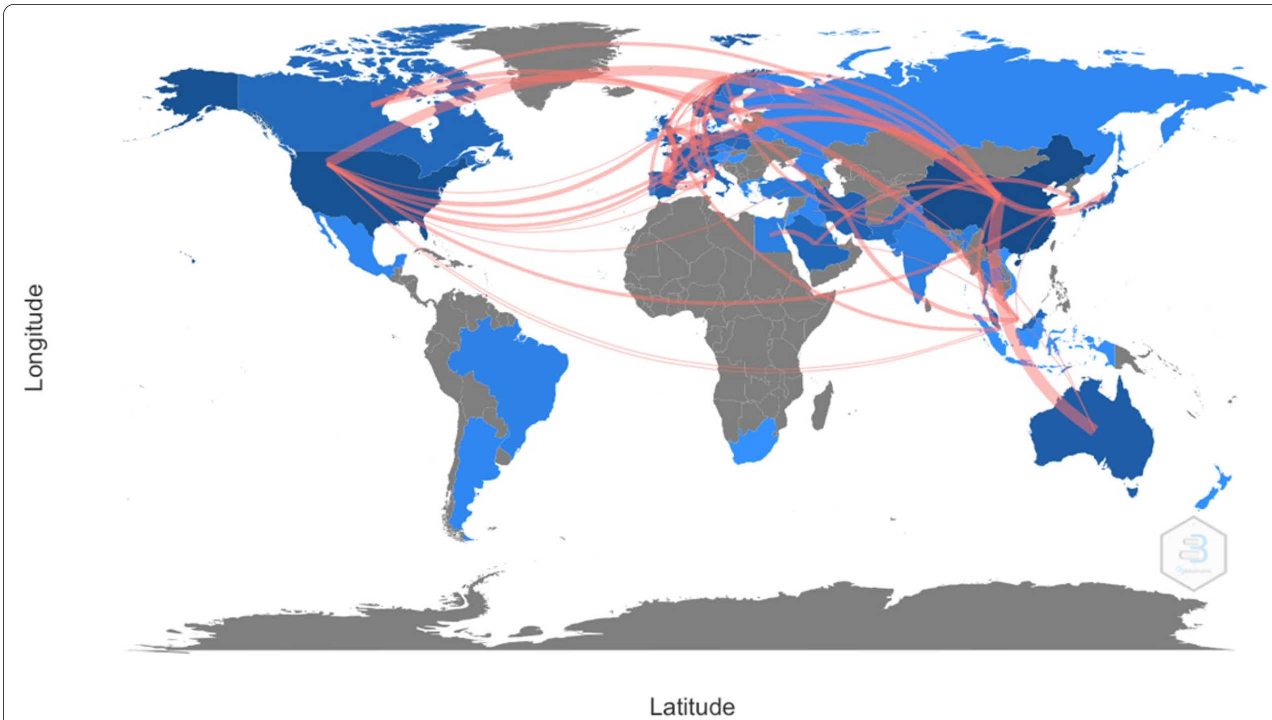

Fig. 36 Membrane, country collaboration map

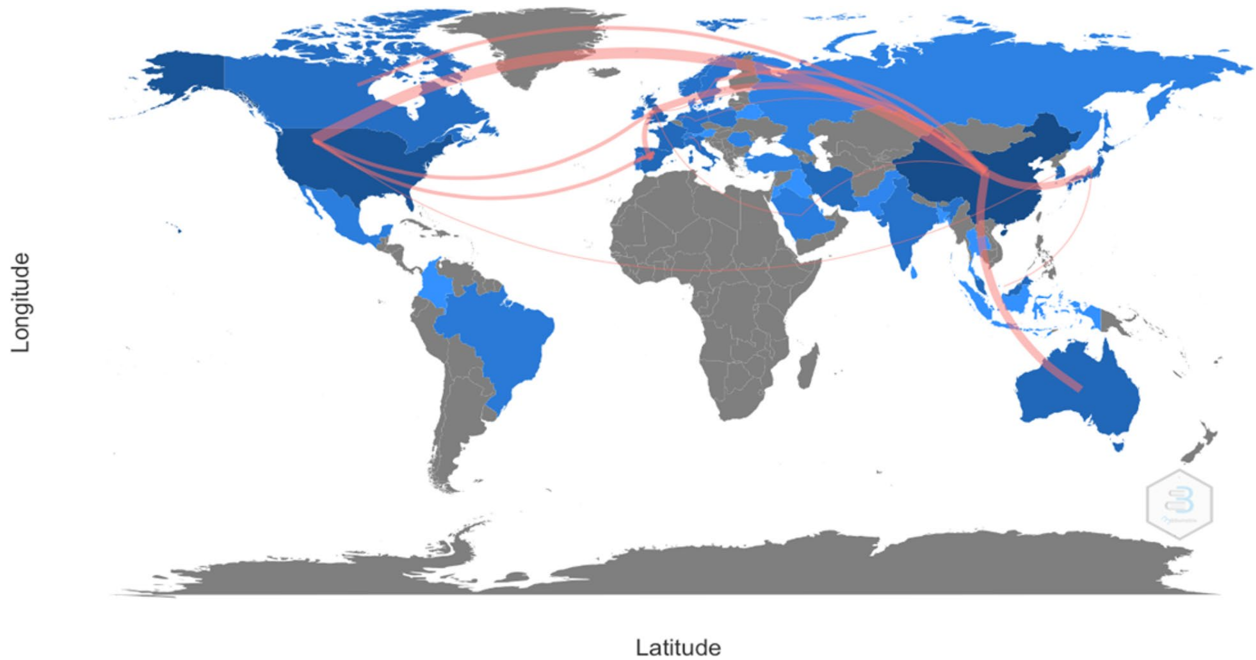

Fig. 37 Hybrid, country collaboration map

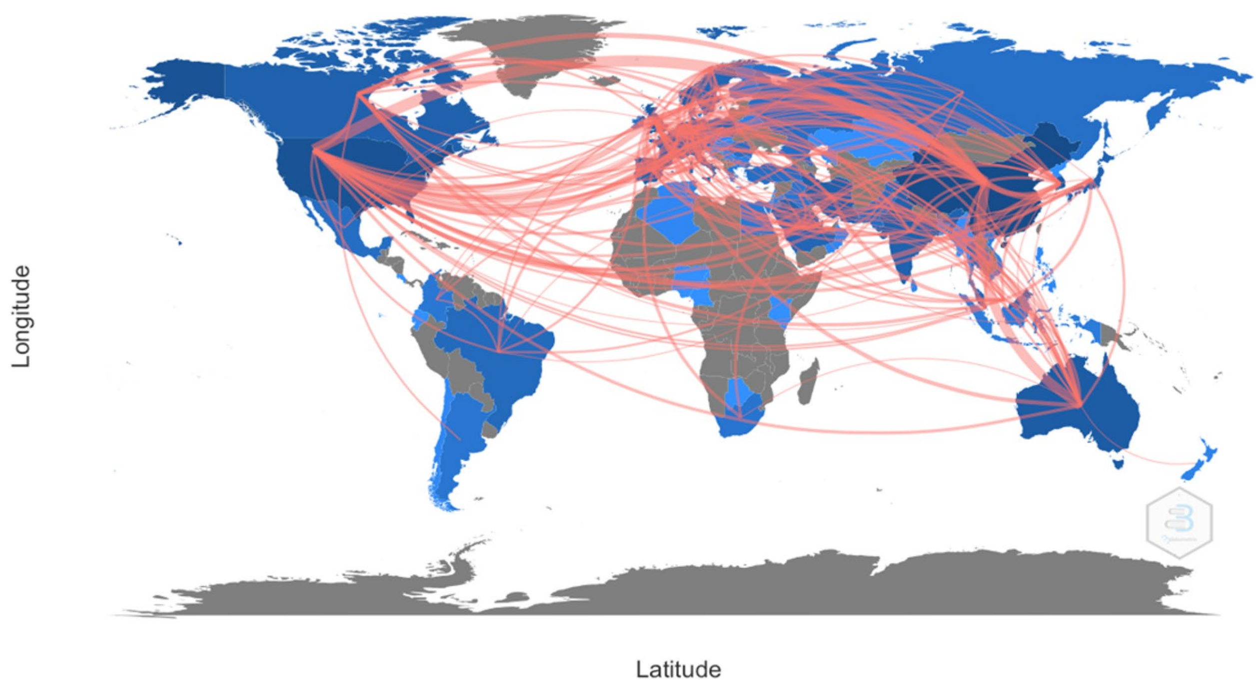

Fig. 38 Combined, country collaboration map

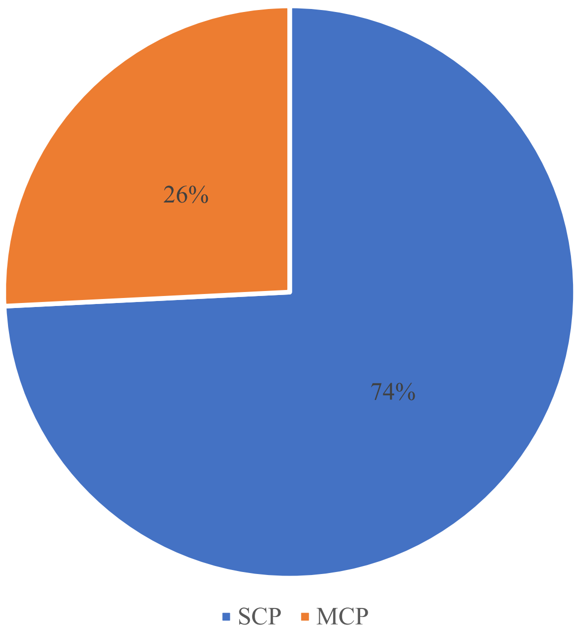

Fig. 39 Country authorship types

to this global crisis. Figures 29, 30, 31, 32, and 33 establishes country partnership networks based on the singular technologies and the combined data set. These images illustrate China's centrality to collaboration across each technology category. These figures depict the cross functional nature of carbon capture researchers. The cross continental cooperation shown in (Figs. 34, 35, 36, 37, and 38) highlights the magnitude of climate change and the technologies available to researchers to communicate and collaborate in this manner. Figure 39 shows the collaborative world of carbon capture, which shows that 26% of articles were multiple nationality authors.

