Underground Carbon Dioxide Sequestration for Climate Change Mitigation - A Scientometric Study

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Abstract

In this study, a scientometric comprehensive analysis has been executed in order to explore the scientific situation of research efforts performed previously with regard underground CO_2 sequestration and encapsulation. To this end, a total of 1280 bibliographic records from the Web of Science (WoS) database were extracted and analysed to report the analysis of scientific state of the authors, journals, countries, and categories. Eventually, geospatial maps of the progress in this field are created and presented. As per the results obtained, efforts on this subject have been initiated significantly since 1990s. Scientific articles and proceeding papers share nearly 63% and 31% of the documents published. The results indicate that USA and China are the most contributing countries. Among the active journals, international journal of greenhouse gas control impact is the most active journal. It may be concluded that no highly active research group has yet been emerged. Hence, more supports and scientific efforts are needed to promote carbon dioxide capture and storage technologies.

Keywords: Scientometric study, CO_2 underground storage, carbon dioxide reservoir, CO_2 sequestration.

1. Introduction

Due to rapid industrialization occurred in the nineteenth century, energy demand has increased enormously [1,2], resulting in a large quantity of CO_2 exhausted from different sources into the atmosphere. The critical problem of uncontrollable CO_2 emission has recently received a huge attention since it is being considered as one of the most effective factors promoting the climate change and global warming [3]. Hence, there is an urgent need for an immediate planning regarding the combination of energy resources

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to provide technologies producing less amounts of greenhouse gases (GHG), facilitating the management of CO_2 emission [4–9]. Although many investments have been placed in renewable energy sources, fossil fuels and especially coal still play the key roles in the production of energy. It is predicted that in the near future, the amount of coal required to produce energy may even rise, despite the fact that application of coal is considered as one of the main sources of environmental pollution, which its ongoing consumption may directly affect the augmentation of CO_2 concentration in the atmosphere [10]. According to the European Commission, it is predicted that by 2050, the CO_2 emission concentration will be extremely high unless considerable modification is imposed on the current trends. In this regard, some strategies have been introduced and implemented to reduce the amount of carbon emitted into the atmosphere. Promoting renewable energy sources, CO_2 capture and storage, and developing smart energy networks are among the strategies to provide both high energy efficiency and environmental conservation [4]. Considering that energy provision appears to continue relying on fossil fuels, the amount of CO_2 concentration in the atmosphere will continue to increase. Therefore, CO_2 capture and storage can be considered an opportunity to achieve a huge reduction in the amount of released carbon dioxide [11]. In this regard, simultaneous application of CO_2 capture and storage technologies with power generation processes may also be considered as a sustainable way to reduce CO_2 emission [1,4,12].

Underground CO_2 capture and storage (UCCS) is performed by capturing pure CO_2 from large stationary sources and waste streams of facilities such as plants operating by utilization of natural gas and oil and also electricity generation plants, and afterwards, transporting the CO_2 to the disposal site located underground in stable geological formations such as wells, coal beds, and aquifers [11,13]. However, the implementation of UCCS may face some difficulties. For instance, some restricted rules should be considered for a careful selection of UCCS sites due to the existing potential risks of the underground CO_2 storage. In order to govern and solve such issues, it is necessary to implement solutions that can meet the safety standards [12].

In this study, scientometric analysis on the application of UCCS technologies was performed in order to equip the relevant industrial and academic parties with a deep insight about relevant research fields and attractive topics in the concerned area. Wider application of carbon capturing process, as one of the most efficient and economic technologies to deal with the environmental problems such as global warming, requires exploring the literature to map science history, active bodies, current applicable technologies, the impact of produced science, and also the future outlook. Hence, after nearly 30 years of scientific efforts to develop CO_2 capturing and underground storage, the present scientometric study is undertaken on the related literature to push the investigations in this field towards decreasing the harmful effects of greenhouse gases globally. To our best knowledge, the present manuscript is the first report on the utilization of scientometric study on the underground carbon storage subject.

2. Historical background

UCCS is one of the most crucial developments to capture CO_2 since 1970 [14]. Previously, innumerable efforts have been made to decrease the potential destructive effects of GHG (such as CO_2), which are considered to be highly responsible for the occurrences of various environmental problems such as global climate change, which was firstly noticed in 1824 by Joseph Fourier, who was focused on extensive greenhouse effect on the Earth's climate [15]. Since the 1970s, a number of underground CO_2 storage facilities have been implemented such as deep geological formations, deep ocean water (ocean storage) and mineral carbonates storage [16]. In a practical perspective, the first underground CO_2 storage was employed in west Texas in 1972 by injection of CO_2 into an oil field. Terrel© gas processing plant in Texas is another underground CO_2 storage facility developed during the early 1970s [17]. In 1982, Koch Nitrogen Company Enid Fertilizer© plant transfer CO_2 to oil reservoirs [18]. Offshore sandstone CO_2 storage backs to 1990s in Norway. For instance, Sleipner CO_2 Storage Facility© offshore of Norway, as the first geologic storage received 0.85×10^6 tons of CO_2 annually [19].

Many other facilities by industries have been developed on the capture and storage of CO_2. For instance, in Abu Dhabi, Emirates, a CO_2 capture technology was initiated in 2016 [19]. In 2017, CO_2 storage was initiated in deep saline from ethanol production by Archer Daniels Midland© in 2017 with an ability of annual storage of 1.1×10^6 tons of CO_2 [20]. Among all the utilized facilities, deep saline aquifers and oil fields have attracted much attention due to high volume of space available in saline aquifers and also high density and high soluble CO_2 in water existing in deeper aquifers [21]. Figure 1 shows the used under construction and under planning CO_2 storage facilities around the world.

