Carbon capture technologies for climate change mitigation

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CARBON CAPTURE TECHNOLOGIES FOR CLIMATE CHANGE MITIGATION: A BIBLIOMETRIC ANALYSIS OF THE SCIENTIFIC DISCOURSE DURING 1998-2018

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Abstract

There are four strategies to combating global warming, namely by directly reducing greenhouse gas emissions, or indirectly through expanding renewable energy employment, more efficient use of energy, or a wide range of climate policies. This study reports a bibliometric analysis of direct carbon dioxide emission reduction through carbon capture. The research trend in carbon capture within the three main types of technologies, namely pre-combustion, post-combustion and oxy-fuel combustion, was investigated using publications from 1998 to 2018 retrieved from the Web of Science database. It was found that from 1998-2007 there was little or no research output on carbon capture, until 2008, when legislation on climate change abatement was introduced and public and industry awareness of clean fossil energy options grew. With these motivating factors, 55 countries engaged in carbon capture technologies and related research in which the United States has the most research output followed by the UK and, China. Among the carbon capture technologies commonly studied, the bibliometric analysis based on a keywords network map showed that post-combustion capture is the most referenced carbon capture technology with about 80.9% of total publications retrieved. Oxy-fuel combustion had the lowest number of publications (3.4%).

Keywords: Bibliometric analysis; Carbon capture; Pre-combustion carbon capture; Post-combustion capture; Oxy-fuel combustion.

1. Introduction

Innovation and research funding from industries and governments are often driven by international policies. In the energy sector, some of the policies that have steered research and investment have been Climate Change Act 2008 in the UK (Pielke, 2009), the Energy Independence and Security Act of 2007 in the U.S.A. (Sissine, 2007) and the more recent Paris conference of parties (COP21) agreement which aim is to limit global warming to ±2 ºC (Horowitz, 2016; UNFCCC, 2015). The continued dependence of the world energy system on fossil fuels such as coal, oil and natural gas makes it imperative to reduce fossil carbon release by employing massive amounts of renewable energies and substantially increasing energy conversion efficiency. In past years, much interest was expressed in the bridging technology of capturing carbon dioxide and storing it in geological formations (Carbon Capture and Storage) (Lemieux, 2011). There is now renewed interest in the capture and utilisation of carbon dioxide, mainly from fossil fuel and biomass sources, in the context of synthetic fuel production.

Up until 2007, little work can be found published in the open literature on carbon capture indexed in Web of Science (WoS) database. However, due to economic development and the rapid increase in world population totalling about 7.7 billion in 2019 (Worldometers, 2019), with a projection of possibly 9.7 billion by 2050 (Worldometers, 2019; WPR, 2019), it is certain that the world demand for energy will continue to rise. The overdependence on fossil sources of energy, emitting large amount of CO_2, is the main cause of global warming. As the transition to low-carbon energy sources has reached full commercial scale, large investments are underway to decarbonise Europe, for instance, until the year 2050. Nevertheless, renewable electricity and biomass fuels may not supply suitable energy vectors for certain applications, such as long-range shipping and air transport. Carbon capture and utilisation are now being re-investigated to simultaneously combat climate change while producing sustainable, synthetic fuels, therefore triggering renewed interest in these technologies. The commonly considered carbon capture technologies (CCT) are pre-combustion, post-combustion and oxy-fuel combustion.

Pre-combustion carbon capture technology involves the capture of carbon from the fuel before combustion is completed. Basically, the fuel undergoes a pre-treatment stage, such as biomass and coal gasification and steam reforming of natural gas, before the actual combustion stage. Syngas (the mixture of H_2 and CO) is formed during this pretreatment stage. Thereafter, CO in the syngas is reacted with steam via the water gas shift (WGS) reaction to produce additional H_2 and CO_2.

The latter can then easily be separated out and processed (Sheikh et al., 2018). After elimination of the CO_2 component, the H_2 gas can be employed as a gaseous fuel in fuel cells, engines, gas turbines or gas turbine combined-cycle plants (Olajire, 2010). This technology can also be used in Integrated Gasification Combined Cycle (IGCC) power plants with biomass or coal as fuel (Leung et al., 2014). Nevertheless, the WGS reaction and the pre-combustion capture systems imply efficiency penalties (Gibbins, J., Chalmers, 2008). Moreover, H_2-combustion engines and gas turbines have lower efficiencies compared to natural gas turbines owing to the lower viscosity of H_2 gas and the increased blow-by (Gibbins, J., Chalmers, 2008).

In post-combustion carbon capture technology, the carbonaceous fuel first undergoes combustion before CO_2 in the flue gas is separated out. The flue gas needs to be pre-treated to ensure that impurities including particulates, sulphur dioxide, nitrogen oxides, and corrosive substances (Cl, F etc.) are removed. Since the temperature of flue gas from the combustion units is likely to be high (in the range of 120 – 180 °C) (Spigarelli and Kawatra, 2013), energy-intensive cooling systems are required before pre-treatment. Likewise, large equipment sizes are required due to the high volume of flue gases and the low partial pressure of CO_2 (between 3 and 20%, depending on the type of combustion and fuel). Both aspects considerably increase the cost of capture (Jiang et al., 2019; Leung et al., 2014; Spigarelli and Kawatra, 2013).

Oxy-fuel combustion technology involves the combustion of carbonaceous fuel in a stream of pure oxygen instead of air. Since the oxidant (O_2) is free of major air components such as nitrogen, the CO_2 concentration in the flue gas will be very high, whilst the water vapour content can be easily removed (Stanger et al., 2015). Therefore, separation/capture is far simpler. However, impurities such as sulphur oxide, nitrogen oxide, and particulates will be present and a pretreatment is again required before CO_2 processing (Gibbins, J., Chalmers, 2008). Additionally, the high cost of supplying oxygen for oxy-fuel combustion may be a limiting factor in commercialisation. Other challenges associated with oxy-fuel combustion, such as high temperatures of combustion, have been extensively discussed in the literature (Jordal et al., 2005; Seddighi et al., 2018; Zheng et al., 2015).

Following this brief overview of the three types of CCT, it is clear that none of the systems is without challenges. Sanders et al. (2013) identified technological, market and political risk as the major barrier towards assessing private funds for carbon capture and storage research from investors. Recent studies have suggested that the availability of economical and affordable facilities is crucial for the advancement of CCS technology on a large scale. The second factor pointed out which is in agreement with the findings in a different study (Durmaz, 2018) was the creation and implementation of regulatory and policy framework to ensure financial stability which will help in building investors' confidence in participating in CCS projects. In 2017, the world energy demand increased by 2.1% (IEA, 2018), in which about 81% of the total energy consumed came from fossil fuels (IEA, n.d.). Consequently, a record high CO_2 emission of about 33.1 Gt was recorded in 2018 (Solano–Olivares et al., 2019). Hence, interest in carbon capture and storage during a transition phase to a decarbonised energy supply system will continue to increase until fossil fuels can be fully substituted by renewable energy sources. Nevertheless, interest in carbon recycling and utilisation in the context of biomass-derived synthetic fuels will increase considerably. Meanwhile, most reports on CCT focus on individual components such as modification of technologies for better capture (Theo et al., 2016; Wu et al., 2018; Zhao et al., 2018) and relationship between policies and investments (Kalkuhl et al., 2015; Zhou et al., 2014). To the best of our knowledge, no study has reported the trend in scientific research in this topic discourse within a wide range of publication years. a recent study that reported the trends in the development of adsorption technologies for carbon dioxide capture during considered 2014 - 2018 (Hussin and Aroua, 2020). Bibliometric analysis of articles on CCT published between 1998 and 2018 is reported in this study. The objective of our study was to provide quantitative analysis and statistics on the trends of publications over a wider range within the timescale, and explore the structure of established networks and trends in the last 20 years. With the aid of this bibliometric analysis, gaps in research can be identified, as well as major players such as authors and institutions, and hot-spot countries and regions.