3.7 Keyword/phrase analysis

Key phrase occurrences analysis employed two techniques, the first being single word occurrences from 'Keyword Plus' section of the article (Figs. 40, 41, 42, 43 and 44) and the second being groups of three words from the abstract (Figs. 45, 46, 47, 48 and 49) of the article.

For the first test (single word) each data sets returned similar words, e.g., 'capture', 'separation', 'carbon' etc. leading to no significant findings as seen in Fig. 40 through to Fig. 44. The paper used a second technique of using a trio of words for the abstract to further identify any trends in key phrases. This analysis shows that adsorption documents focused on both Temperature

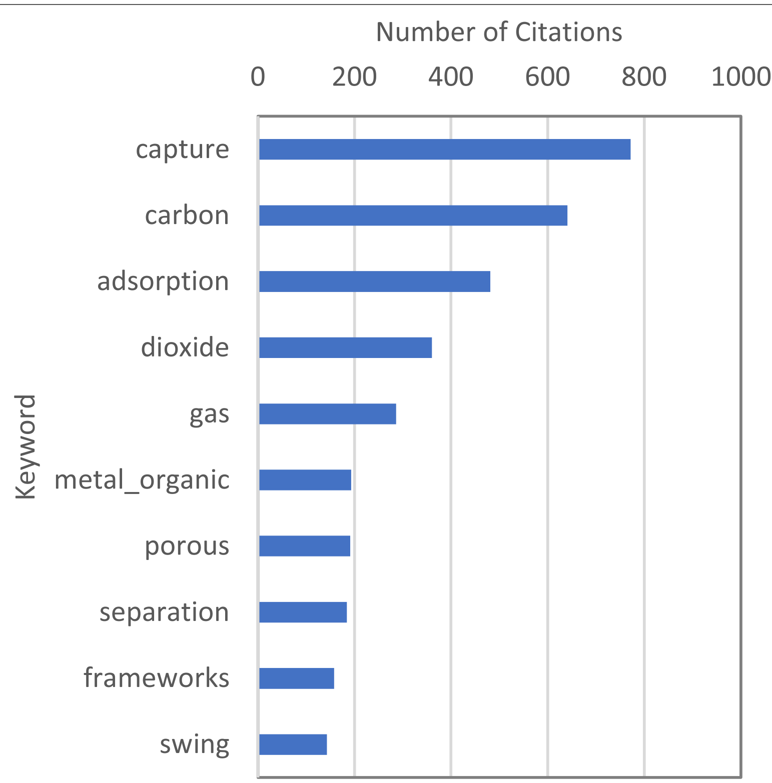

Fig. 40 Adsorbent, top keywords (keyword Plus)

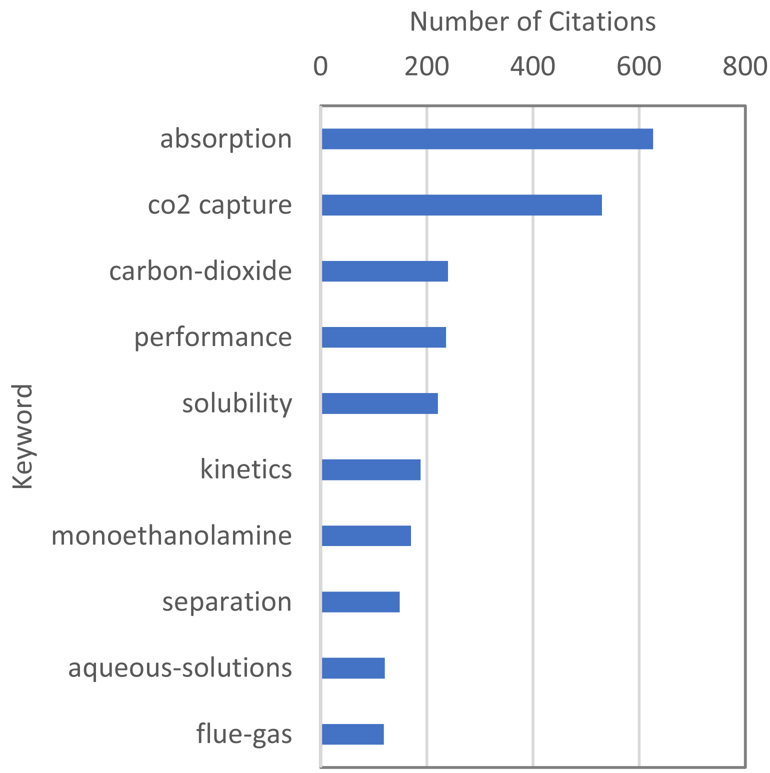

Fig. 41 Absorbent, top keywords (keyword Plus)