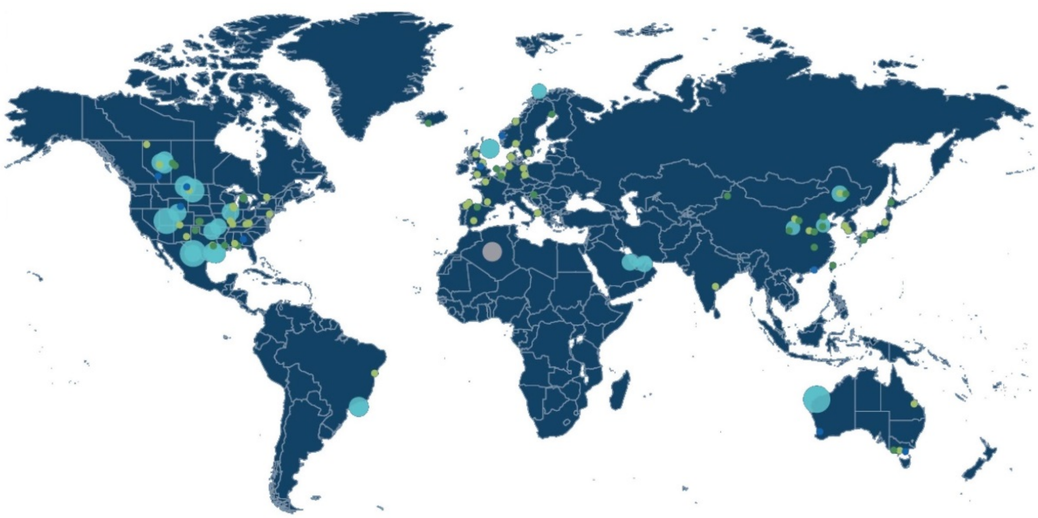

Fig. 1.
A global map presenting establishments and provisions of CO_2 underground storage have been constructing till 2018 [20].
Indicator of massive platforms under development Large-scale facility in operation or under construction.
Indicator of finished massive projects Large-scale facility completed.
Indicator of moderate platforms under development Smaller-scale facility in operation.
Indicator of finished moderate projects Smaller-scale facility completed.
Test centre = 1 million tonnes per annum of CO_2 (area of circles).

A brief review of the historical background of CO_2 storage facilities demonstrates their efficiency to capture atmospheric CO_2 and to deal with the associated global problems. In this regard, a critical discussion on studies performed hitherto and the opportunities of development in this area have considerably pushed the technology rapidly for commercialization. The execution of a bibliometric analysis in this area may therefore be useful to pave the road to achieve the objectives. However, to the best of our knowledge, scientometric study on the application of underground CO_2 capture has not been attempted. Due to increasing use of fossil fuels, the amount of CO_2 emitted from various activities has risen considerably, causing the global temperatures to rise. In order to stop significant increase of global temperature and climate change, the amount of CO_2 should be exported from the environment [22].

3. Methodology

In this study, all research publications from 1990 to 2018 (29 years) in all languages indexed in Thomson ISI Web of Science (WoS) have been considered and diverse central journals publishing houses were covered. To name a few, Elsevier, Wiley Online Library, Taylor & Francis, Springer Link, ASEC Library, Emerald, ProQuest, EBSCO, and IEEE Explore. The reason for selecting the ISI Web of Science was that it is accounted to be the most precise database providing scientific publications. Moreover, it includes dominant journals and publications, which provides data with high accuracy and validity [23]. The search on the literature, selection and screening of the most relevant publications were executed on WoS central collection via the search string, "Scientometry", "CO_2 underground storage", and "CO_2 reservoir" represented in the keywords, abstract or title of articles. Then the research was integrated with a fuzzy search containing "*". Detailed data on the year of publication, personal information of the first authors such as their names and e-mails, their affiliations, and keywords were extracted from each article and were further categorized. The selected articles taken were mostly written in English with few exceptions. In order to facilitate the execution of scientometric analysis, CiteSpace software (5.3.R4) was adopted, so the records captured from WoS, which have also been saved in WoS "Marked List", were further inserted in the CiteSpace manually as the essential raw data [24–26]. Then by employing the model of linear regression, the quantity of published papers over the adopted duration was examined and their respective developing direction to which they are the most attractive, are illustrated. In addition, identification of countries containing the largest number of publications was performed on the basis of the location of all authors' institutions [27]. The flow chart (Fig. 2) demonstrates the steps taken in the order to proceed with this study.

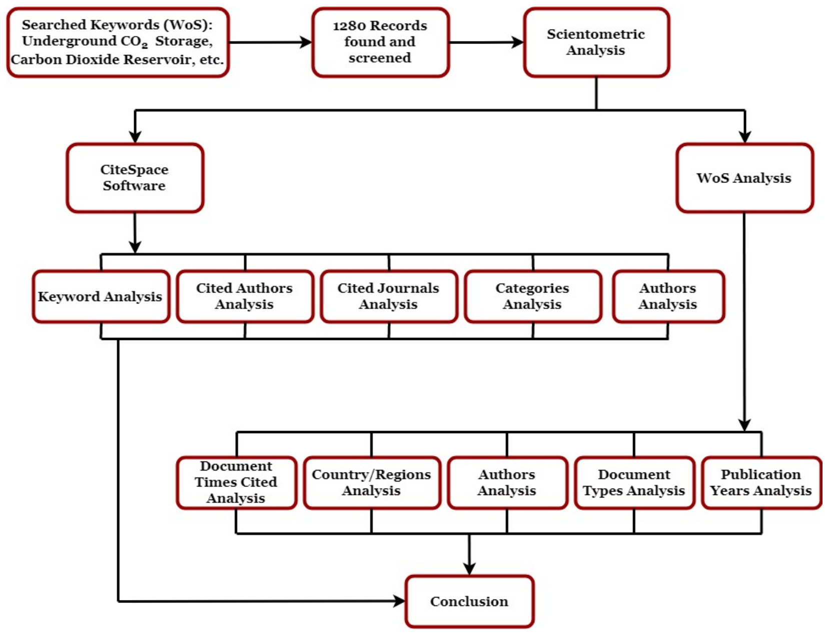

Fig. 2.
The flowchart demostrating the implemented procedures.

4. Results and discussion

By implementing our methodology on the output from the search performed in WoS and fulfilment of research design in the selected period (1990 –2018), the numbers of 1280 multilingual bibliographic records were gathered. Among the scientometric analysis approaches, nine techniques were employed to proceed with this study, which are defined as the analysis following (1) publication history, (2) analysis on the variety of documents, (3) country/regions analysis, (4) authors' contributions analysis, (5) keywords analysis, (6) cited authors analysis, (7) cited journals analysis, (8) categories analysis, and (9) cited document frequency analysis. Consequently, these techniques have been implemented and important part of CiteSpace software outcomes are represented.

4.1. Publication history

In this section, the distribution of publication over the adopted interval time was investigated. The maximum and minimum number of publications belonging to 2017 with 177 publications (13.83%) and 1994 with only one study (less than 1%). From 1990 till 2018, respectively, the number of 2, 2, 8, 1, 5, 4, 9, 10, 9, 6, 15, 2, 39, 11, 22, 28, 31, 43, 64, 50, 92, 72, 123, 125, 116, 122, 177 and 92 articles in the mentioned subject were published. As can be seen in Fig. 3, the overall trend of number of records is increasing, which indicates that the growing problem of GHG as a global serious dilemma has provoked engineers and researchers to progressively engage with this problem such that CO_2 underground storage, as one of the important solutions, has been investigated progressively. The considerable sudden decrease in the number of records from 2017 to 2018 perhaps is due to new policy of the USA about global climate change and its reaction to Paris Agreement in 2018 [28]. Table 1 gives more statistics on the recorded publications.