2. Materials and methods

2.1. Dataset used

Data on the occurrence of the three CCT types in scientific papers was obtained from the Web of Science (WoS) Core Collection Database on July 14, 2019. The decision to use the WoS database was based on its large spectrum of data compared to other databases (Šubelj et al., 2015; Zyoud et al., 2017). The scope of search included all research articles and proceeding papers relating to post- and pre-combustion carbon capture, as well as oxy-fuel combustion capture in the WoS database. This was to ensure the data captured was reflective of research activities only.

Fig. 1 outlines the steps taken to retrieve the relevant papers for this work. A total of twelve keywords was used in the literature search to ensure that all relevant articles and proceedings papers within the timeline were captured. At the end of the search, 1020 papers were obtained. The data was imported into the VOSViewer software which was used to create network maps of co-authorships of countries, co-authorships of institutions, journal participation, co-authorships of authors, and co-occurrence of authors' keywords. Total citation numbers were obtained from the papers retrieved, and thereafter, VOSViewer analysis was carried out to obtain network maps of co-citation analysis of authors. The search strategy used to retrieve publications during 1998 to 2018 from WoS was basic search, and the following command was executed on the title search box ((capture OR "carbon capture" OR "carbon dioxide capture" OR "CO_2 capture" OR "carbon sequestration" OR "CO_2 sequestration") AND ("post combustion" OR "post-combustion" OR "precombustion" OR "pre-combustion" OR "oxyfuel combustion" OR "oxy-fuel combustion")), while *year published* was set as1998-2018 and *document types* as Article OR Proceedings Paper. *Timespan was 1998-2018.*

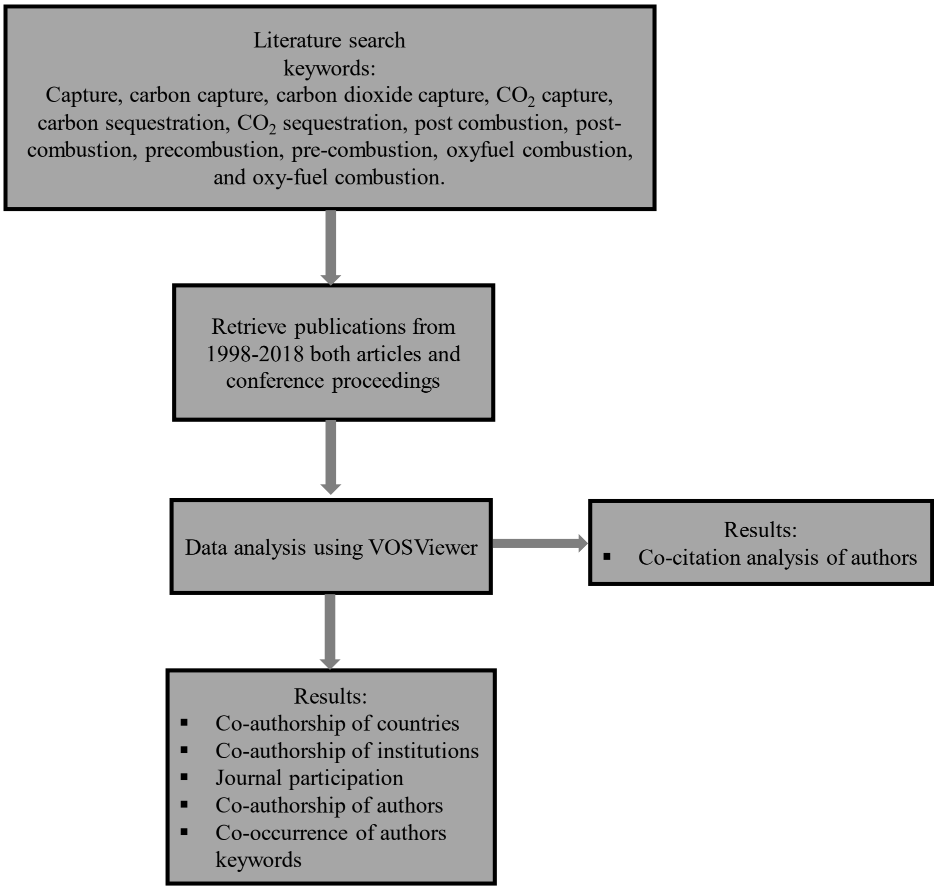

Fig. 1. Methodology flowchart.

The introduction of the sign (*) in the *title* search box aimed at retrieving both singular and plural versions of a keyword, while quotation marks (" ") were used for exact keyword or phrases search. Fig. 2 shows the flow of data from WoS to MS Excel and VOSViewer enabling visual network mapping. VOSViewer was also used to analyse the most co-occurring words. It is noteworthy that in this study, the search words or phrases were restricted to an article or a conference paper with a title containing the keyword(s), unlike with topic search, where a keyword can appear in the title, abstract and author's keywords, thereby delivering false positive results (Sweileh, 2018). Finally, the documents retrieved were vetted using Microsoft Excel 2010 to remove duplicates in order to ensure that an accurate data ensemble was analysed.

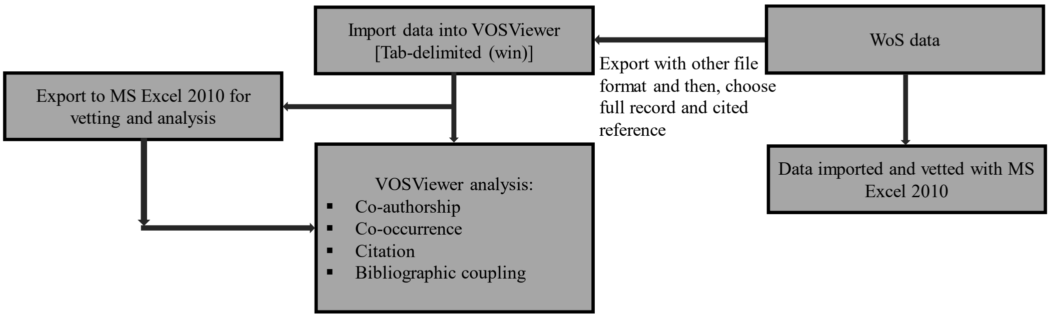

Fig. 2. Flow of data and analysis.

3. Results and discussion

The results of the bibliometric analysis on carbon capture in the period from 1998 to 2018 based on articles indexed in WoS will be presented in the following sections. The analysis was based on countries, institutions, authors and co-occurrence of authors' keywords. These indicators were chosen to highlight countries as well as institutions at the forefront of CCT, identifying leading experts in the field and exploring networks of collaborations across these indicators.

3.1. Trend based on publication year

A total of 1020 documents were retrieved from the WoS database and analysed using VOSViewer software. From the data obtained, research articles constituted 62.4% and proceeding papers 37.6%. Fig. 3 shows the number of publications and citations per year on CCT-related research published between 1998 and 2018. As can be seen, the number of publications gradually increased to a maximum of 49 from 1998 to 2009, and declined to 30 in 2010. Since then, there has been a drastic increase in published research covering CCT, with slight with fluctuation in numbers from 2010 to 2018.