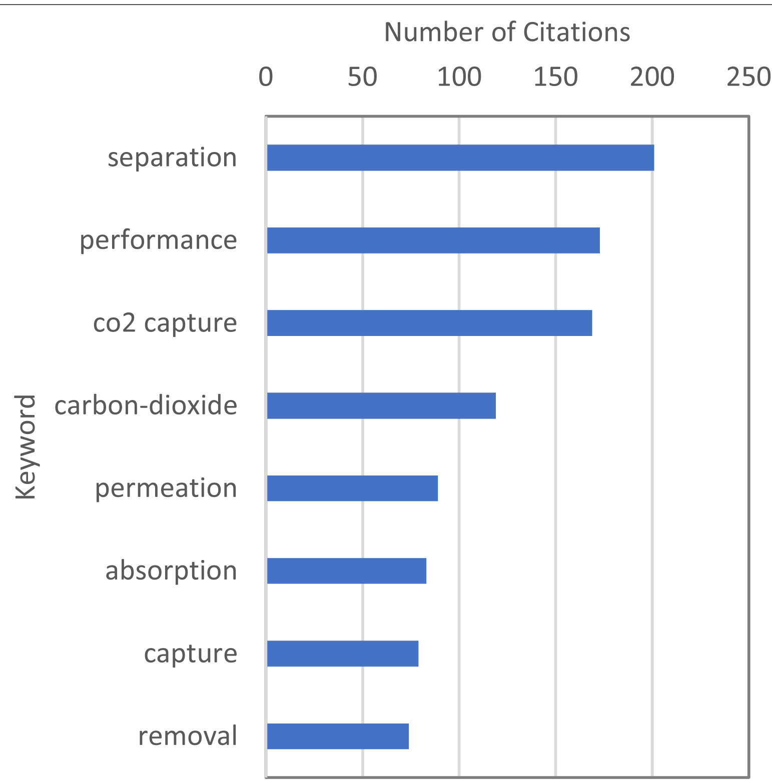

Fig. 42 Membrane, top keywords (keyword Plus)

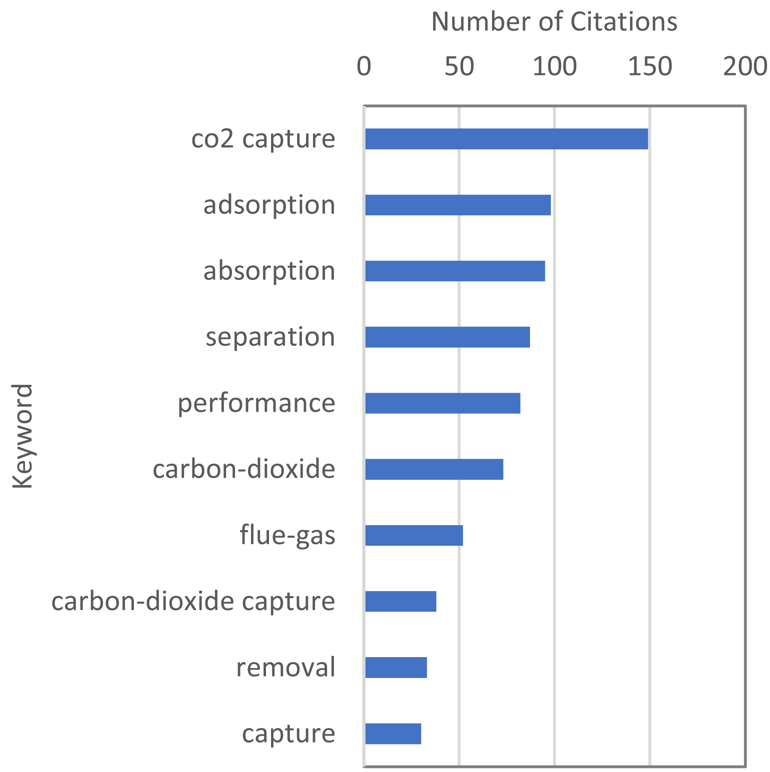

Fig. 43 Hybrid, top keywords (keyword Plus)

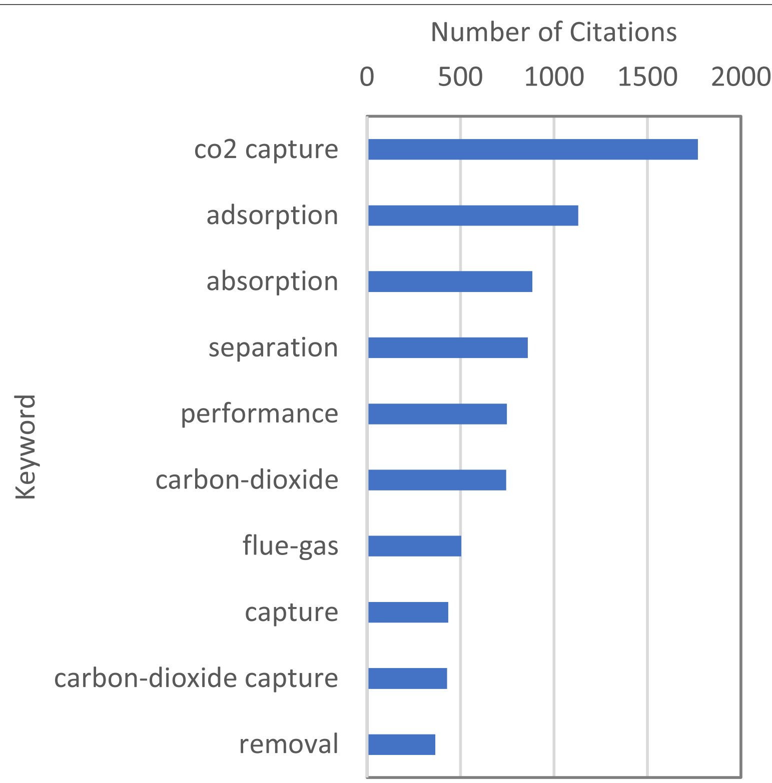

Fig. 44 Combined, top keywords (keyword Plus)

Swing Adsorption (TSA) and PSA systems, as shown in Fig. 45. This suggests that many studies used this technique while conducting their research. For absorption, the most common key phrase from Fig. 46 'mass transfer coefficient', suggests publications of theoretical based articles, or authors supplying calculations within their articles. 'Ionic liquids', another common absorption key phase, highlights the extensive research performed with these promising liquid solvent absorbents [38]. For the membranes, 'hollow fiber membrane', the most common key phrase, suggests this type of membrane is a promising configuration for membrane performance [44]. Within this category, 'mixed matrix membrane' proved to be common, an emerging technology within membrane carbon capture, which modifies membranes to increase the capture performance [10, 46]. For the hybrid technology keywords in Fig. 48 'hollow fiber membrane', the most common showing that many hybrid systems employed a membrane as one technology within the system, other common key phrases included ionic liquids which suggests that absorption systems have been a part of hybrid technologies, as they are common absorbents. Freeman et al. [16] and Bhattachatyya [7] have shown the effectiveness of hybrid systems employing hybrid membranes-absorption systems. 'Scanning electron microscopy', another key phrase is a common way to analyze and characterize materials hinting at novel materials within the hybrid technology [51].

3.7.1 Keyword co-occurrence

To find any other significant findings within the keywords, this study created a keyword co-occurrence network for each technology and the combined bibliometric data, shown in Figs. 50, 51, 52, 53 and 54.

