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Global characteristics and trends of research on ceramic membranes from 1998 to 2016: Based on bibliometric analysis combined with information visualization analysis

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ABSTRACT

Using bibliometric analysis combined with information visualization analysis, this paper aims at investigating the global characteristics and trends of research on ceramic membranes. According to the 3697 publications from 1998 to 2016 in Science Citation Index Expended, this study was conducted from five major aspects, including basic growth trends analysis, countries/ territories and institutions analysis, categories and journals analysis, keywords analysis, and citation bursts detection. This study revealed positive growth trends of the research on ceramic membranes. The most productive countries and institutions were both from Peoples R China, and the collaborations among countries and institutions were frequent worldwide. The result of categories analysis revealed that the major discipline groups of the research on ceramic membranes were distributed in chemistry, physics, material, and application. Water resource, energy, environmental science and food engineering were the main application fields of ceramic membranes according to the journals analysis. Furthermore, three keyword clusters were identified, indicating that the main research directions of the research on ceramic membranes included membrane filtration, oxygen permeation and the fabrication of ceramic membranes. Finally, the top 20 citation bursts with the maximum burst strength were detected, indicating that the research on oxygen separation and water treatment has been flourishing in recent years.

1. Introduction

Ceramic membranes are a type of artificial membranes fabricated with inorganic ceramic materials through specific processes. The traditional but important function of ceramic membranes is to realize the separation of substances. Relying on the trans-membrane pressure and pore size, when the fluid with multiple components pass the ceramic membranes, the target substance will be separated from others. In recent years, the function of ceramic membranes has been extended to substances transformation via coating some catalytic materials on the surface [1]. Compared with organic membranes, ceramic membranes have many advantages such as good separation efficiency, excellent chemical resistance, high mechanical strength and stable thermal property [2]. Therefore, ceramic membranes have been widely used in many fields such as food [3], chemical engineering [4]and environmental protection [5,6]etc. It is noting that the ceramic membrane technique has been improved constantly and a growing body of research on ceramic membranes has been done, especially in recent years. Therefore, it is essential for the stakeholders to capture the state of art and development of the research on ceramic membranes.

The characteristics and trends of the research on a discipline can be reflected from the information of related publications [7,8]. However, it is hard for the stakeholders in this field to read all of the publications thoroughly, especially for the beginner. Certainly, this issue also existed in the research on ceramic membranes. Therefore, with the booming of the research on ceramic membranes, it is necessary to summary the existing research using an appropriate means to assess the characteristics and trends of the research on ceramic membranes.

Bibliometric analysis is a method to analyze the literature information based on mathematics and statistics but avoid people reading extensive publications [9]. By quantificationally analyzing some objects such as publications, countries, institutions, authors, journals, categories and keywords, bibliometric analysis can evaluate the present situation and growth trend of a specific research field in general [10]. However, it is difficult for traditional bibliometric to fabricate the collaboration or co-occurrence networks, which are also the important messages for relationship analysis of one research field. Moreover, bibliometric is unable to make cluster analysis, burst detection and other deep analyses. Information visualization analysis is an approach which can convert the complicated raw materials of publications into

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the formats easy to observe [11]. Although information visualization analysis is not convenient to do the quantitative analysis, it is competent to conduct the network analysis [7], cluster analysis [12], burst detection [13] etc. Therefore, the method integrating the bibliometric analysis and information visualization analysis is much possible to assure the results of accuracy as well as comprehensiveness. There have been various research fields applying the bibliometric analysis or information visualization analysis, including environmental protection [9], medicine [14], information technology [15], energy [16], education [17] etc. However, most of the existing studies just used the single analysis tool and the burst detection were imperfect to give the comprehensive descriptions of the related research area. In addition, to our best knowledge, there is a lack of comprehensive and multi-perspective description of the research on ceramic membranes based on bibliometric analysis combined with information visualization analysis.

The aim of this study is to identify the characteristics and trends of the research on ceramic membranes based on bibliometric analysis combined with information visualization analysis. Using various analysis tools from different aspects, a comprehensive and multi-perspective summary of the research on ceramic membranes was given based the publications from 1998 to 2016. In more detail, the study was conducted from 5 main aspects according to the different analysis objects, including basic growth trends analysis, countries/territories and institutions analysis, categories and journals analysis, keywords analysis and citation bursts detection.