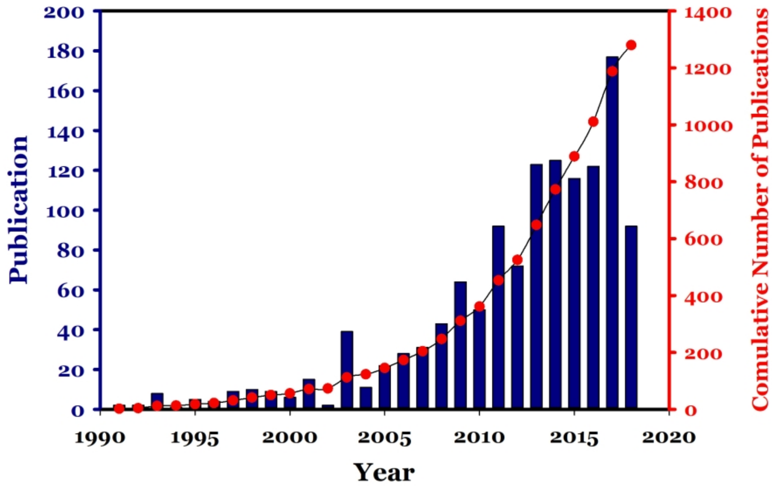

Fig. 3.
The number of the documents published in the field since 1990.

Table 1.
Rate and percentage of documents published in the field since 1990

NO.	Year	Publication (No.)	Contribution %	Total
1	2018	92	7.19	1280
2	2017	177	13.83	1188
3	2016	122	9.53	1011
4	2015	116	9.06	889
5	2014	125	9.77	773
6	2013	123	9.61	648
7	2012	72	5.63	525
8	2011	92	7.19	453
9	2010	50	3.91	361
10	2009	64	5.00	311
11	2008	43	3.36	247
12	2007	31	2.42	204
13	2006	28	2.19	173
14	2005	22	1.72	145
15	2004	11	0.86	123
16	2003	39	3.05	112
17	2002	2	0.16	73
18	2001	15	1.17	71
19	2000	6	0.47	56
20	1999	9	0.70	50
21	1998	10	0.78	41
22	1997	9	0.70	31
23	1996	4	0.31	22
24	1995	5	0.39	18
25	1994	1	0.08	13
26	1993	8	0.63	12
27	1992	2	0.16	4
28	1991	2	0.16	2

4.2. Analysis on the variety of documents

Based on the output results of the WoS, Fig. 4, from all records in the area of the considered topic, CO_2 underground storage, appeared 63% in articles, 31% in Proceeding Papers, 5% in Reviews and 1% in other documents.

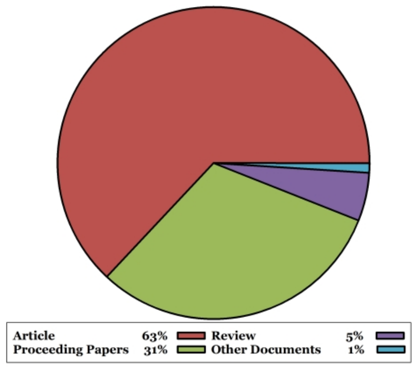

Fig. 4.
Document types analysis results.

4.3. Country/regions analysis

In these criteria, rate of contribution of countries was extracted from the WoS and are presented in Fig. 5 and Table 2. In harmony with the outcomes gained from the WoS, among the 25 countries with the highest rank of contribution, the USA with 342 articles and 26.72%, owns the most remarkable performance, while China (162 articles, 12.66%) and England (129 articles, 10.08%) obtained the second and third positions. Afterwards, there were France (111, 8.67%), Germany (101, 7.89%), Canada (87, 6.80%), Japan (76, 5.94%), Australia (75, 5.86%), Italy (64, 5.00%), and finally Netherlands (63, 4.92%), respectively, which stand in the upcoming positions. It is noticeable that two industrial countries, USA and China, as the first and the second ranks on scientific contributions, are also responsible for the main portion of GHG production in the world. In addition, among the six continents, Europe relatively shows more concern and dedicates a significant contribution in this field of research.

Table 2.
The number of published documents and contribution of countries in the subject

Rating	Country	Counts (No.)	Contribution (%)
1	USA	342	26.72
2	China	162	12.66
3	England	129	10.08
4	France	111	8.67
5	Germany	101	7.89
6	Canada	87	6.80
7	Japan	76	5.94
8	Australia	75	5.86
9	Italy	64	5.00
10	Netherlands	63	4.92

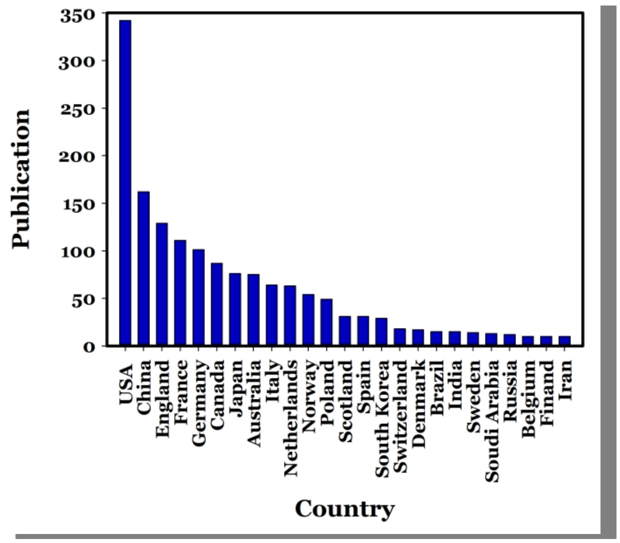

Fig. 5.
The number of published documents in the subject based on the host country.

4.4. Authors' contributions analysis

The rate of cooperation is the fourth technique of this scientometry analysis in which results obtained from both WoS and CiteSpace softwares were considered. These collected data not only contain features that enable performing an efficient comparison among authors being productive in performing research on this specific field, but also provide the ability to compare their correspondent profiles. Figure 6 and Table 3 illustrate these obtained data. Thereafter the execution of this analysis, it was comprehended that Kempka T (17 articles), Li XC (16 articles), Tarkowski R (13 articles), Holloway S (12 articles), Li Q (12 articles), Rutqvist J (11 articles), Koide H (10 articles), Wei N (10 articles), Ohsumi T (9 articles), Bachu S (8 articles), Keith DW (8 articles), Uliasz-misiak B (8 articles), gained the respective ranks of 1 to 12.As depicted in Fig. 6, the network representing the authors activities includes both nodes and few (or almost no) links. Each symbolic node indicates an author, while each link, if exists, presents the pattern of cooperation among authors. The state of no-link may refer to as a no cooperation or newborn field of study.