The increase in research output can be attributed to several factors such as public perception and acceptance of CO_2 capture, funding available, developing policies, and commitment to agreements. Indeed, Huang et al. (2020) reported the influence of policy and technology uncertainty on CCS investment strategy. It was found that investment risk can be minimised by reducing uncertainty in incentive policy which, which will boost investors interests in CCS investments. It was found that peak years (2009, 2014 and 2017) in Fig. 3 were years preceding or immediately following many climate change agreements or acts were passed, for instance, the Energy Independence and Security Act of 2007 (U.S.A.) (Sissine, 2007) and the Climate Change Act of 2008 (UK) (Pielke, 2009). The aim of the Climate Change Act was to ensure a minimum of 80% reduction of CO_2 emissions in the UK by 2050. The 2015 Paris Agreement was to ensure that the global average temperature rise is well below 2°C above pre-industrial levels and with commitments of further limiting the temperature increase to 1.5°C (Horowitz, 2016). Considering these observations and the time it takes to pass a manuscript from writing to publication, it is likely that public discussion prior to and post an event translate into a temporary increase in the number of publications. Notwithstanding such findings, further study is needed to understand the relationship between policies development and publication intensity.

On the other hand, there was a gradual continuous increase in the total number of citations per year until 2017 (total of 3996 citations) and a slight decrease in 2018 (total of 3800 citations). Despite the fluctuation in number of publication, this trend in the number of citations is an indication of the growing interest from researchers globally in CCT technologies.

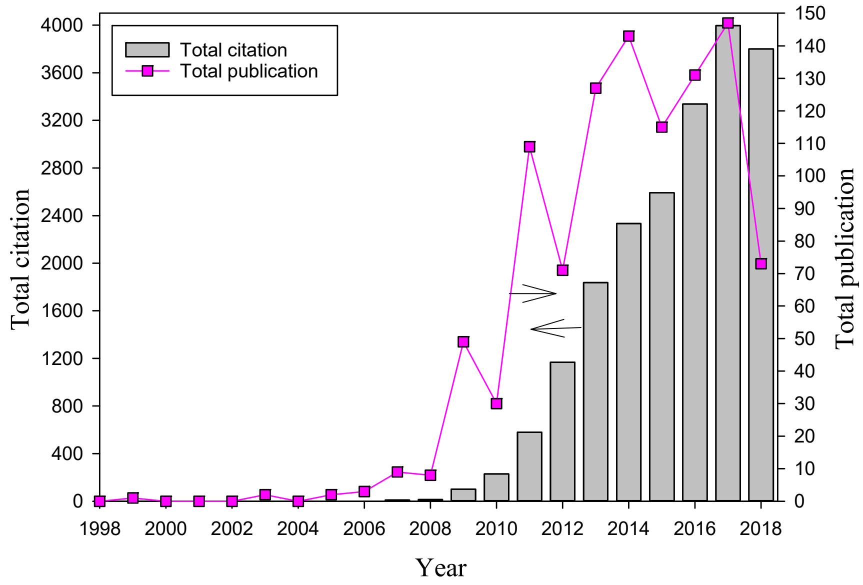

Fig. 3. Total number of publications and citations per year for CCT related research during 1998-2018.

3.2. Countries/regions participation

A total of 55 countries were involved in research related to CCT all over the world. Among these countries, only 25 countries have a minimum of 10 publications (see Fig. 4) with most publications on post-combustion capture (16) followed by pre-combustion capture (10 papers) (see Table 1). Oxy-fuel combustion had the least number of publication (4). In terms of total number of publications (TP), the U.S.A. (total publications of 146) topped the table followed by England (total publications 124) and China (total publications 120). The research output suggested that these countries were leading the research on carbon capture and storage for greenhouse gas emissions abatement. This was not unexpected since the U.S.A. and China are the top two emitters of CO_2 worldwide ("Climate change report card: These countries are reaching targets," 2019). Conversely, the countries with the least publications on CCT related research were Bangladesh, Colombia, the Czech Republic, Estonia, Hungary, Indonesia, Kazakhstan, Tunisia, Turkey and Vietnam with only one publication each. In terms of total number of citations (TC), the U.S.A. also had the highest citations. The top ten countries in order of citation were the U.S.A. (4416 citations) > England (3178 citations) > Germany (2505 citations) > Netherlands (1971 citations) > Norway (1911 citations) > Australia (1888 citations) > China (1876 citations) > France (1795 citations) > Canada (1367 citations) > Spain (1161 citations). Continentally, Europe was the most active continent (53.86% of total publications) and the second highest percentage came from Asia

(20.68%), while Africa and South America were the least active continents (0.68% publications) (see Fig. 5).

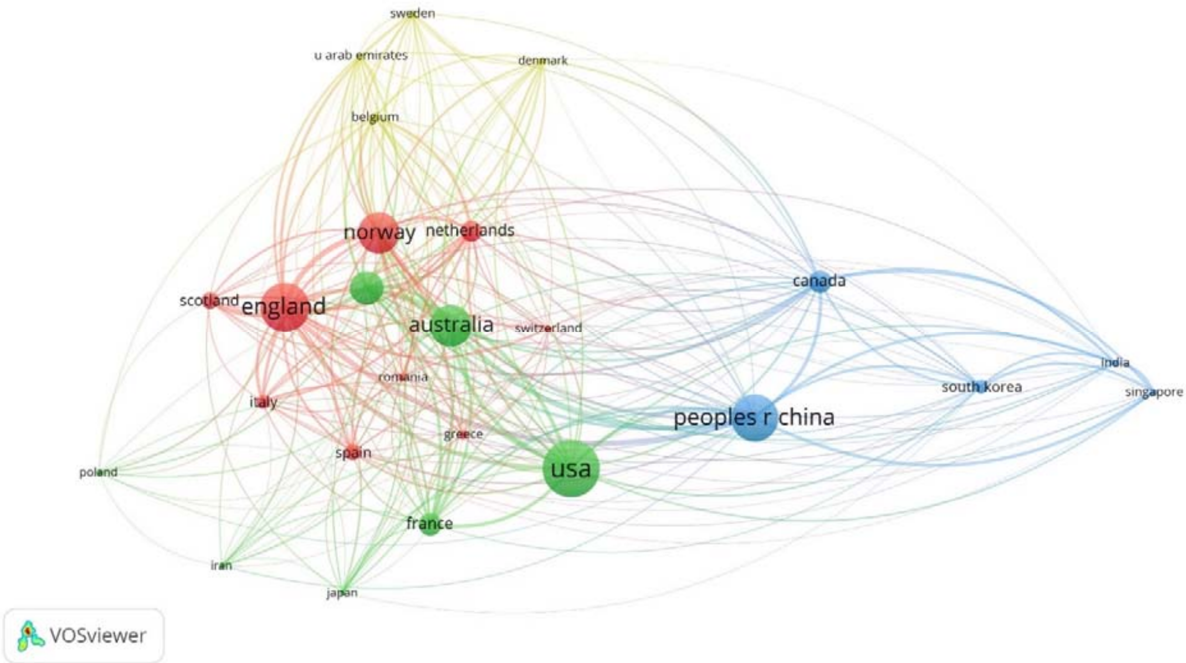

Fig. 4. Visualization of the collaboration strengths of countries actively with at least 10 publications on CCT related research (1998-2018).

Table 1

List of countries with a minimum of 10 publications on CCT during the period of 1998 to 2018.