2. Materials and methods

The data collection was conducted on September 12th, 2017. Web of Science Core Collection was chosen as the source database, but only the publications recorded in Science Citation Index Expanded(SCI-E) from 1998 to 2016 were collected in this study. “Ceramic membrane*” was used as the topic keyword and then 3697 records were found. The 3697 full records and their cited references were downloaded as the raw materials for further analysis. Of all collected publication records, article (3052, 82.55%) is the most frequent publication type, followed by proceeding paper (474, 12.82%), review (133, 3.60%), meeting abstract (25, 0.68%) and others (13, 0.35%).

The statistical data, such as the information of publications, authors, pages, citations, journals and categories, were calculated by Excel and HistCite [18]. The basic collaboration networks between institutions and countries were waved by VOSviewer [19,20] and the graphical collaboration map was fabricated by Citespace [8,21]. In addition to the network analysis, the VOSviewer and Citespace were also used to find the keywords clusters and detect the citation bursts, respectively.

3. Results and discussion

3.1. Basic growth trends analysis

The trends of the number of publications and average number of authors per publication are shown in Fig. 1. It is evident that the number of publications increased steadily despite some fluctuations, which was 118 in 1998 but increased into 331 in 2016. This phenomenon reveals that the research on ceramic membranes has attracted an increasing attention. Similarly, the average number of authors per publication also increased in general, from 3.64 in 1998 to 4.94 in 2016. This rising tendency indicates the increasingly close collaborations between authors. Fig. 2 shows the trends of the average number of references, citations and pages per publication. As is shown in the figure, there was an increasing tendency of the average number of references from 1998 to 2016. The average number of references reached 43.15 in 2016, about 2 times many as that of 21.31 in 1998. The increasing number of the publications available for reference may be one reason for this phenomenon. Another reason is that the journals need more sufficient evidences to make the publications more convincing

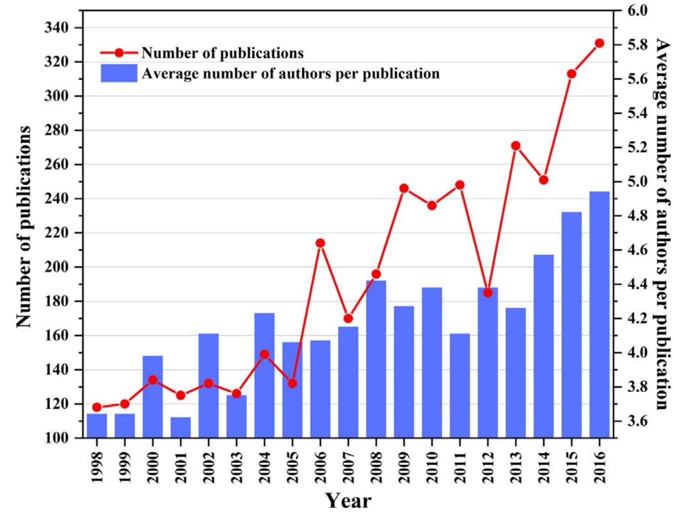

Fig. 1. Trends of the number of publications and average number of authors per publication.

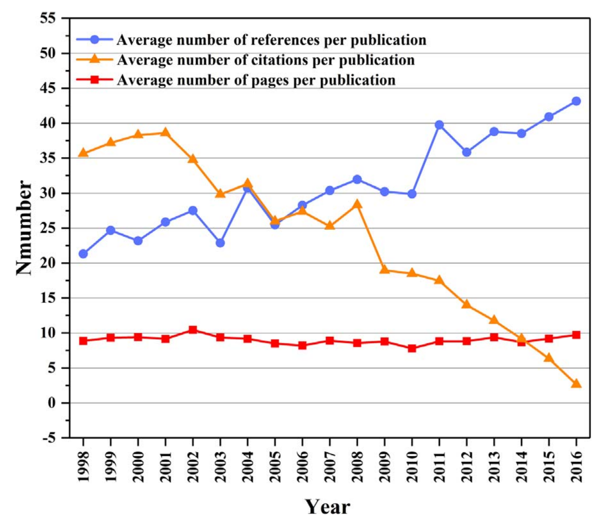

Fig. 2. Trends of the average number of references, citations and pages per publication.

with the development of the quality of journals. The average number of citations per publication showed an increasing tendency at the beginning of the collection period, then peaked at 38.58 in 2001. However, it decreased sharply from then on, which was just 2.65 in 2016. The reason for this declining phenomenon may be that the new publications need adequate time to accumulate the citations. Interestingly, the average number of pages per publication fluctuated around 9 slightly with no evident growth trend, indicating the length of publications was steady.