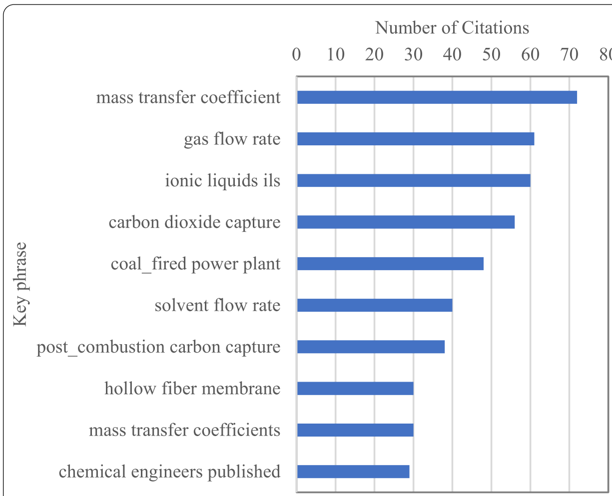

Fig. 46 Absorbent, top key phrases

As seen below Figs. 50, 51, 52 and 53 the most dominant keywords for each technology were 'CO2 Capture' and a word associated with the technology, e.g. 'adsorption' or 'absorption' etc. Figure 53 is the most significant figure being the co-occurrence network of the hybrid carbon capture articles. As seen here, 'absorption' and 'adsorption' appear the most linked keywords, no other technology-based keywords were significant, suggesting that absorption and adsorption systems dominate hybrid separation systems. 'flue-gas' is another common co-occurrence seen in Fig. 53, which shows that hybrid systems work on

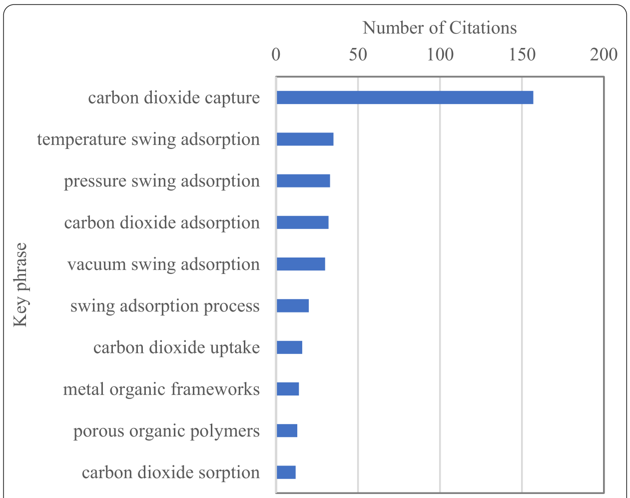

Fig. 45 Adsorbent, top key phrases

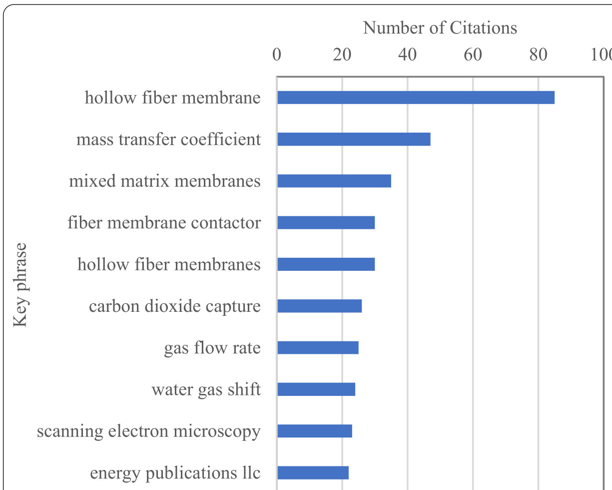

Fig. 47 Membrane, top key phrases

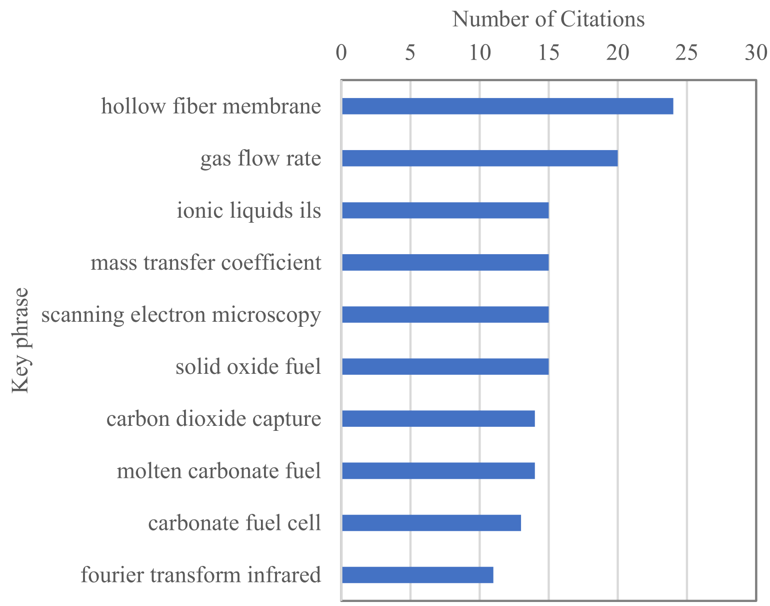

Fig. 48 Hybrid, top key phrases

post combustion technologies. 'Performance' was a prominent keyword within the combined keyword co-occurrence network as shown in Fig. 54, 'separation' was another dominant word here showing that many papers may have focused on separation performance of equipment/processes, again highlighting that results in this field are quantifiable.

4 Conclusion

There is a large quantity of research conducted surrounding carbon capture, as shown from the productivity graphs developed with adsorbent technologies leading the way in terms of quantity, in both articles and citations. This high productivity includes high-quality papers with the top five overall journals displaying high H-index, G-index, and M-index, each category