Country	Total publications (TP)	Total citations (CT)	Average citation per publication (TC/TP)	Most Cited document	No. of Citations	Type of CCT
U.S.A.	146	4416	30.25	(Merkel et al., 2010)	680	Post-combustion
England	124	3178	25.63	(Wang et al., 2011)	560	Post-combustion
China	120	1876	15.63	(Drage et al., 2012)	172	Post-combustion
Australia	107	1888	17.64	(Stanger et al., 2015)	128	Oxy-fuel combustion
Norway	105	1911	18.20	(Kvamsdal et al., 2009)	150	Post-combustion
Germany	87	2505	28.79	(Oexmann and Kather, 2010)	154	Post-combustion
France	58	1795	30.95	(Kanniche et al., 2010)	350	Pre, post and oxy-fuel combustion
Canada	58	1367	23.57	(Linga et al., 2007)	302	Pre and post combustion

Netherlands	54	1971	36.50	(Mason et al., 2011)	525	Post-combustion
Scotland	43	409	9.51	(Lucquiaud, 2011)	61	Post-combustion
Spain	42	1161	27.64	(Martín et al., 2011)	222	Pre-combustion
South Korea	38	762	20.05	(Lee et al., 2010)	145	Pre-combustion
Italy	36	505	14.03	(Giuffrida et al., 2013)	55	Post-combustion
Belgium	25	319	12.76	(Mertens et al., 2013)	66	Post-combustion
Greece	22	252	11.45	(Ekström et al., 2009)	65	Pre and oxy-fuel combustion
Sweden	21	609	29.00	(Hedin et al., 2013)	198	Post-combustion
Romania	21	412	19.62	(Padurean et al., 2012)	85	Pre-combustion
Singapore	19	721	37.95	(Babu et al., 2013)	138	Pre-combustion
India	19	490	25.79	(Babu et al., 2013)	138	Pre-combustion

United Arab Emirates	19	223	11.74	(Mokhtar et al., 2012)	62	Post-combustion
Switzerland	18	331	18.39	(Jansen et al., 2015)	50	Pre-combustion
Denmark	16	282	17.63	(Ekström et al., 2009)	65	Pre and oxy-fuel combustion
Japan	15	336	22.40	(Goto et al., 2013)	202	Post-combustion
Poland	11	119	10.82	(Hanak et al., 2014)	41	Post-combustion
Iran	10	85	8.50	(Afkhamipour and Mofarahi, 2013)	30	Post-combustion

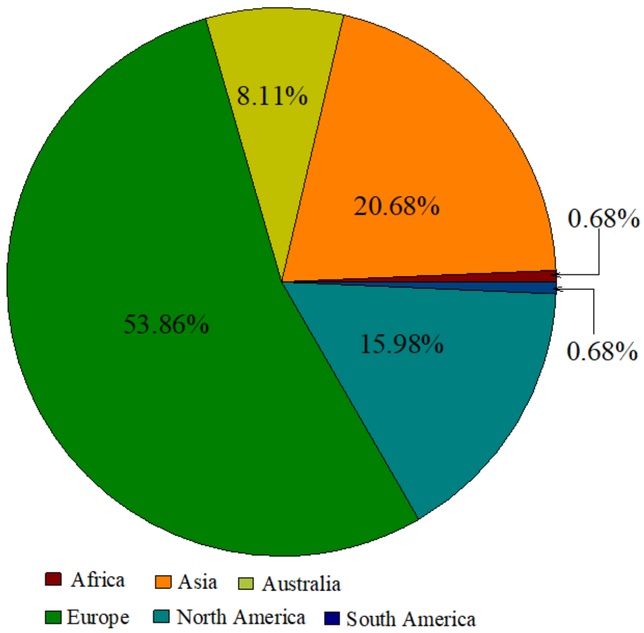

Fig. 5. Participation of continents in CCT related research in terms of percentage of publications.

The higher participation of European countries may be attributed to the fact that Europe has been on the forefront of the movement towards "zero emission" starting even before the United Nations Framework Convention on Climate Change was adopted on 9 May 1992 and the Kyoto Protocol on 11 December 1997 (Breidenich et al., 1998). Indeed, the first publication on zero emission (Seifritz, 1989) is attributed to the Paul Scherrer Institute in Switzerland. In Asia, China which is currently the second largest economy in the world after the U.S.A. ("The World's Largest Economies (2018-2022)," 2019) is expected to lead by example. Moreover, China is among the 37 industrialized countries that were committed to reducing greenhouse gas emission under the Kyoto Protocol (Kuh, 2017). Consequently, China's commitment to the climate change agreement might have encouraged other Asian countries to participate in research relating to the reduction of CO_2 emissions which is seen in the high number of publication from the region. In contrast, the participation of North America is not as high as expected considering that the U.S.A. emits the second highest amount of CO_2 annually in the world. Findings revealed that the U.S.A. had long withdrawn from the 1997 Kyoto Protocol since 27th of March 2001, outlining that the agreement was not fairly reached since economies such as China and India were exempted from complete compliance (Kahn, 2003; Phillipson, 2001). Consequently, after several years of policy debate, Canada formally announced its withdrawal from the Kyoto Protocol on the 12th of December 2011 which took effect on the 15th of December 2012 (Grubb, 2016). One of the reasons cited for the withdrawal was the non-involvement of the U.S.A. in the agreement which was translated as unfair to a balanced economic growth on the North American continent. Meanwhile, the poor participation observed in Africa may be due to the total exemption from the named agreements and the slow speed of respective technological advancement in the region.

The collaboration strengths of various countries represented in Fig. 4 was divided into 4 clusters, each represented by a unique colour. The lines linking the nodes in Fig. 4 show the partnership among countries and the thickness indicates the network strength in terms of number of co-authorship, citations or co-citations between two nodes (van Eck and Waltman, 2017). The distance between nodes (length of the connecting lines) can be used to determine the similarities in research interests between two countries such that the shorter the distance between countries the more similar they are and vice versa (van Eck and Waltman, 2010). The size of each node in Fig. 4 represents the number of publications. In cluster 1 (red colour), England had the greatest collaboration strength with other countries (total link strength = 772). In cluster 2 (green colour), the U.S.A. had the strongest network with other countries (total link strength = 557). This indicates that in spite of the U.S.A.'s withdrawal from the Kyoto Protocol, its research and collaborations with other countries on carbon capture were still strong, reinforcing a potential commitment to reducing own CO_2 emissions. China had the strongest network in cluster 3 (blue colour) with total link strength of 600. Finally, Belgium with a total link strength of 214 had the strongest collaboration strength in cluster 4 (yellow colour). The average link strength for all clusters was 12.9. This means that on an average, a country from any of the clusters had a collaboration with at least 13 other countries on CCT related research. This indicates that countries are not tackling climate change alone but with many others on carbon capture research.

3.3. Institutional participation

A total of 685 institutions was recorded to have been actively involved in CCT research. Eleven among these institutions had at least 20 publications on CCT related research (Fig. 6).

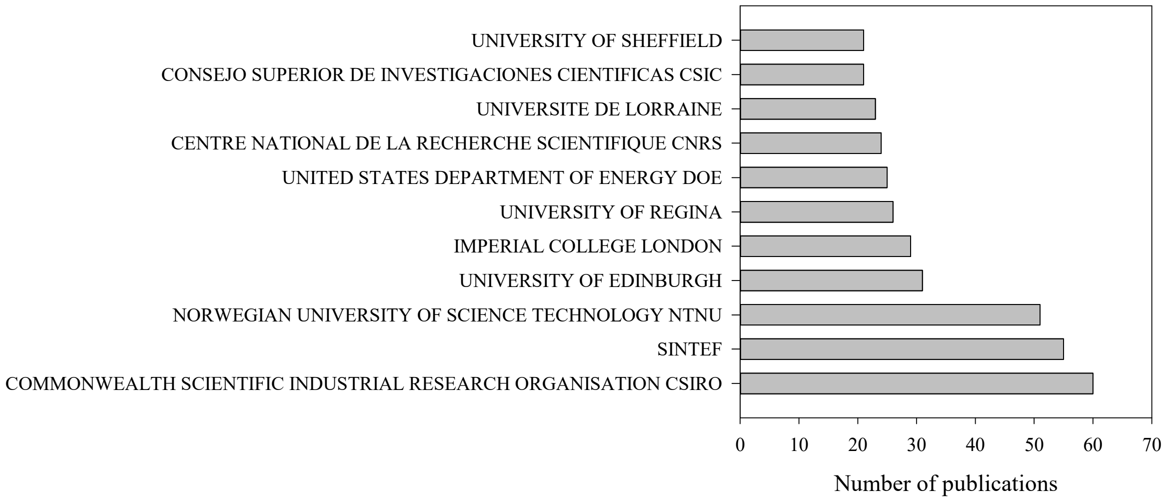

Fig. 6. Representation of participating institutions with at least 20 publications on CCT related research between 1998 and 2018).