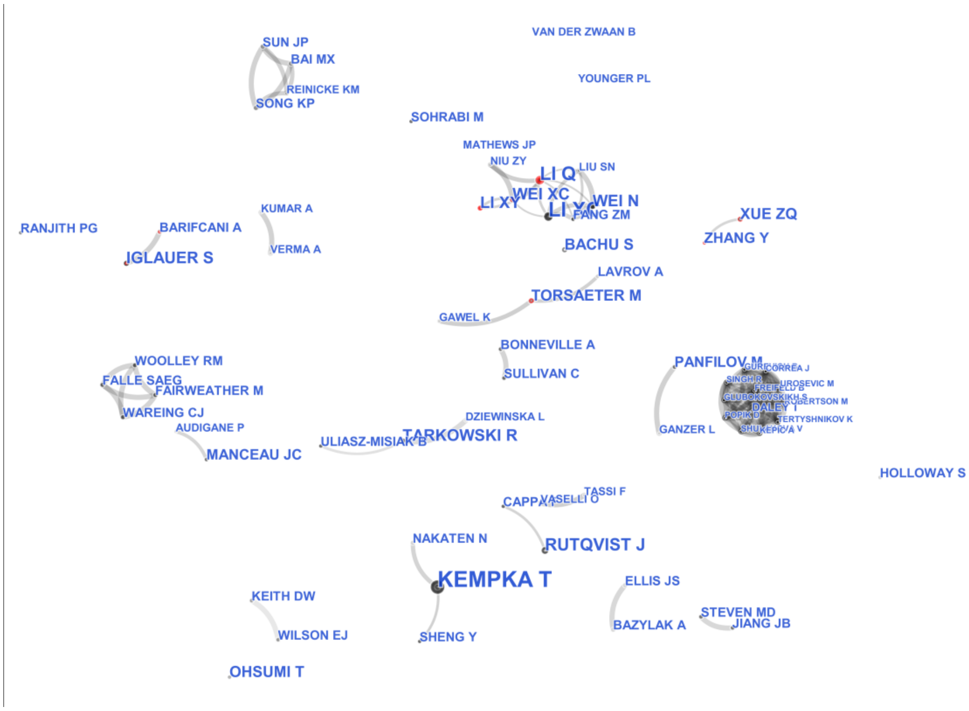

Fig. 6.
The illustration representing the authors' contributions in the scientific domain

Table 3.
Analysis of the author's contributions in the subject

Rating	Author	Contribution (%)	Record Counts (No.)
1	Kempka T	1.33	17
2	Li XC	1.25	16
3	Tarkowski R	1.02	13
4	Holloway S	0.94	12
5	Li Q	0.94	12
6	Rutqvist J	0.86	11
7	Koide H	0.78	10
8	Wei N	0.78	10
9	Ohsumi T	0.70	9
10	Bachu S	0.63	8
11	Keith DW	0.63	8
12	Uliasz-misiak B	0.63	8
13	Benson SM	0.55	7
14	Lglauer S	0.55	7
15	Li XY	0.55	7
16	Lindeberg E	0.55	7
17	Nakaten N	0.55	7
18	Ranjith PG	0.55	7
19	Vaselli O	0.55	7
20	Wei XC	0.55	7
21	Wilson EJ	0.55	7
22	Zevenhoven R	0.55	7
23	Zhang Y	0.55	7
24	Audigane P	0.47	6
25	Babadagli T	0.47	6

4.5. Keywords analysis

To continue our analysis with the fifth technique, subjects and themes of numerous researches have been integrated, formed and generated influencing the topic, leading to a new paper. This is because of the coexistence of multiple keywords in various publications. Then, the extracted keywords for this investigation were considered and inserted into the CiteSpace software.

The influence of authors and their cooperation was investigated by employing two indicators of the citation burst [29] and betweenness. The citation burst measures the increase in citations within a short time span. By utilization of the software, the following results were obtained. The twenty keywords which had the highest frequency to the lowest frequency are: Carbon Dioxide (frequency of 230, burst of 4.12), Sequestration (frequency of 151, burst of 3.83), Storage (frequency of 136, burst of 1.12), CO_2 (frequency of 132, burst of 1.19), CO_2 Storage (frequency of 103, burst of 1.23), CO_2 Sequestration (frequency of 63, burst of 0.46), Injection (frequency of 62, burst of 1.77), Reservoir (frequency of 62, burst of 0.56), Model (frequency of 58, burst of 0.00), CC (frequency of 56, burst of 0.49), Permeability (frequency of 55, burst of 1.90), Porous Media (frequency of 54, burst of 0.70), Leakage (frequency 51, burst of 0.56), Flow (frequency of 49, burst of 0.55), Simulation (frequency of 48, burst of 1.23), Water (frequency of 47, burst of 0.52), Carbon Sequestration (frequency of 47, burst of 0.79), Aquifer (frequency of 47, burst of 0.79), Climate Change (frequency of 44, burst of 4.58), and Carbon Capture (frequency of 41, burst of 1.55). This provided data with more statistical information about their centrality and Sigma are presented in Table 4 and Fig. 7.

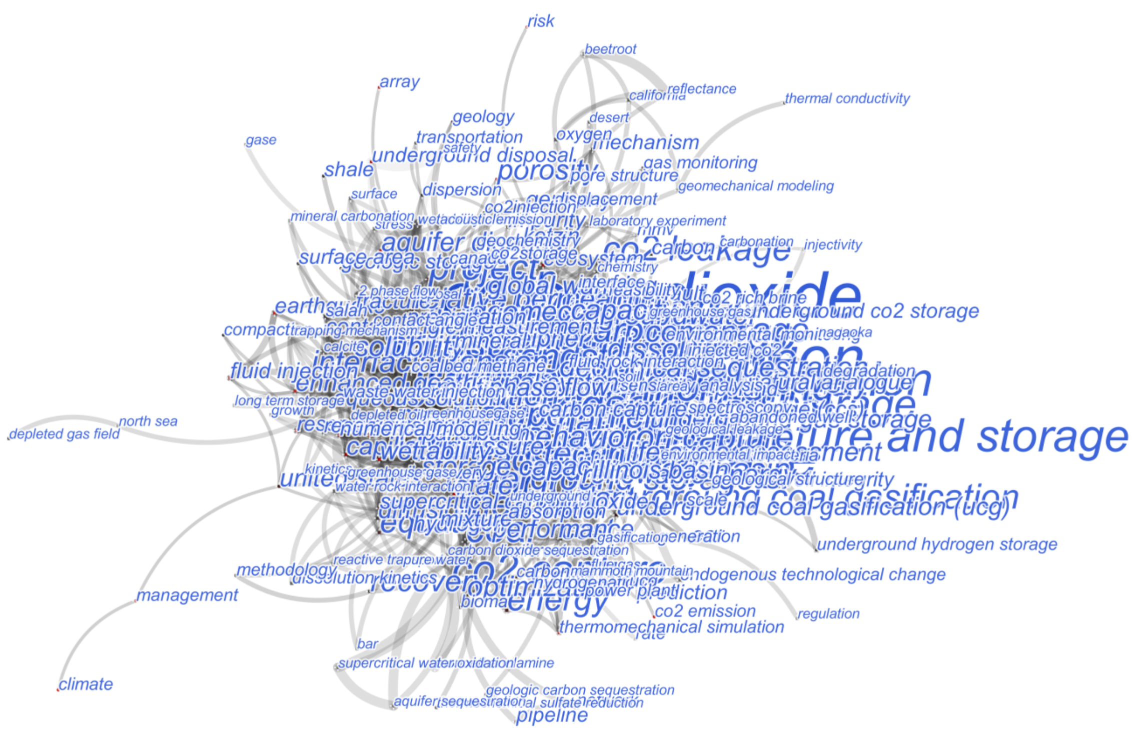

Fig. 7.