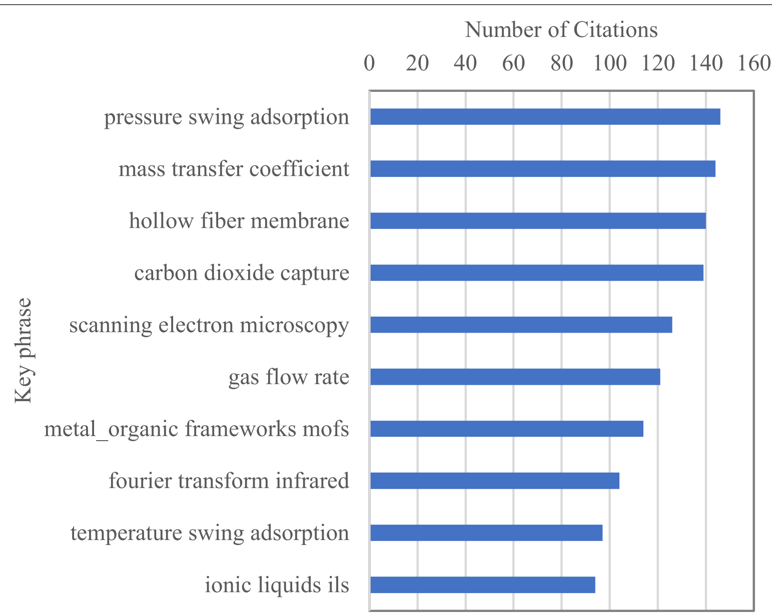

Fig. 49 Combined, top key phrases

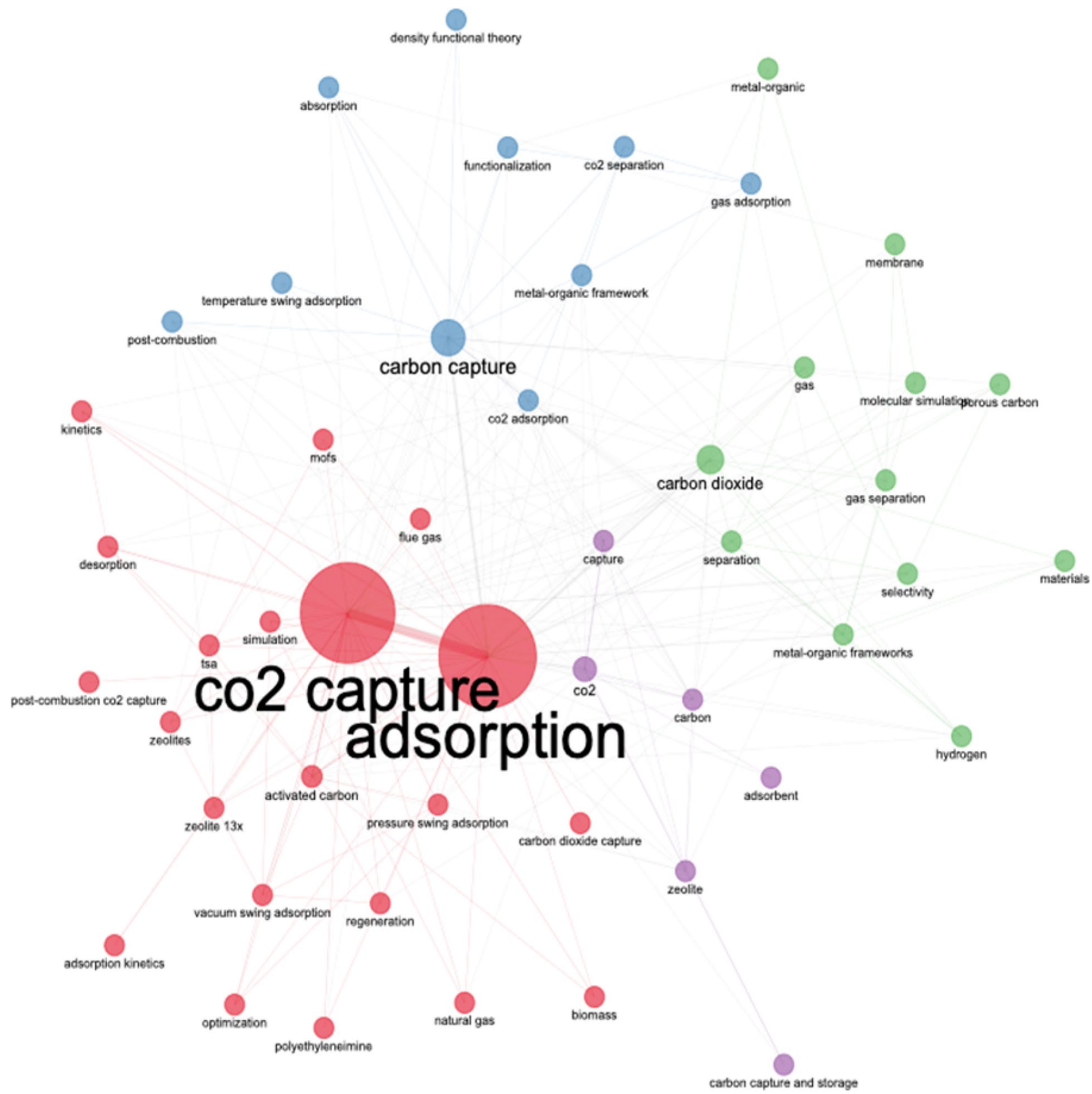

Fig. 50 Adsorbent, keyword co-network

scoring over one highlighting successful research. High quantities of citations, again, show the high-quality articles published within the bibliometric data.

China is the leading country in terms of scientific production and citations received. China is the top producer of articles, but global collaboration within the field shows the danger of the issue at hand and the need for solutions.

Within hybrid capture systems, both adsorption and absorption were common keywords. However, there were indications of membranes in these systems, with 'hollow fiber membrane' being the most common key phrase for the hybrid data. This specific category of technologies has the lowest documents per author, which highlight the number of researchers investigating hybrid systems.

This paper highlights bibliometric analysis's utility, highlighting the ease of performing a quantitative analysis of a specific research field and, in this case, giving an insight into the field of carbon capture.

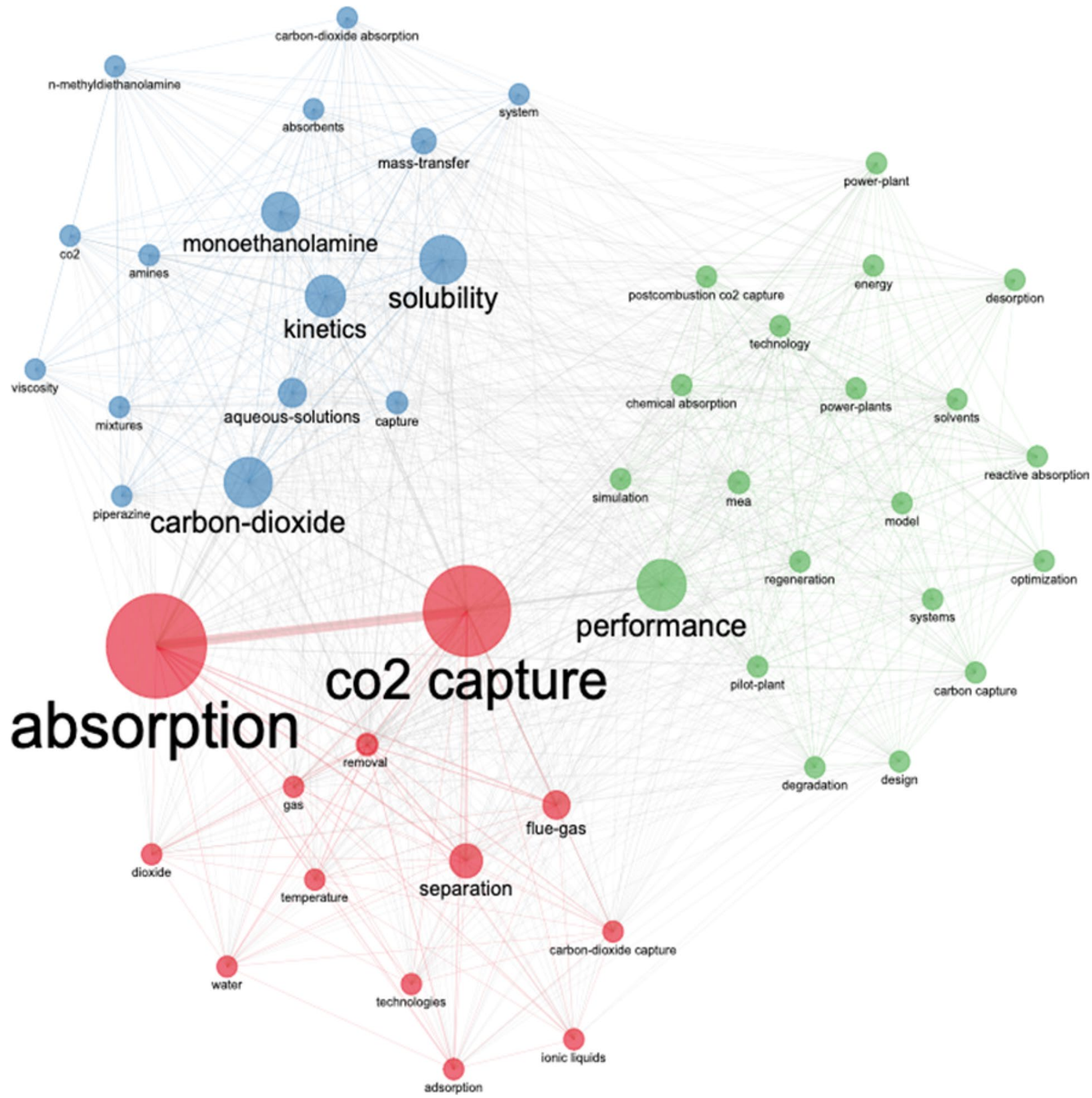

Fig. 51 Absorbent, keyword co-network

4.1 Future prospects

The removal of CO_2 from our atmosphere is a key task in our fight against climate change. This article quantitatively assessed carbon capture technologies based on research article production using a bibliometric analysis. Future developments in this area could include continual research and funding into this hot topic and the development of a database to perform a qualitative analysis of the topic. Quantitatively, hybrid capture systems appear to be trending and investments in these technologies may aid in our climate change struggles. Research into the individual technologies is also required to allow more developed and mature technologies be employed in the hybrid systems.