As seen in the Figure, the Commonwealth Scientific Industrial Research Organisation (CSIRO, Australia) has the highest number of publications followed by SINTEF (Norway) and the Norwegian University of Science & Technology (NTNU). But in terms of citations, University of California Berkeley with just 4 publications is the third most cited institution (1,151 citations) after SINTEF (1,410 citations) and CSIRO (1,216 citations). This is an indication that irrespective of the total number of publications from one institution, its impact on other research can be very high.

For the co-authorship network analysis of the institutions two cases were considered for simplicity of data analysis: viz. 1. Institutions with a minimum of zero citation and at least 10 publications (capturing the more active institutions), and 2. Institutions with a minimum of 100 citations and at least 1 publication (capturing the most influential institutions). In Fig. 7, the strongest co-authorship collaboration existed between NTNU and SINTEF Materials & Chemistry (link strength = 9.33) followed by the Netherlands Organisation for Applied Scientific Research (TNO) and Delft University of Science & Technology (link strength = 5.00), and by University of Regina and Hunan University (link strength = 5.00). This implies that NTNU co-authored approximately 9 publications with SINTEF while University of Regina co-authored about 5 publications with Hunan University. Overall, CSIRO is the most connected institution followed by NTNU and SINTEF.

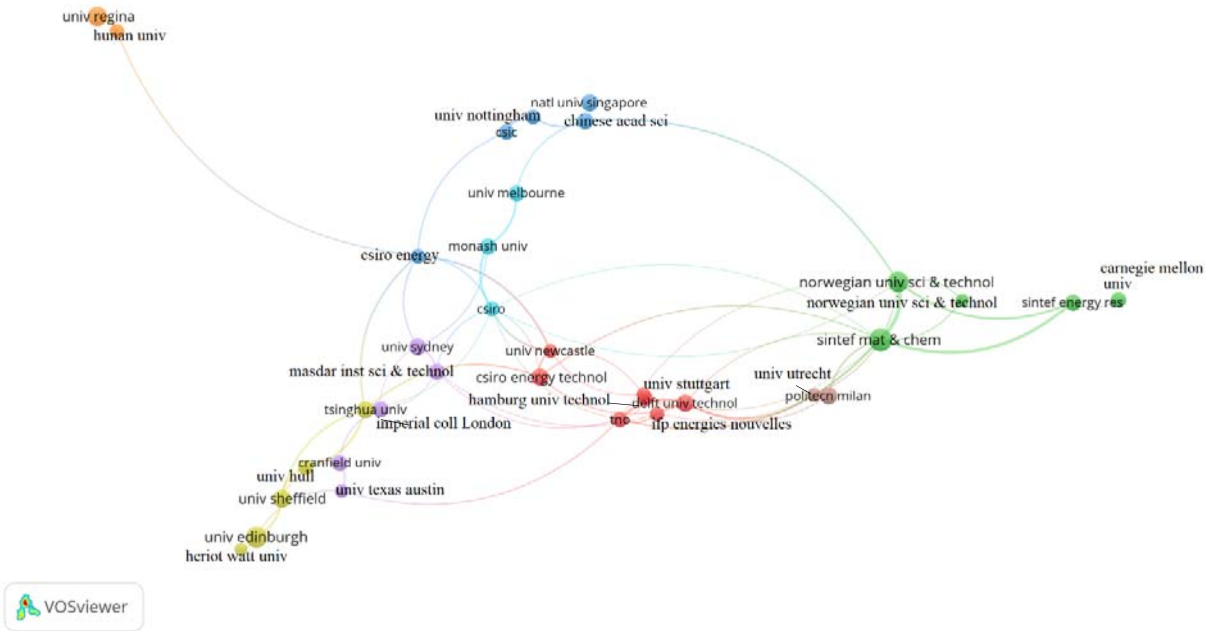

Fig. 7. Co-authorship network of institutions with minimum of zero citation and at least 10 publications on CCT related research within 1998 and 2018.

3.4. Journals participation

A total of 204 Journals participated in the publication of CCT related articles and proceeding papers. The journals with minimum of 5 publications are represented in Fig. 8. The journals were grouped into 4 distinct clusters. Journal of Energy (total link strength = 747) has the greatest connection in cluster 1 (red). Journal of Applied energy (total link strength = 884) is the most connected in cluster 2 (green). International Journal of Greenhouse Gas Control (total link strength = 2,533) has the strongest connection in cluster 3 (blue).

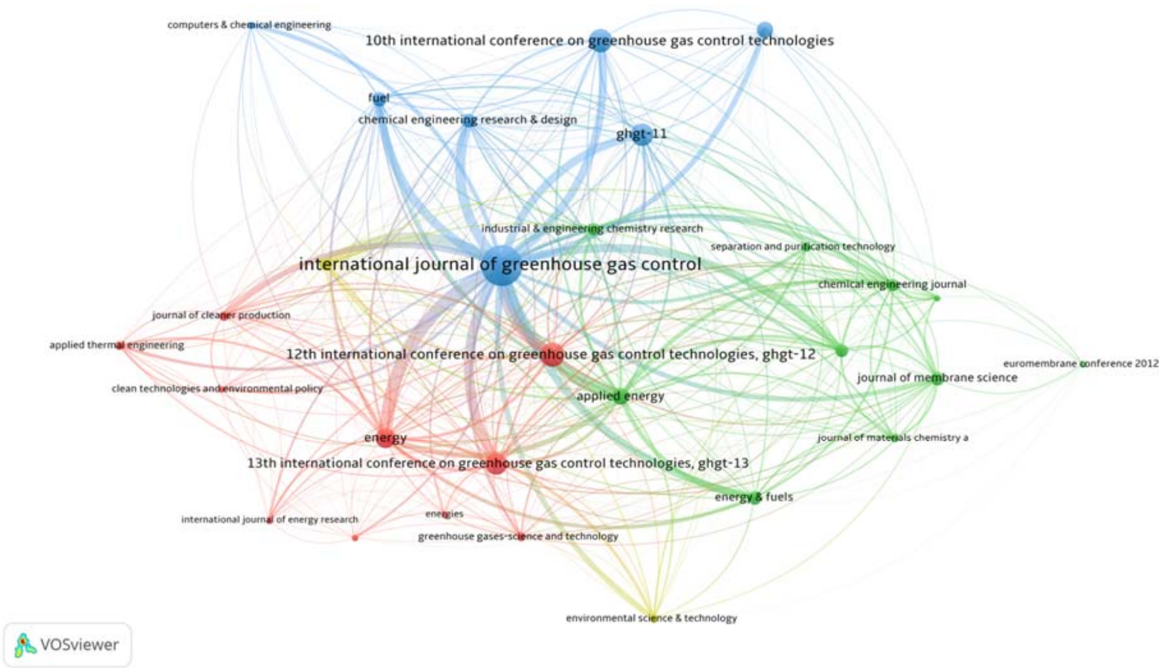

Fig. 8. Network visualization map of journals with minimum of 5 publications on CCT during 1998-2018.

Finally, Absorption-Based Post-Combustion Capture of Carbon Dioxide (total link strength = 468) has the highest network in cluster 4 (yellow). Considering the network between two journals, the connection between International Journal of Greenhouse Gas Control and Journal of Applied Energy is the strongest (link strength = 232) followed by the connection between International Journal of Greenhouse Gas Control and Journal of Energy (link strength = 223). Overall, International Journal of Greenhouse Gas Control with 166 publications has the greatest impact by way of total citations. The strong participation by International Journal of Greenhouse Gas Control is expected since the journal is mainly centred on the publication of work relating to greenhouse gas emissions and climate change mitigation via carbon dioxide capture, transport and storage as compared to other journals that are majorly multidisciplinary.