A general graphical representation of keywords analysis results. A version of this figure with minimized overlaps has been provided in supplementary information (Fig. A.1).

Table 4. Statistical information on the keywords analysis results

Rating	Keyword	Sigma	Centrality	Burst	Frequency
1	Carbon Dioxide	1.42	0.09	4.12	230
2	Sequestration	1.4	0.09	3.83	151
3	Storage	1.08	0.07	1.12	136
4	CO_2	1.08	0.06	1.19	132
5	CO_2 Storage	1.06	0.05	1.23	103
6	CO_2 Sequestration	1.03	0.07	0.46	63
7	Injection	1.14	0.07	1.77	62
8	Reservoir	1.02	0.03	0.56	62
9	Model	1	0.03	0.00	58
10	CC	1.03	0.06	0.49	56
11	Permeability	1.16	0.08	1.90	55
12	Porous Media	1.05	0.08	0.70	54
13	Leakage	1.05	0.08	0.56	51
14	Flow	1.02	0.04	0.55	49
15	Simulation	1.07	0.06	1.23	48
16	Water	1.06	0.12	0.52	47
17	Carbon Sequestration	1.04	0.05	0.79	47
18	Aquifer	1.05	0.07	0.79	47
19	Climate Change	1.17	0.04	4.58	44
20	Carbon Capture	1.01	0.01	1.55	41

4.6. Cited authors analysis

After the fulfilment of analysis on scientometry in CiteSpace software, the impacts of authors and their collaborations were examined by utilizing their citation numbers, citation bursts, betweenness centrality and citation sigma. The achieved outcomes of this analysis are represented in Fig. 8a and b, and are also categorized in Table 5.

In addition to considering the citation numbers of authors, it was found that the top ranked item by citation counts is Bachu S (1999) in Cluster #0 with citation counts of 227. The second one is Metz B (2003) in Cluster #2, with citation counts of 141. The third is [Anonymous] (2009) in Cluster #6, with citation counts of 140. The 4th is Pruess K (2007) in Cluster #1, with citation counts of 105. The 5th is Holloway S (1997) in Cluster #0, with citation counts of 104. The 6th is IPCC (2007) in Cluster #2, with citation counts of 85. The 7th is Benson SM (2003) in Cluster #4, with citation counts of 79. The 8th is Rutqvist J (2010) in Cluster #1, with citation counts of 69. The 9th is Oldenburg CM (2003) in Cluster #1, with citation counts of 68. The 10th is Gunter WD (1997) in Cluster #0, with citation counts of 65. Moreover, in order to compare the citation bursts, it was comprehended that the top ranked item by bursts is Holloway S (1997) in Cluster #0, with bursts of 12.28. The second one is Gunter WD (1997) in Cluster #0, with bursts of 10.58. The third is Herzog HJ (2001) in Cluster #0, with bursts of 9.84. The 4th is Zoback MD (2013) in Cluster #1, with bursts of 9.78. The 5th is Vilarrasa V (2015) in Cluster #1, with bursts of 9.42. The 6th is Stevens SH (2001) in Cluster #3, with bursts of 8.71. The 7th is *IPCC (2006) in Cluster #2, with bursts of 8.14. The 8th is Lindeberg E (1997) in Cluster #0, with bursts of 8.06. The 9th is Verdon JP (2015) in Cluster #1, with bursts of 7.87. The 10th is Lackner KS (2006) in Cluster #2, with bursts of 7.40. In order with execution of this analysis in regards with the betweenness centrality, it was understood that the top ranked item by centrality is Holloway S (1997) in Cluster #0, with centrality of 0.00. The second one is Gunter WD (1997) in Cluster #0, with centrality of 0.00. The third is Herzog HJ (2001) in Cluster #0, with centrality of 0.00. The 4th is Zoback MD (2013) in Cluster #1, with centrality of 0.00. The 5th is Vilarrasa V (2015) in Cluster #1, with centrality of 0.00. The 6th is Stevens SH (2001) in Cluster #3, with centrality of 0.00. The 7th is *IPCC (2006) in Cluster #2, with centrality of 0.00. The 8th is Lindeberg E (1997) in Cluster #0, with centrality of 0.00. The 9th is Verdon JP (2015) in Cluster #1, with centrality of 0.00. The 10th is Lackner KS (2006) in Cluster #2 with centrality of 0.00.