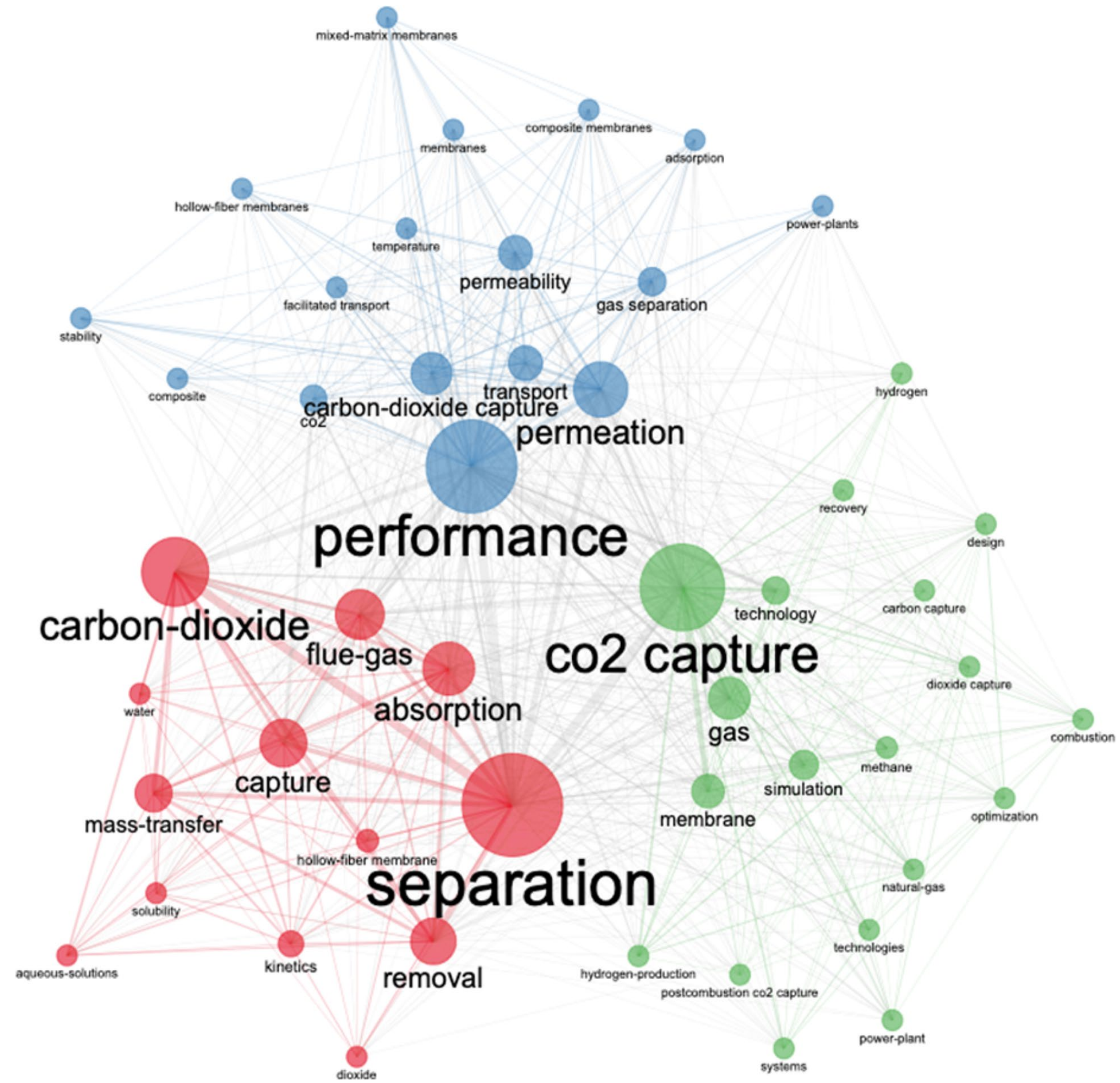

Fig. 52 Membrane, keyword co-network

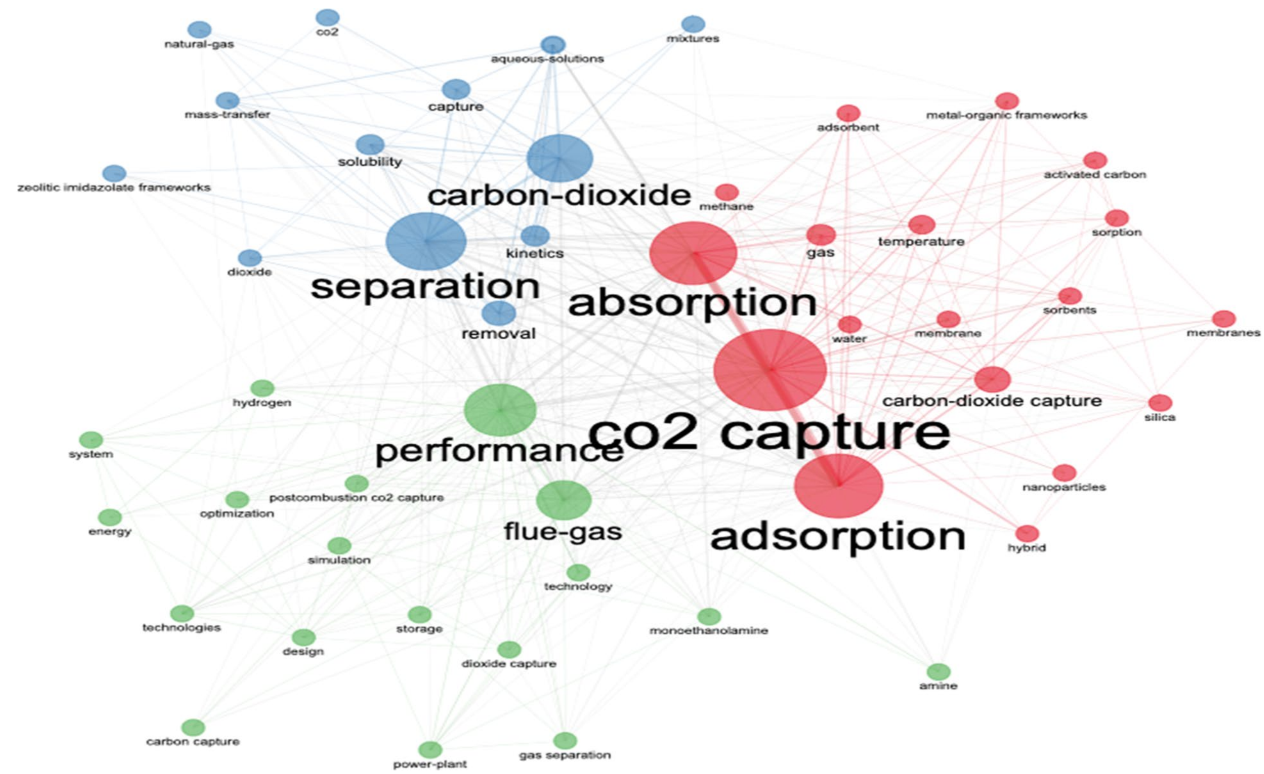

Fig. 53 Hybrid, keyword co-network

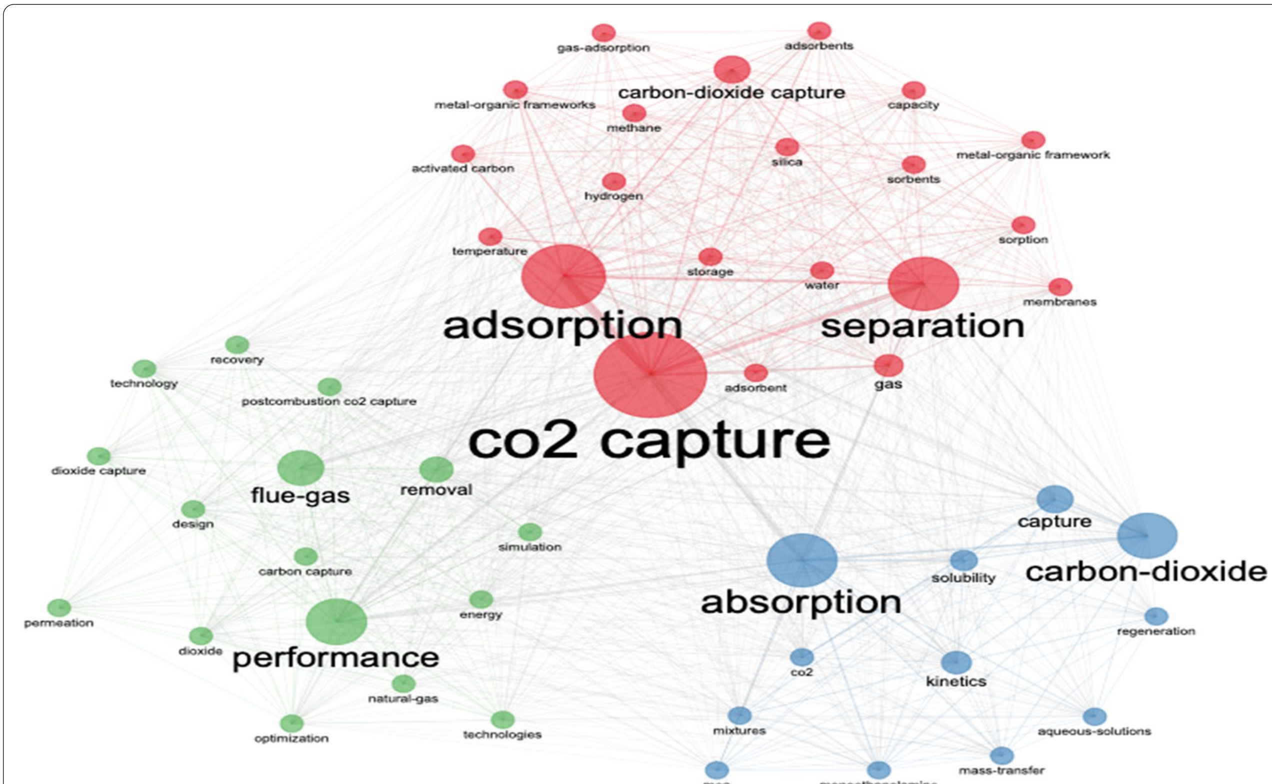

Fig. 54 Combined, keyword co-network

Abbreviations

CO_2: Carbon Dioxide; IR: Infrared; GHG: Greenhouse gas; N_2: Nitrogen; DAC: Direct Air Capture; KP: Keyword Plus; TI: Title; AK: Author Keyword; SCP: Single Country Publication; MCP: Multi Country Publication; USA: United States of America; TSA: Temperature Swing Adsorption; PSA: Pressure Swing Adsorption.

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N/A.

Authors' contributions

SR collected the bibliometric data and applied the R software code to the data. SR and ET prepared the manuscript. All authors read and approve the final manuscript.

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Availability of data and materials

Data can be made available upon request.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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References

1. Adsorption Journal of the International Adsorption Society, n.d. . Springer. [WWW Document]. URL https://www.springer.com/journal/10450. Accessed 12 Mar 2021
2. Andreoli E, Dillon EP, Cullum L, Alemany LB, Barron AR (2014) Cross-linking amine-rich compounds into high performing selective CO2 absorbents. Sci Rep 4. https://doi.org/10.1038/srep07304
3. Anyanwu JT, Wang Y, Yang RT (2020) Amine-grafted silica gels for CO2 capture including direct air capture. Ind Eng Chem Res 59:7072–7079. https://doi.org/10.1021/acs.iecr.9b05228
4. Applied Materials and Interfaces, n.d. . ACS publications. [WWW Document]. URL https://pubs.acs.org/page/aamick/about.html. Accessed 12 Feb 2021
5. Aria M, Cuccurullo C (2017) Bibliometrix: an R-tool for comprehensive science mapping analysis. J Inf Secur 11:959–975. https://doi.org/10.1016/j.joi.2017.08.007
6. Barnard P, Moomaw WR, Fioramonti L, Laurance WF, Mahmoud MI, O'Sullivan J, Rapley CG, Rees WE, Rhodes CJ, Ripple WJ, Semiletov IP, Talberth J, Tucker C, Wysham D, Ziervogel G (2021) World scientists' warnings into action, local to global. Sci Prog 104:003685042110562. https://doi.org/10.1177/00368504211056290
7. Bhattacharyya D (2022) Design and optimization of hybrid membrane–solvent-processes for post-combustion CO2 capture. Curr Opin Chem Eng. https://doi.org/10.1016/j.coche.2021.100768
8. Castel C, Bounaceur R, Favre E (2021) Membrane processes for direct carbon dioxide capture from air: possibilities and limitations. Front Chem Eng 3. https://doi.org/10.3389/fceng.2021.668867
9. Chemical Engineering Journal. n.d.. Elsevier. [WWW Document], URL https://www.journals.elsevier.com/chemical-engineering-journal. Accessed 12 Feb 2021
10. Chen G, Wang T, Zhang G, Liu G, Jin W (2022) Membrane materials targeting carbon capture and utilization. Advanced Membranes 2:100025. https://doi.org/10.1016/j.advmem.2022.100025
11. Climate change. n.d. . Encyclopædia Britannica. [WWW Document], URL https://academic-eb-com.ucc.idm.oclc.org/levels/collegiate/article/climate-change/384741. Accessed 12 Feb 2021
12. Egghe L (2006) Theory and practise of the g-index, Dordrecht Scientometrics. Springer. vol. 69, pages 131–152. https://doi.org/10.1007/s11192-006-0144-7
13. European Academies Science Advisory Council, n.d. Negative emission technologies: what role in meeting Paris Agreement targets?
14. Fatima SS, Borhan A, Ayoub M, Abd Ghani N (2021) Development and progress of functionalized silica-based adsorbents for CO2 capture. J Mol Liq. https://doi.org/10.1016/j.molliq.2021.116913