Table 2
List of top ten journals and proceedings with highest citations in publications on CCT during 1998-2018.

Journal Name	TC	TP	TC/TP
International Journal of Greenhouse Gas Control	4532	166	27.3
Journal of Membrane Science	1466	22	66.6
Applied Energy	1451	32	45.3
Energy	1444	43	33.6
Chemical Engineering Research & Design	1042	22	47.4
10th International Conference on Greenhouse Gas Control Technologies	1006	56	18.0
Energy & Environmental Science	866	4	216.5
Chemical Engineering Journal	863	16	53.9
Greenhouse Gas Control Technologies 9	800	28	28.6
Fuel	644	23	28.0

In terms of number of citations, the top ten most cited journals (see

Table 2) accounted for about 63% of the total citations during 1998-2018. While the International Journal of Greenhouse Gas Control was the most cited and published journal, the Journal of Energy & Environmental Science had the highest average citations per publication of 216.5. The average citation per publication of International Journal of Greenhouse Gas Control was 27.3. Therefore, the criteria for determining participation strength vary. One may rank the impact of a journal based on its number of publications or based on the total citations received.

3.5. Participating Authors

3.5.1. Co-authorship of authors

An author's number of publications and citations are an indication of experts in a given field as well as the visibility of their research output. In co-authorship analysis of authors, a total of 2,393 authors were recorded. Among these authors, M.H. Wang (from University of Sheffield)had the highest number of publications (24) followed by E. Favre (University of Lorraine), P. Feron (CSIRO) and P. Tontiwachwuthikul (University of Regina) with 20 publications each (see Fig. 9). Meanwhile, P. Linga (National University of Singapore) with 14 publications was the most cited author (936 citations) followed by Z.R. Herm (University of California, Berkeley) and R. Krishna (University of Amsterdam) who received 840 citations each with 2 publications while M.H. Wang only received 361 citations. R. Baker, H. Lin, T.C. Merkel and X Wei affiliated with Membrane Technology and Research (MTR), Inc. and with only one topical publication received 680 citations each. Apparently there are cases where a discrepancy exists between the activity of an author and the impact achieved. This imbalanced trend is likely one of the reasons for ambivalence when setting criteria for ranking authors, journals, institutions and countries/regions. While many believed that citation number is a reflection of the relevance (Parmar et al., 2019), others think the number of publications may also be used as an indication of an author's productivity in a particular research area (Bottle et al., 1994). Accordingly, the co-authorship analysis was conducted bearing in mind that an author with just one publication may have high relevance in terms of number of citations. In this regard, authors with minimum of 1 publication and at least 200 citations were considered as shown in Fig. 10. The authors were grouped into 23 clusters according to their co-authorship relationship. The colours of the nodes, in this case, signify research activities in terms of average publication year (APY). For instance, M.H. Wang with a dark red node had an APY of 2015.5. Similarly, the APY of P. Englezos (University of British Columbia) with purple node and P. Linga with yellow node are 2009 and 2012.8, respectively. The node size represents the number of publications while the thickness of the connecting lines (link strength) represents the number of co-authored publications.

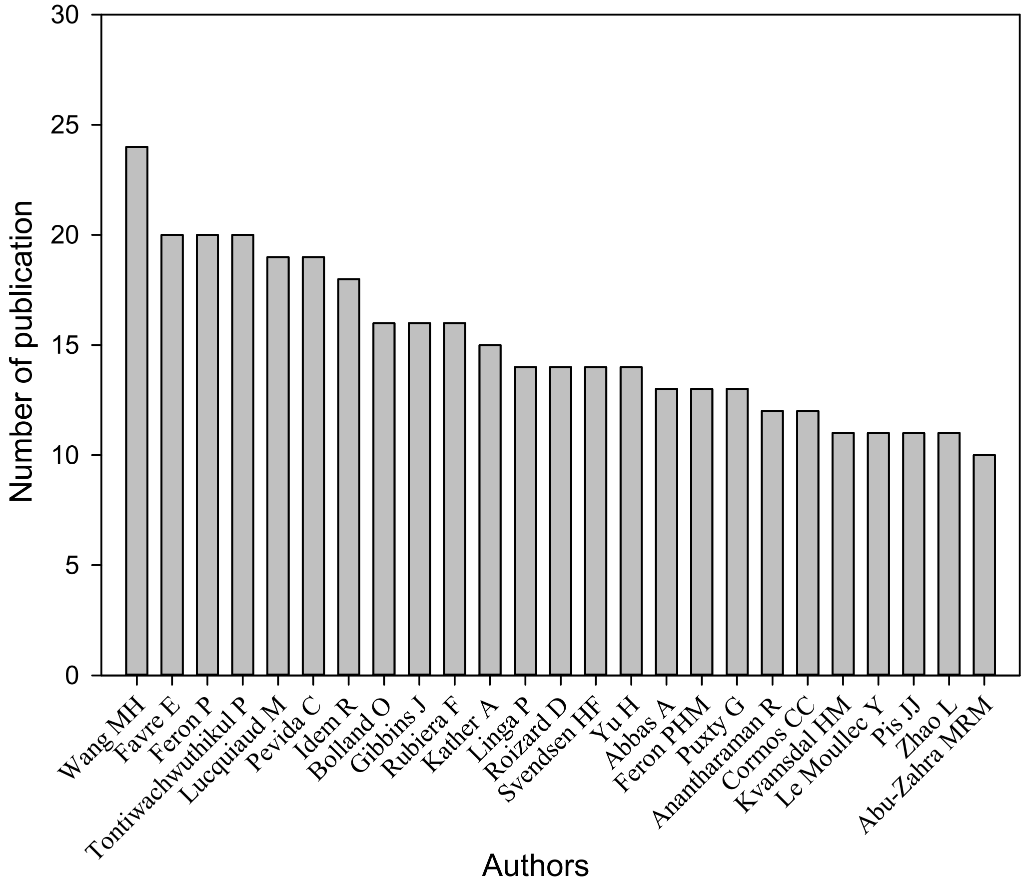

Fig. 9. Representation of authors with minimum of 10 publications on CCT during 1998-2018.