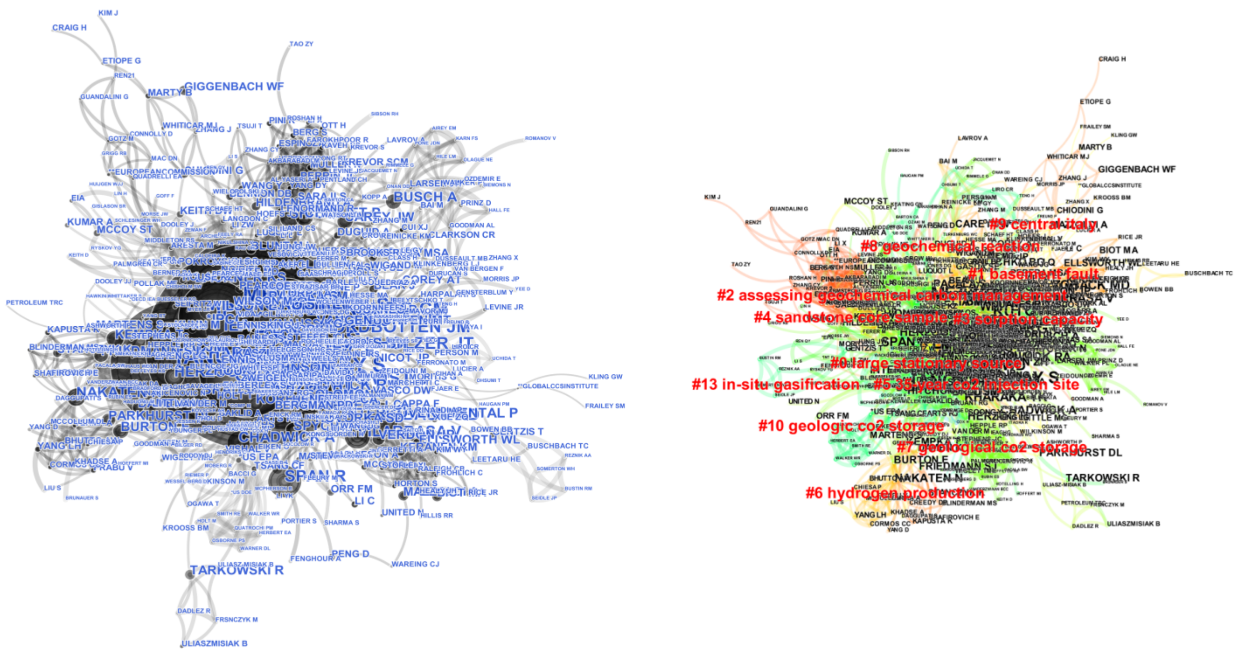

Fig. 8.
Graphical outcomes from the CiteSpace software regarding the cited authors analysis (a) A version of this figure with minimized overlaps has been provided in supplementary information (Fig. A.2). Outcome of the CiteSpace software on the clusters of cited authors' analysis (b).

It is worthy to mention here regarding the citation sigma as it was observed that the top ranked item by sigma is Holloway S (1997) in Cluster #0, with sigma of 1.00. The second one is Gunter WD (1997) in Cluster #0, with sigma of 1.00. The third is Herzog HJ (2001) in Cluster #0, with sigma of 1.00. The 4th is Zoback MD (2013) in Cluster #1, with sigma of 1.00. The 5th is Vilarrasa V (2015) in Cluster #1, with sigma of 1.00. The 6th is Stevens SH (2001) in Cluster #3, with sigma of 1.00. The 7th is *IPCC (2006) in Cluster #2, with sigma of 1.00. The 8th is Lindeberg E (1997) in Cluster #0, with sigma of 1.00. The 9th is Verdon JP (2015) in Cluster #1, with sigma of 1.00. The 10th is Lackner KS (2006) in Cluster #2, with sigma of 1.00.

Table 5. Statistical results regarding cited authors' analysis.

Rating	Author	Year	Sigma	Centrality	Burst	Frequency
1	Bachu S	1999	1.00	0.00	1.42	227
2	Metz B	2003	1.00	0.00	11.27	141
3	Anonymous	2009	1.00	0.00	5.67	140
4	Pruess K	2007	1.00	0.00	2.96	105
5	Holloway S	1997	1.00	0.00	1.33	104
6	IPCC	2007	1.00	0.00	0.85	85
7	Benson SM	2003	1.00	0.00	0.45	79
8	Rutqvist J	2010	1.00	0.00	3.77	69
9	Oldenburg CM	2003	1.00	0.00	0.38	68
10	Gunter WD	1997	1.00	0.00	1.36	65
11	Xu TF	2006	1.00	0.00	2.44	64
12	Gaus I	2006	1.00	0.00	0.61	58
13	Nordbotten JM	2010	1.00	0.00	1.85	49
14	Birkholzer JT	2012	1.00	0.00	7.14	42
15	Zoback MD	2013	1.00	0.00	7.19	40
16	IEA	2012	1.00	0.00	3.59	39
17	Span R	2003	1.00	0.00	6.42	39
18	Kharaka YK	2009	1.00	0.00	1.95	38
19	White CM	2005	1.00	0.00	1.06	32
20	Lindeberg E	1997	1.00	0.00	0.56	30
21	Chadwick RA	2005	1.00	0.00	2.41	30
22	Vilarrasa V	2015	1.00	0.00	9.42	29
23	Chadwick A	2008	1.00	0.00	1.06	27
24	Stevens SH	2001	1.00	0.00	1.55	27
25	Celia MA	2007	1.00	0.00	1.74	25
26	Gale J	2003	1.00	0.00	1.04	25
27	Lewicki JL	2008	1.00	0.00	1.84	24
28	Nakaten N	2014	1.00	0.00	6	23
29	Arts R	2003	1.00	0.00	1.96	23
30	Herzog HJ	2001	1.00	0.00	9.84	23

4.7. Cited journals analysis

As it was mentioned before, during the selected interval from 1990 till 2018, the total number of 1280 bibliographic records in all languages about the main topic of this study were extracted and inserted into the CiteSpace software in order to carry out a careful examination regarding the journals in which they were published. The analysis was executed based on their main characteristics such as citation quantities, citation bursts, betweenness centrality as well as the citation sigma in this regards Fig. 9a and b are generated for graphical representation and also more statistics are given in Table 6.

Consequently, it is understood that the top ranked item by the citation counts i (b) JGGASCON (2008) in Cluster #0, with citation counts of 474. The second one is Enrgy P (2009) in Cluster #0, with citation counts of 391. The third is Energ CM (1997) in Cluster #2, with citation counts of 333. The 4th is Environ SCIT (2003) in Cluster #3, with citation counts of 264. The 5th is ENERGY (2003) in Cluster #4, with citation counts of 253. The 6th is Chem G (1997) in Cluster #1, with citation counts of 223. The 7th is SCIENCE (1998) in Cluster #1, with citation counts of 212. The 8th is NATURE (1997) in Cluster #2, with citation counts of 199. The 9th is Geophys RESL (2003) in Cluster #1, with citation counts of 195. The 10th is Geochim CAC (1997) in Cluster #1, with citation counts of 177.

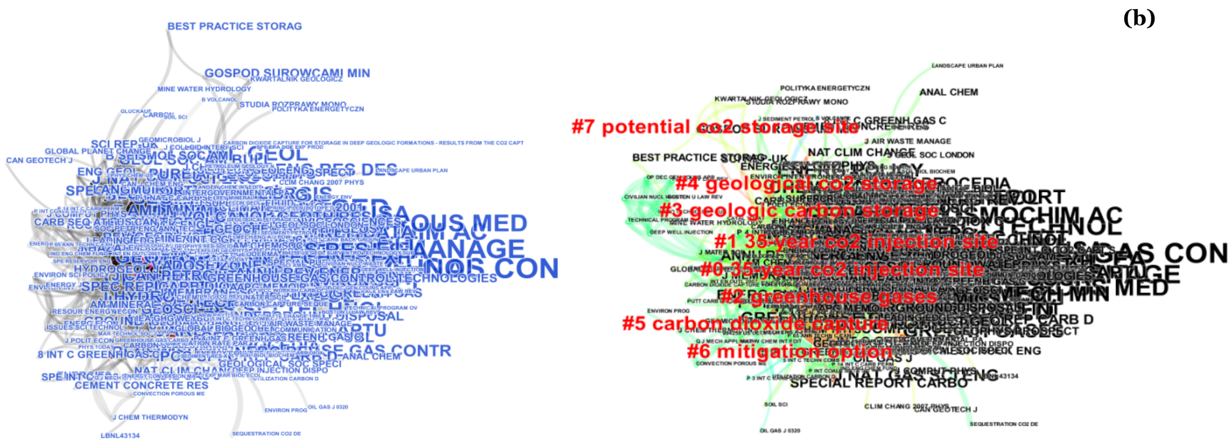

Fig. 9.
The results of CiteSpace Software regarding cited journals analysis (a). A version of this figure with minimized overlaps has been provided in supplementary information (Fig. A.3). Results from the CiteSpace software regarding clusters of the cited journals' analysis (b).