3.2. Countries/territories and institutions analysis

3.2.1. Countries/territories analysis

According to the 3697 records collected, there were 75 different countries/territories that published their works on ceramic membranes in SCI-E from 1998 to 2016. It is noted that 70% of the countries/territories published more than 10 works but 12% of the countries just published a single work. Table 1 lists the top 20 most productive countries. To evaluate the quality of publications, TLCS and TGCS were introduced as metrics. TLCS represents the total local citation score, which shows the total number of citations of all publications from a specific country based on the local records. TGCS represents the total global citation score, showing the total number of citations of all

Table 1
Top 20 most productive countries during 1998–2016.

Country	N(*R*)	TLCS(*R*)	TGCS(*R*)
Peoples R China	783(1)	4045(1)	13673(2)
USA	491(2)	2637(2)	14013(1)
France	289(3)	1482(3)	6568(3)
Germany	242(4)	1175(5)	5961(4)
Spain	227(5)	791(8)	4667(8)
Japan	216(6)	1011(6)	4931(7)
Australia	175(7)	1177(4)	5256(6)
South Korea	154(8)	340(12)	2197(11)
UK	145(9)	619(9)	3311(9)
India	129(10)	422(10)	1811(12)
Netherlands	129(10)	862(7)	5630(5)
Iran	103(12)	293(14)	1250(16)
Poland	95(13)	301(13)	982(18)
Italy	89(14)	193(17)	2402(10)
Russia	85(15)	113(20)	533(20)
Canada	76(16)	171(18)	1103(17)
Brazil	73(17)	131(19)	907(19)
Portugal	68(18)	360(11)	1380(14)
Singapore	65(19)	226(15)	1299(15)
Belgium	56(20)	213(16)	1508(13)

N total number of publications; R ranking in column; TLCS total local citation score; TGCS total global citation score.

publications from a specific country in Web of Science. Obviously, in addition to the number of publications, the TLCS and TGCS of Peoples R China, USA and France also occupied the top three places. This phenomenon indicates that the three countries above were dominated in the research on ceramic membranes. It is noted that though the number of publications from Netherlands, Portugal, Singapore and Belgium were not at the top, both the TLCS and TGCS of them were relatively high. On the contrary, South Korea and Russia performed better in terms of the number of publications instead of TLCS or TGCS. This phenomenon could reveal that there is no evident connection between the number of publications and citations for a specific country. Interestingly, the number of publications, TLCS and TGCS of UK all ranked in 9th, indicating the coordinated development between the quality and quantity of the publications form UK.

Fig. 3 shows the growth trends of the number of publications from the top 10 most productive countries (India and Netherlands tie for 10th). It is not difficult to identity that the number of publications of USA had been the first place before 2005, indicating the good research foundation of USA on ceramic membranes. However, Peoples R China overtook USA in 2005 and then has maintained the first place ever since. Though there were some fluctuations, the publications number of Peoples R China showed an overall upward trend from 1998 to 2016. The most dramatic growth of publications number of Peoples R China occurred during the period of 2014–2015, when the number of publications increased abruptly from 53 to 105. The reason for this increasing tendency is that the government of Peoples R China has introduced a series of powerful polices to support the research and development of membrane materials [22]. It is noted that the number of publications from Germany, South Korea, Spain and India also increased in general, but other countries fluctuated with no evident growth trends.

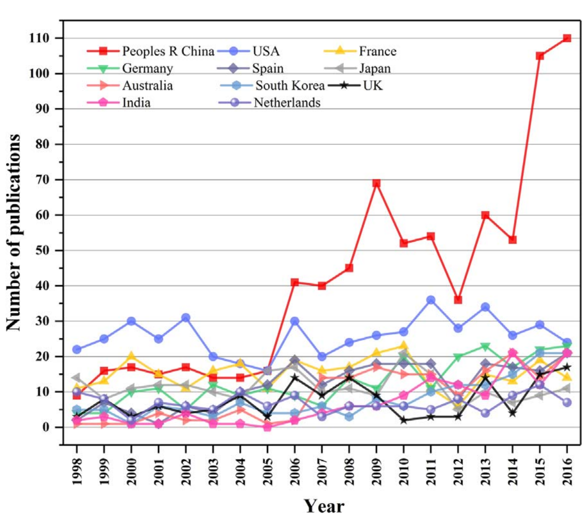

Fig. 3. Growth trends of the number of publications from the top 10 most productive countries.