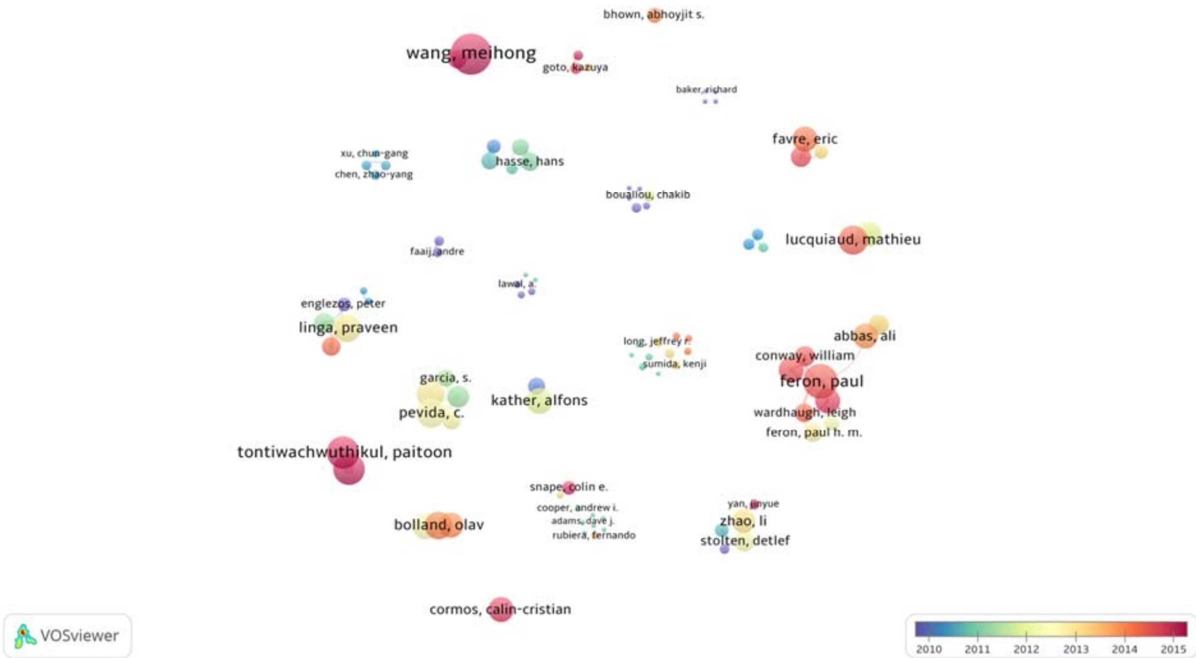

Fig. 10. Co-authorship network of authors with minimum of 1 publication and at least 200 citations during 1998-2018. The colours of the nodes are based on average publication year of the authors which can be obtained by comparing with the colour pattern shown in the legend.

Furthermore, P. Feron (total link strength = 15) was found to have a strong co-authorship network with various authors. Other authors with strong co-authorship network include C. Pevida and F. Rubiera affiliated with CSIC, Spain and total link strength = 14 and R. Idem (University of Regina), P. Linga and P. Tontiwachwuthikul (total link strength = 12). Considering the link between two authors, the strongest co-authorship network was between R. Idem and P. Tontiwachwuthikul (link strength = 12) and then, the link between J. Gibbins and M. Lucquiaud affiliated with University of Edinburgh with link strength = 10. It is worth mentioning that while total link strength indicates the total network strength of an author, only shows the partnership strength between two authors.

3.5.2. Co-citation of authors

Co-citation analysis is one of the tools that can be used for establishing the connection among authors who have been co-cited by a set of publications (García-Lillo et al., 2019; Mora et al., 2019). In this study, the co-citation analysis of authors with a minimum of 20 citations were considered. Accordingly, only 232 authors out of 9,944 co-cited authors in the publications between 1998 and 2018 met the criteria. As shown in Fig. 11, the authors were grouped into 6 clusters. G.T. Rochelle (University of Texas Austin), M.G. Plaza (CSIC, Spain), M.R.M. Abu-Zahra (Masdar Institute of Science and Technology), E.S. Rubin (Carnegie Mellon University), B. Metz (European Climate Foundation) and P. Linga are authors with highest co-citation in clusters red, green, blue, yellow, purple and turquoise colour, respectively. Overall, M.R.M. Abu-Zahra was the most co-cited author. By pairing authors, the strongest co-citation strength was found between P. Linga and R. Kumar (National Chemical Laboratory, India) followed by S.C. Lee (Kyungpook National University) and C.W. Zhao (Nanjing Normal University) and then H.M. Kvamsdal (SINTEF) and A. Lawal (Cranfield University).

Following the results obtained, the closeness in terms of research interests and activities between any two authors shown in Fig. 11 was determined. For instance, the co-citation of authors in the turquoise cluster was received in publications mainly on pre-combustion CCT. General findings showed that most authors that were co-cited had publications largely on post-combustion CCT and then on pre-combustion CCT with very few publications on oxy-fuel combustion. Finally in this section, we compared the research activities of authors based on the three types of CCT considered in this study. As expected, our findings showed that post-combustion CCT was the most researched area with 835 publications, followed by pre-combustion (162 publications), while the least researched was oxy-fuel combustion with 35 publications (see Fig. 12). Taking into account the uneven distribution of research activities in the three types of CCT, authors in the top 5 most cited article publications in each type of CCT are listed in Table 3.

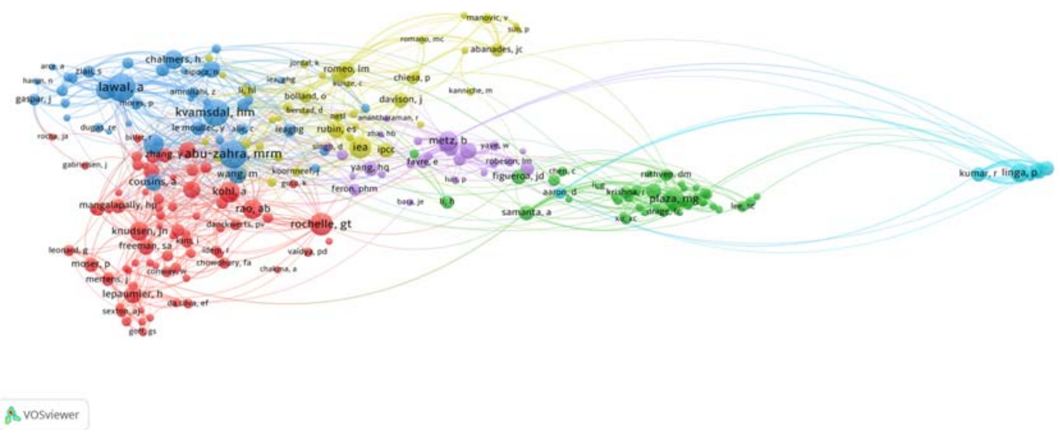

Fig. 11. Network visualization of co-citation of authors with minimum of 20 citations in CCT related publications during 1998-2018.

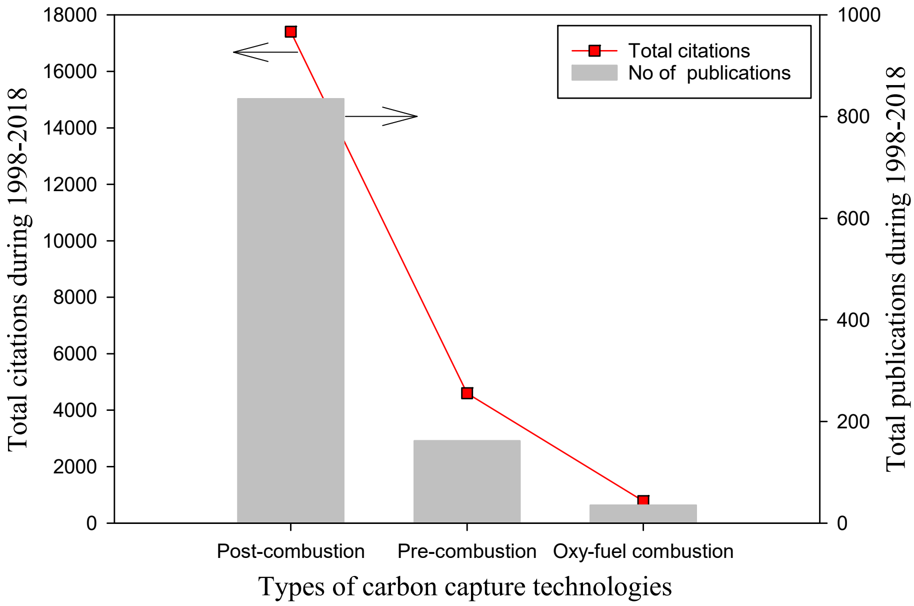

Fig. 12. Comparison of the three types of CCT based on the number of publications and citations in the period 1998 to 2018.