In this scientometry study, not only citation quantities were considered for evaluation, but also citation burst was the criteria of journal assessment. As a result, the top ranked item by bursts is Energ CM (1997) in Cluster #2, with bursts of 23.83. The second one is THESIS (2015) in Cluster #3, with bursts of 20.95. The third is J NATGASSCIENG (2017) in Cluster #0, with bursts of 12.04. The 4th is Fuel PT (2008) in Cluster #3, with bursts of 10.80. The 5th is Renew SEREV (2017) in Cluster #4, with bursts of 10.75. The 6th is Geophys JINT (2014) in Cluster #1, with bursts of 10.00. The 7th is Ipcc SREPCD (2008) in Cluster #5, with bursts of 9.82. The 8th is Nat G (2017) in Cluster #1, with bursts of 9.58. The 9th is Ipcc SR (2009) in Cluster #4, with bursts of 8.60. The 10th is Appl E (2003) in Cluster #4, with bursts of 8.54. Moreover, regarding the centrality of these journals, after the CiteSpace analysis, it was attained that the top ranked item by centrality is Environ SCIT (2003) in Cluster #3, with centrality of 0.16. The second one is Energ CM (1997) in Cluster #2, with centrality of 0.13. The third is Annu REVEENV (2003) in Cluster #3, with centrality of 0.13. The 4th is NATURE (1997) in Cluster #2, with centrality of 0.13. The 5th is ENERGY (2003) in Cluster #4, with centrality of 0.12. The 6th is Geochim CAC (1997) in Cluster #1, with centrality of 0.12. The 7th is Energ F (2003) in Cluster #0, with centrality of 0.12. The 8th is Chem G (1997) in Cluster #1, with centrality of 0.08. The 9th is Appl G (2000) in Cluster #6, with centrality of 0.08. The 10th is Environ G (2003) in Cluster #1, with centrality of 0.07. Ultimately, regarding the citation sigma of the provided journals gained from the software, it was comprehended that the top ranked item by sigma is Energ CM (1997) in Cluster #2, with sigma of 18.29. The second one is Annu REVEENV (2003) in Cluster #3, with sigma of 2.10. The third is Environ SCIT (2003) in Cluster #3, with sigma of 1.68. The 4th is Chem G (1997) in Cluster #1, with sigma of 1.40. The 5th is Chem ENGRESDES (2007) in Cluster #7, with sigma of 1.32. The 6th is J FM (2003) in Cluster #0, with sigma of 1.32. The 7th is Fuel PT (2008) in Cluster #3, with sigma of 1.19. The 8th is Ipcc SREPCD (2008) in Cluster #5, with sigma of 1.17. The 9^{th} is 7 INTCGGASC (2005) in Cluster #0, with sigma of 1.16. The 10^{th} is Greenhouse GASCT (2001) in Cluster #2, with sigma of 1.15.

Table 6. A summary of the statistical results regarding the cited journals analysis

Rating	Journal	Year	Sigma	Centrality	Burst	Frequency
1	Int J Greenh Gas Con	2008	1.00	0.05	0.00	474
2	EnrgyProced	2009	1.00	0.01	0.00	391
3	Energ Convers Manage	1997	18.29	0.13	23.83	333
4	Environ Sci Technol	2003	1.68	0.16	3.59	264
5	Energy	2003	1.13	0.12	1.07	253
6	Chem Geol	1997	1.4	0.08	4.47	223
7	Science	1998	1.11	0.06	1.79	212
8	Nature	1997	1.05	0.13	0.43	199
9	Geophys Res Lett	2003	1.00	0.07	0.00	195
10	GeochimCosmochim AC	1997	1.07	0.12	0.58	177
11	Water Resour Res	1996	1.07	0.05	1.34	171
12	J Geophys Res-Sol Ea	2003	1.12	0.04	3.29	171
13	Transport Porous Med	2009	1.00	0.03	0.00	168
14	Appl Geochem	2000	1.11	0.08	1.42	159
15	Energ Fuel	2003	1.04	0.12	0.37	151
16	Fuel	2003	1.00	0.07	0.00	147
17	Environ Geol	2003	1.1	0.07	1.39	134
18	Environ Earth Sci	2011	1.04	0.01	5.32	127
19	Aapg Bull	1996	1.04	0.04	0.84	124
20	P Natl Acad Sci Usa	2009	1.03	0.04	0.75	123
21	J Petrol Sci Eng	2009	1.00	0.02	0.00	118
22	Geology	2000	1.04	0.04	0.89	109
23	Adv Water Resour	2010	1.02	0.02	0.75	97
24	Int J Rock Mech Min	2005	1.07	0.04	1.63	96
25	Earth Planet Sc Lett	2007	1.04	0.04	0.96	92
26	Spe J	2006	1.12	0.04	3.18	89
27	Thesis	2015	1.00	0.00	20.95	87
28	J Geophys Res	1997	1.06	0.02	2.37	86
29	Oil Gas Sci Technol	2008	1.05	0.01	3.9	85
30	Int J Coal Geol	2003	1.03	0.01	2.71	82

4.8. Categories analysis

According to the results of scientometric analysis regarding the frequency of categories, Table 7 and Fig. 10 were produced. Here, ten most frequent categories could be classified from the first to tenth as: “Energy & Fuels” (with frequency of 576 and burst of 5.76), “Engineering”(with frequency of 519 and burst of 0.00), “Environmental Science and Ecology” (with the frequency of 274 and burst of 26.23), “Environmental Science” (with frequency of 261 and burst of 26.31), “Engineering Environmental”(with the frequency of 237 and burst of 14.95), “Geology” (with frequency of 209 and burst of 1.94), “Geosciences Multidisciplinary” (with frequency of 185 and burst of 1.85), “Science & Technology - Other Topics”(with the frequency of 179 and burst of 9.31), “Green & Sustainable Science & Technology” (with the frequency of 145 and burst of 9.10) and “Engineering Chemical” (with the frequency of 138 and burst of 1.40).