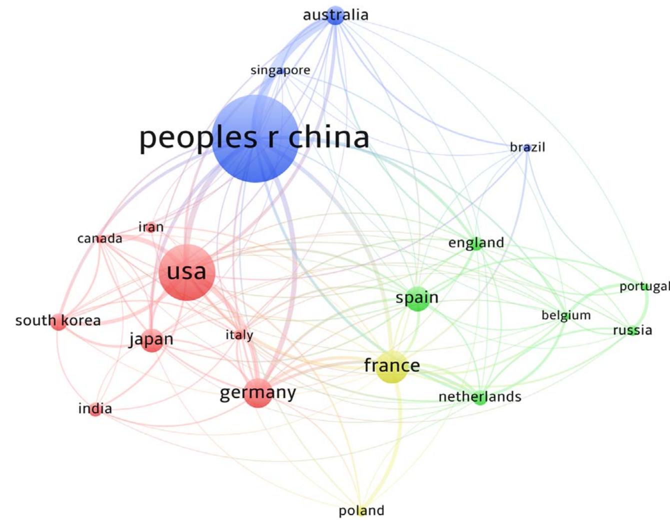

Fig. 4. Collaboration network between the 20 most productive countries.

The collaboration network between the top 20 most productive source countries is shown in Fig. 4. In this picture, each circle represents a country and each curve represent the cooperative relationship between the two countries linked. It is noted that the circle size and link thickness are proportional to the number of publications and the strength of collaborations, respectively. Evidently, the network is dense in general which indicates that the collaboration between countries was frequent in the research on ceramic membranes. In accordance with the message in Table 1, the biggest circle was labeled with Peoples R China, indicating its largest number of publications. It is easy to identify that some countries such as USA, Germany, France and UK also had the relatively large number of publications. In terms of the collaboration between countries, some countries such as Peoples R China, USA, Japan, Spain and UK had the most intensive collaboration with other countries. The maximum collaboration intensity appeared between Peoples R China and Austria, but USA had the broadest collaboration with other countries. It is also worth noting that Italy, Canada and Belgium, had relatively small number of publications but frequent collaborations with other countries.

3.2.2. Institutions analysis

The 3697 records collected are from 1962 different institutions. However, only 115 institutions had the publications more than 10, accounting for 5.86% of the total number of institutions. The top 20 most productive institutions are listed in Table 2 (Indian Institute of Technology Guwahati, Nanyang Technological University and The Imperial College of Science tie for 19th). Similar to the countries analysis above, N, TLCS and TGCS were also chosen as the metrics to evaluate the performance of the institutions. As is shown in Table 2, the most productive institution was Nanjing Tech University, the number publications of which was 200, accounting for 4.08% of the total collected records. In addition to the number of publications, Nanjing Tech University also occupied the first place both in TLCS and TGCS,

Table 2
Top 20 most productive institutions during 1998–2016.

Institution	N(*R*)	TLCS(*R*)	TGCS(*R*)
Nanjing Tech University, Peoples R China	200(1)	1127(1)	3559(1)
Chinese Academy of Sciences, Peoples R China	133(2)	1010(2)	3297(4)
University of Science and Technology of China, Peoples R China	83(3)	414(6)	1590(6)
University of Twente, Netherlands	70(4)	628(4)	3446(2)
University of Queensland, Australia	64(5)	766(3)	3331(3)
Universitat Politècnica de València, Spain	56(6)	248(10)	1216(8)
University of Aveiro, Portugal	47(7)	315(8)	1055(11)
Université de Montpellier II2, France	46(8)	141(16)	731(13)
Russian Academy of Sciences, Russian	43(9)	42(21)	212(21)
South China University of Technology, Peoples R China	42(10)	195(14)	517(17)
University of Cincinnati, USA	41(11)	628(4)	2397(5)
Hiroshima University, Japan	40(12)	362(7)	1240(7)
Forschungszentrum Jülich, Germany	37(13)	271(9)	1134(9)
Shanghai University, Peoples R China	37(14)	244 (12)	565(14)
National University of Singapore, Singapore	35(15)	108(19)	533(15)
University of Oviedo, Spain	35(15)	151(15)	506(19)
Centre national de la recherche scientifique, France	33(17)	128(17)	518(16)
Universiti Sains Malaysia, Malaysia	29(18)	101(20)	507(18)
Indian Institute of Technology Guwahati, India	28(19)	198(13)	450(20)
Nanyang Technological University, Singapore	28(19)	118(18)	751(12)
The Imperial College of Science, Technology and Medicine, UK	28(19)	245(11)	1008(10)