3.6. Co-occurrence of author keywords

Co-occurring keywords used by authors were retrieved and analysed. A total of 1,913 keywords with 4261 co-occurrences were obtained. In this study, consideration was given to keywords with a minimum of 5 occurrences as shown in Fig. 13. These keywords were grouped into 9 coloured clusters according to similarities in the areas of research. The 15 most occurring keywords were "CO_2 capture" (256 occurrences), Post-Combustion (79 occurrences), Post-Combustion CO_2 Capture (76 occurrences), Carbon Capture (59 occurrences), Post-Combustion Capture (48 occurrences), MEA – monoethanolamine (44 occurrences), Absorption (40 occurrences), CO_2 (40 occurrences), CCS – carbon capture and storage (34 occurrences), IGCC – integrated gasification combined cycle (33 occurrences), Adsorption (31 occurrences), Carbon Dioxide (29 occurrences), Chemical Absorption (29 occurrences) and Pre-Combustion (28 occurrences).

Meanwhile, the first appearance of oxy-fuel combustion was found in the 51st position with 11 occurrences. The strongest co-occurrence networks were between CO_2 capture and post-combustion (link strength = 13.4) followed by CO_2 capture and adsorption (link strength = 10.6).

Table 3

List of authors in the first 5 most cited publications on the various types of CCT during 1998-2018.

Types of CCT	Author	Document	TC	Av. citations per year
Pre-combustion capture	Kanniche Mohamed; Gros-Bonnivard Rene; Jaud Philippe; Valle-Marcos Jose; Amann Jean-Marc; Bouallou Chakib	(Kanniche et al., 2010)	350	35.0
	Herm Zoey R.; Swisher Joseph A.; Smit Berend; Krishna Rajamani; Long Jeffrey R.	(Herm et al., 2011)	315	35.0
	Linga Praveen; Kumar Rajnish; Englezos Peter	(Linga et al., 2007)	302	23.2
	Martin Claudia F.; Stoeckel Ev; Clowes Rob; Adams Dave J.; Cooper Andrew I.; Pis Jose J.; Rubiera Fernando; Pevida Cova	(Martín et al., 2011)	222	24.7
	Lee Hyun Ju; Lee Ju Dong; Linga Praveen; Englezos Peter; Kim Young Seok; Lee Man Sig; Kim Yang Do	(Lee et al., 2010)	145	14.5
Post-combustion capture	Merkel Tim C.; Lin Haiqing; Wei Xiaotong; Baker Richard	(Merkel et al., 2010)	680	68.0
	Wang M.; Lawal A.; Stephenson P.; Sidders J.; Ramshaw C.	(Wang et al., 2011)	560	62.2
	Mason Jarad A.; Sumida Kenji; Herm Zoey R.; Krishna Rajamani; Long Jeffrey. R.	(Mason et al., 2011)	525	58.3

	Kanniche Mohamed; Gros-Bonnivard Rene; Jaud Philippe; Valle-Marcos Jose; Amann Jean-Marc; Bouallou Chakib	(Kanniche et al., 2010)	350	35.0
	Goto Kazuya; Yogo Katsunori; Higashii Takayuki	(Goto et al., 2013)	202	28.9
Oxy-fuel combustion	Stanger Rohan; Wall Terry; Spoerl Reinhold; Paneru Manoj; Grathwohl Simon; Weidmann Max; Schefflmecht Guenter; McDonald Denny; Myohanen Kari; Ritvanen Jouni; Rahiala Sirpa; Hyppanen Timo; Mletzko Jan; Kather Alfons; Santos Stanley	(Stanger et al., 2015)	128	25.6
	Li H.; Yan J.; Yan J.; Anheden M.	(Li et al., 2009)	125	11.4
	Habib M. A.; Badr H. M.; Ahmed S. F.; Ben-Mansour R.; Mezghani K.; Imashuku S.; la O' G. J.; Shao-Horn Y.; Mancini N. D.; Mitsos A.; Kirchen P.; Ghoneim A. F.	(Habib et al., 2011)	98	10.9
	Jia L.; Tan Y.; Wang C.; Anthony E. J.	(Jia et al., 2007)	95	7.3
	Zheng L.	(Zheng, 2011)	63	7.0

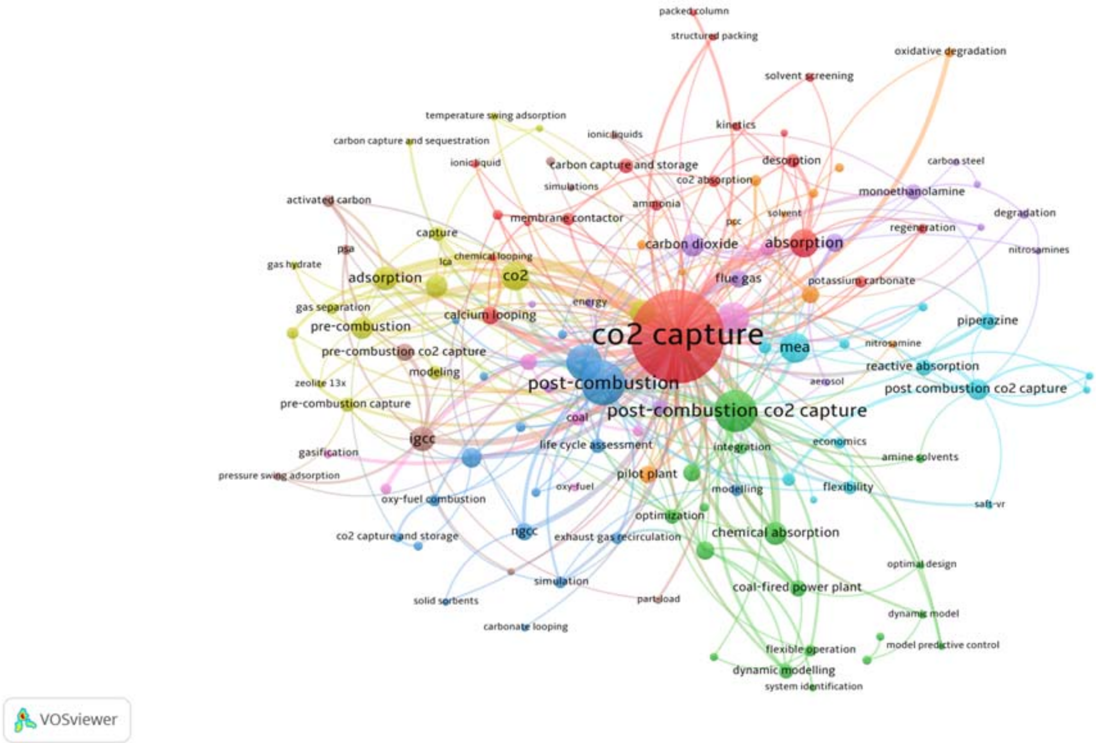

Fig. 13. Network of keywords with minimum of 5 co-occurrences in publications on CCT related research between 1998 and 2018.

Essentially, the results from keywords occurrences revealed that research on carbon capture ranges from the capture technologies, separation processes (MEA, Absorption and adsorption), to storage and the process simulation. However, research on post-combustion capture showed to have a wider range of activity whilst oxy-fuel combustion attracted least interest globally.

This study showed that there is a global awareness and ongoing efforts towards ensuring that carbon capture is more prominently employed. This study also revealed that the most researched CCT was the post-combustion type whilst oxy-fuel combustion CCT gained less attention. Our findings revealed that high cost of supplying the oxygen required for the process was a major factor responsible for the low interest in oxy-fuel combustion CCT. On the other hand, post-combustion CCT was widely used in the industry because it can be retrofitted with existing power plants without severely changing the process operations (Nathan, 2019; Olajire, 2010). Additionally, the process flexibility allows a power plant to continue operating in a situation where the capturing system malfunctions (Rashidi and Yusup, 2016). One of the advantages of pre-combustion CCT is that lower amount of energy is required compared to post-combustion CCT for solvent regeneration after CO_2 ab- or adsorption (separation process) (Rahman et al., 2017).