15. Font-Palma C, Cann D, Udemu C (2021) Review of cryogenic carbon capture innovations and their potential applications. C (Basel) 7:58. https://doi.org/10.3390/c7030058
16. Freeman B, Hao P, Baker R, Kniep J, Chen E, Ding J, Zhang Y, Rochelle GT (2014) Hybrid membrane-absorption CO2 capture process, in: Energy Procedia 63. Elsevier Ltd, pp 605–613. https://doi.org/10.1016/j.egypro.2014.11.065
17. Friedman A (2015) The power of Lotka's law through the eyes of R
18. Greenhouse gas, n.d. . Encyclopædia Britannica. [WWW Document] URL https://academic-eb-com.ucc.idm.oclc.org/levels/collegiate/article/greenhouse-gas/473968. Accessed 12 Feb 2021
19. Han Y, Ho WSW (2020) Design of Amine-Containing CO2-selective membrane process for carbon capture from flue gas. Ind Eng Chem Res 59:5340–5350. https://doi.org/10.1021/acs.iecr.9b04839
20. Hasheminasab H, Hashemkhani Zolfani S, Kazimieras Zavadskas E, Kharrazi M, Skare M (2021) A circular economy model for fossil fuel sustainable decisions based on MADM techniques. Econ Res Ekonomska Istrazivanja. https://doi.org/10.1080/1331677X.2021.1926305
21. He X (2018) A review of material development in the field of carbon capture and the application of membrane-based processes in power plants and energy-intensive industries. Energy Sustain Soc. https://doi.org/10.1186/s13705-018-0177-9
22. Hersher R (2020) 2020 may be the hottest year on record. Here's The Damage It Did,NPR. https://www.npr.org/2020/12/18/943219856/2020-may-be-the-hottest-year-on-record-heres-the-damage-it-did. Accessed 28 Nov 2022
23. Heyck-Williams S (2019) Climate change, natural disasters, and wildlife
24. Hirsch JE (2005) An index to quantify an individual's scientific research output
25. I&EC Research, n.d. . ACS publications [WWW Document]. URL https://pubs.acs.org/journal/iecred. Accessed 12 Feb 2021
26. Ida JI, Lin YS (2003) Mechanism of high-temperature CO2 sorption on lithium zirconate. Environ Sci Technol 37:1999–2004. https://doi.org/10.1021/es0259032
27. Idryma Technologias Kai Erevnas, 2013. Hybrid membrane - pressure swing adsorption (PSA) hydrogen Purification systems
28. International Journal of Greenhouse Gas Control, n.d. . Science direct. [WWW Document] URL https://www.sciencedirect.com/journal/international-journal-of-greenhouse-gas-control. Accessed 12 Feb 2021
29. Jaschik M, Tanczyk M, Jaschik J, Janusz-Cygan A (2020) The performance of a hybrid VSA-membrane process for the capture of CO2 from flue gas. Int J Greenhouse Gas Control 97. https://doi.org/10.1016/j.ijggc.2020.103037
30. Khalilpour R, Mumford K, Zhai H, Abbas A, Stevens G, Rubin ES (2015) Membrane-based carbon capture from flue gas: a review. J Clean Prod. https://doi.org/10.1016/j.jclepro.2014.10.050
31. Lee SY, Park SJ (2015) A review on solid adsorbents for carbon dioxide capture. J Ind Eng Chem. https://doi.org/10.1016/j.jiec.2014.09.001
32. Li J, Hou Y, Wang P, Yang B (2019) A review of carbon capture and storage project investment and operational decision-making based on bibliometrics. Energies (Basel) 12. https://doi.org/10.3390/en12010023
33. Lindsey, R., Dahlman, L., 2021. Climate Change: Global Temperature. [WWW Document] Climate.gov. URL https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature. Accessed 10 July 2021
34. Lotka AJ (1926) The frequency distribution of scientific productivity. J Wash Acad Sci 16:317–323
35. Masters J, Nuccitelli D (2020) The top 10 extreme weather and climate events of 2020 [WWW document]. EcoWatch URL https://www.ecowatch.com/extreme-weather-climate-2020-2649628910.html. Accessed 10 July 2021
36. Naseer MN, Zaidi AA, Dutta K, Wahab YA, Jaafar J, Nusrat R, Ullah I, Kim B (2022) Past, present and future of materials' applications for CO2 capture:

a bibliometric analysis. Energy Rep 8:4252–4264. https://doi.org/10.1016/j.egyr.2022.02.301
37. Nuccitelli D (2017) We're now breaking global temperature records once every three years. The Guardian https://www.theguardian.com/environment/climate-consensus-97-per-cent/2017/jan/23/were-now-breaking-global-temperature-records-once-every-three-years. Accessed 28 Nov 2022
38. Ochedi FO, Yu J, Yu H, Liu Y, Hussain A (2021) Carbon dioxide capture using liquid absorption methods: a review. Environ Chem Lett. https://doi.org/10.1007/s10311-020-01093-8
39. Omoregbe O, Mustapha AN, Steinberger-Wilckens R, El-Kharouf A, Onyeaka H (2020a) Carbon capture technologies for climate change mitigation: a bibliometric analysis of the scientific discourse during 1998–2018. Energy Rep 6:1200–1212. https://doi.org/10.1016/j.egyr.2020.05.003
40. Osman AI, Hefny M, Abdel Maksoud MIA, Elgarahy AM, Rooney DW (2021a) Recent advances in carbon capture storage and utilisation technologies: a review. Environ Chem Lett. https://doi.org/10.1007/s10311-020-01133-3
41. Rackley SA (2010) Membrane separation systems, in: carbon capture and storage. Elsevier, pp 159–194. https://doi.org/10.1016/b978-1-85617-636-1.00008-0
42. Raganati F, Miccio F, Ammendola P (2021) Adsorption of carbon dioxide for post-combustion capture: a review. Energy Fuels 35:12845–12868. https://doi.org/10.1021/acs.energyfuels.1c01618
43. Riboldi L, Bolland O (2017) Overview on pressure swing adsorption (PSA) as CO2 capture technology: state-of-the-art, limits and potentials, in: Energy Procedia. Elsevier Ltd, pp 2390–2400. https://doi.org/10.1016/j.egypro.2017.03.1385
44. Sanni ES, Sadiku ER, Okoro EE (2021) Novel systems and membrane technologies for carbon capture. Int J Chem Eng. https://doi.org/10.1155/2021/6642906
45. Sanz-Pérez ES, Murdock CR, Didas SA, Jones CW (2016) Direct capture of CO2 from ambient air. Chem Rev. https://doi.org/10.1021/acs.chemrev.6b00173
46. Shen Y, Wang H, Liu J, Zhang Y (2015) Enhanced performance of a novel polyvinyl amine/chitosan/Graphene oxide mixed matrix membrane for CO2 capture. ACS Sustain Chem Eng 3:1819–1829. https://doi.org/10.1021/acssuschemeng.5b00409
47. Stylianou N, Guibourg C (2019) Hundreds of temperature records broken over summer. BBC News https://www.bbc.com/news/science-environment-49753680. Accessed 28 Nov 2022
48. Theo WL, Lim JS, Hashim H, Mustaffa AA, Ho WS (2016) Review of pre-combustion capture and ionic liquid in carbon capture and storage. Appl Energy. https://doi.org/10.1016/j.apenergy.2016.09.103
49. Unfccc, n.d.. Adoption of the paris agreement - Paris agreement text english
50. Varghese AM, Karanikolos GN (2020) CO2 capture adsorbents functionalized by amine – bearing polymers: a review. Int J Greenhouse Gas Control. https://doi.org/10.1016/j.ijggc.2020.103005
51. Vernon-Parry, K.D., n.d. Scanning Electron microscopy: an introduction
52. Viebahn P, Chappin EJL (2018) Scrutinising the gap between the expected and actual deployment of carbon capture and storage - a bibliometric analysis. Energies (Basel) 11. https://doi.org/10.3390/en11092319
53. Wang Y, Zhao L, Otto A, Robinius M, Stolten D (2017) A review of post-combustion CO2 capture technologies from coal-fired power plants, in: Energy Procedia. Elsevier Ltd, pp 650–665. https://doi.org/10.1016/j.egypro.2017.03.1209
54. Warmuzinski K, Tanczyk M, Jaschik M, Janusz-Cygan A (2013) A hybrid separation process for the recovery of carbon dioxide from flue gases, in: Energy Procedia 37. Elsevier Ltd, pp 2154–2163. https://doi.org/10.1016/j.egypro.2013.06.094
55. Yadav S, Mondal SS (2022) A review on the progress and prospects of oxy-fuel carbon capture and sequestration (CCS) technology. Fuel. https://doi.org/10.1016/j.fuel.2021.122057
56. Yue MB, Sun LB, Cao Y, Wang Y, Wang ZJ, Zhu JH (2008) Efficient CO2 capturer derived from as-synthesized MCM-41 modified with amine. Chem Eur J 14:3442–3451. https://doi.org/10.1002/chem.200701467

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