N total number of publications; R ranking in column; TLCS total local citation score; TGCS total global citation score.

showing its dominance in the field of the research on ceramic membranes. The reason for this phenomenon is that Nanjing Tech University is one of the foregoers of the research on ceramic membranes in Peoples R China which has undertaken multiple of national key projects since 1990s. It is also noted that the top three most productive institutions were all from Peoples R China. Some institutions such as Université de Montpellier II2, Russian Academy of Sciences, South China University of Technology had the relatively large number of publications, however, their performances on TLCS and TGCS were not as good as the number of publications. On the country, some countries have the good performance in terms of TLCS and TGCS instead of the number of publications. For instance, though the publications number of University of Cincinnati ranked in 11th, but its TLCS and TGCS ranked in 4th and 5th, respectively.

Similar to the countries discussed in 3.2.1, the collaboration network between the top 20 most productive institutions is showed in Fig. 5. It is noted that University of Aveiro, Russian Academy of Sciences, National University of Singapore, Universiti Sains Malaysia and Indian Institute of Technology Guwahati were not connected with each other in the top 20 most productive institutions list, thus only 16 connected institutions were showed in the figure. In addition, some labels of overlapped circles were hidden for the clarity of figure. It is easy to identity that the circles with the biggest radius was labeled with Nanjing Tech University, followed by Chinese Academy of Sciences, University of Science and Technology of China. This phenomenon is consistent with the statistical result listed in Table 2. In addition, the maximum collaboration strength appeared between Nanjing tech University and University of Queensland. Besides University of Queensland, Nanjing tech University also collaborated with numbers of institutions such as Nanyang Technological University, Chinese Academy of Sciences and The Imperial College of Science, Technology and Medicine. Moreover, the collaborative relationship between Chinese Academy of Sciences and South China University of Technology was also close.

To detect the locations of source institutions and the collaborative relationships in a geographic perspective, a global map was generated. As is shown in Fig. 6, each dot represents the location of a specific source institution and each line represents the collaboration relationship between the institutions linked. It is evident that the dots were distributed most densely in Europe, indicating that there were a large number of European institutions which participated in the research on ceramic membranes. In addition to European, the dots located in Eastern USA, Eastern China, Southeastern Brazil, India and Middle East were also distributed densely. However, there were only small number of African institutions participated in the research on ceramic membranes. This uneven distribution in geography of institutions revealed that economic level is an important factor to impact the research on ceramic membranes. In terms of collaborative relationships, European countries cooperated with USA and Peoples R China most frequently. Besides European, USA also had extensive collaborations with Peoples R Chia and Austria. Peoples R China also collaborated with Australia frequently. However, it is also identified that some institutions only had a single collaborator and some institutions even had no collaboration with other institutions.

3.3. Categories and journals analysis

3.3.1. Categories analysis

89 kinds of web of science categories were identified from the collected records, however, only 23 of them included more than 20 publications. The top 20 web of science categories with the largest number of publications is showed in Fig. 7. It is evident *Engineering Chemical* was the most productive category, the number of publications of which was 1939, three times as many as that of second place. The categories showing in Fig. 7 can be classified into 4 major discipline groups in general. To distinguish the groups from each other clearly, the categories were filled with different colors according to their affiliations. The four groups include chemistry (*Engineering Chemical*, *Chemistry Multidisciplinary*, *Chemistry Applied*, *Electrochemistry*) in green, physics (*Chemistry Physical*, *Physics Condensed Matter*, *Physics Applied*) in light red, material (*Polymer Science*, *Materials Science Multidisciplinary*, *Materials Science Ceramics*, *Nanoscience Nanotechnology* and *Materials Science Coatings Films*) in orange and application (*Water Resources*, *Energy Fuels*, *Engineering Environmental*, *Environmental Sciences*, *Food Science Technology*, *Biotechnology Applied Microbiology*, *Metallurgy Metallurgical Engineering* and *Green Sustainable Science Technology*) in dark blue. The four groups above indicate that the research on ceramic membranes is multidisciplinary.