Table 7. The statistical results regarding the categories analysis

Rating	Categories	Burst	Frequency

1	Energy & Fuels	5.76	576
2	Engineering	0.00	519
3	Environmental Sciences & Technology	26.23	274
4	Environmental Sciences	26.31	261
5	Engineering Environmental	14.95	237
6	Geology	1.94	209
7	GeosciencesMultidisciplinary	1.85	185
8	Science & Technology - Other Topics	9.31	179
9	Green & Sustainable Science & Technology	9.10	145
10	Engineering Chemical	1.40	138

Fig. 10.
The results regarding the categories analysis. A version of this figure with minimized overlaps has been provided in supplementary information (Fig. A.3).

4.9. Cited documents frequency analysis

According to the results exported from WoS, as represented in Fig. A4 (in the annex file), the 10 following articles had the highest rates of being cited during the period from 1990 till 2018 which respectively are; “Progress in carbon dioxide separation and capture: A review” by 1088 times, “Tansley review no-71 - effects of elevated atmospheric CO_2on woody-plants” by 607 times, “Interpreting carbon-isotope excursions: carbonates and organic matter” by 487 times, “Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery - a review” by 468 times, “Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change” by 455 times, “Polymeric CO_2/n-2 gas separation membranes for the capture of carbon dioxide from power plant flue gases” by 442 times, “Separation and capture of CO_2 from large stationary sources and sequestration in geological formations - coalbeds and deep saline aquifers” by 441 times, “Sequestration of CO_2 in geological media in response to climate change: capacity of deep saline aquifers to sequester CO_2in solution” by 339 times, “Co-production of hydrogen, electricity and $CO_2$from coal with commercially ready technology. Part A: performance and emissions" by 276 times and "Carbon dioxide reaction processes in a model brine aquifer at 200°Cand 200 bars: implications for geologic sequestration of carbon" by 225 times.

The climate change is among one of the most critical concerns that human being have faced since the beginning of urbanization. However, there are serious concerns in scientific communities on the destructive effects of this phenomenon on the environment [28]. As the CO_2 has been accumulated in the ambient, biodiversity will be more threatened and likewise the chance of occurrence of extreme weather events such as flooding and droughts specifically in urban areas will rise[30,31]. Carbon dioxide is believed to be one of the most important sources of greenhouse gases which has been released in high quantities especially from industrial activities [32]. In spite the international agreements on the reduction of carbon dioxide released into the atmosphere as well as the incentive plans to persuade reducing the release rate of carbon dioxide, there is still a long way to reach a sustainable situation and a real balance between the amount of carbon dioxide releases and the environmental caring capacity for this greenhouse gas[33]. Hence, the research on how to mitigate the effects of the carbon dioxide by exporting it from the atmosphere would be very welcome. The UCCS which began since last century is among the most acceptable strategies to deal with this problem with a number of advantages including the reduction of the ambient carbon dioxide while the required amount of CO_2 as the resource for the relevant application is provided. In this regard, UCCS can open up a new window towards sustainable carbon dioxide storage because in addition to technical benefits arise from such a technique, the initial investments required for the establishment of a carbon dioxide storage facility is normally very low. This is due to the fact that the underground tanks such as depleted oil and gas fields already exist, and they can be utilized for such applications after the recovery. This method is considered a young discovery during the recent years on contrary to the trial operations in regards with these procedures. It can provide long storage durations [34]. It is as sufficient as being able to store the global emission for decades and even up to hundred years. The industrial usage of compressed and encapsulated CO_2 aims to obtain highly pure CO_2 for various applications such as enhanced oil recovery applications, beverages carbonization, cooling, tap water treatment, welding processes, and foam fabrication [12].

As mentioned before, the bibliometric study is a technique in which the research growth, academic endeavour, involved countries and journals in a specific field are evaluated and examined [35–37]. The specific scientific knowledge relevant to a research area and its trends during a selected duration will be identified via utilization of mathematical formulas and visualization [23,38]. This study aimed to implement this technique in order to study the progress in the application of USSC investigations made during the time period of 1990-2018. According to the results, the scientific efforts in this subject have started since the late of 20th century and were accelerated by the beginning of the 21th century. However, it seems that there is not still a meaningful connection between the individual researches made in this area among the scientific communities. The United State and People's Republic of China, respectively are the two main countries with the highest numbers of published documents. In addition to this fact that these countries are housed with a number of scientists in such areas, so these countries are among the industrial countries with the highest amount of carbon dioxide production. Hence, the concerns of environmental subsequence of CO_2 emissions from the industrial activities may push scientific communities in such countries to proceed with the scientific research in this area in order to find the sustainable solution for this problem.

Additionally, as per the results of this study, there is still room for further investigations, especially in terms of technical and economic considerations of underground CO_2 storage. For instance, site selection studies [39]in order to find the best locations for underground CO_2 storage or to evaluate the existing facilities, which can be used for this purpose is among the prospects with high interests in this domain. In addition, it seems there is a need for comprehensive studies on the sustainability of various types of underground CO_2 storage facilities considering all the social, technical, economic, environmental considerations. Such activities can push the commercialization of this technology, especially in some regions of the world with high amount of carbon dioxide release to the atmosphere.

5. Practical implications

The concerns about global warming and climate change due to the release of high amounts of carbon dioxide have gained a huge attention in recent years. Underground CO_2 capture and storage is among the novel approaches, which might aid to considerably reduce carbon dioxide into the atmosphere. The scientometric study performed indicated that research in this field was initiated in the 1990s. Various scientometric parameters analyzed in this study can clearly demonstrate this fact that the knowledge in the field of UCCS is yet in its infancy stage; the number of studies performed in this field is still limited, no significantly active research group has been formed and no evidence on the commercialization of this technology was identified.

Like any other new technology, the initial investments in this field to establish active and productive research groups and to commercialize this technology can be considered to be the most important barriers, which are to be overcome by adopting effective measures. In this situation, results of this study can be used by the stakeholders, such as government among others, to initiate incentives to promote effective studies in this field. This study can also provide up-to-date information on the most effective scientific efforts in the related scientific history. Although this study has provided a comprehensive overview on the current situation of scientific research in this field, discussing the trends in UCCS, existing barriers and possible solutions to overcome the sustainable (i.e., technical, environmental, economic and social) development barriers are highly recommended for future studies.

6. Conclusions

The objective of the present study is to perform a comprehensive scientometric study on the underground CO_2 storage scientific publications based on WoS database. A total 1280 documents (mainly articles) were critically analysed to extract bibliographic maps. It was observed that in the scientific area of the chosen topic, no significant research group or authors are well connected, and no scientific loop has been fully constructed. Mainly USA and China (the first and second ranks of the global scientific contributions) with the highest number of active industries are the leading counties to investigate the underground CO_2 storage as the promising opportunity to be at least the part of a solution for GHG dilemma.

Acknowledgments

Thanks to FCT for the doctoral scholarship No. SFRH/BD/103695/2014.

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