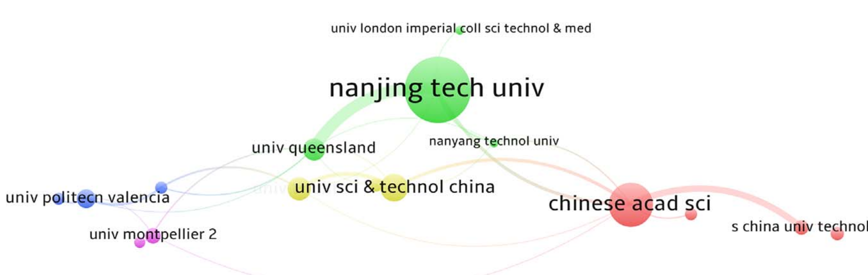

Fig. 5. Collaboration network between the 20 most productive institutions.

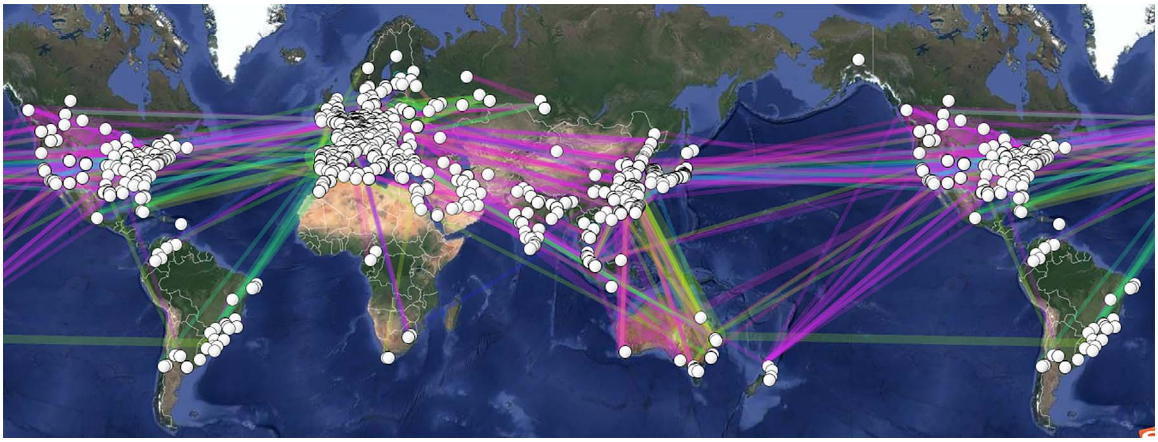

Fig. 6. Collaboration network in geographical map.

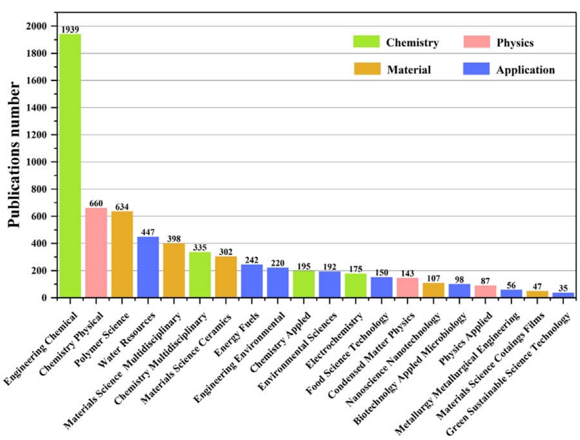

Fig. 7. Top 20 web of science categories with the largest number of publications.

3.3.2. Journals analysis

The 3697 collected records were originated from 522 journals, but only 58 journals contained more than 10 publications, accounting for 11.11% of the total journals number. The top 20 most productive journals are shown in Table 3. It is evident that the most productive journal was *Journal of Membrane Science*, the number of publications of which was 623, about 2.5 times as many as that of the second place –*Desalination*. It is not surprising that some journals such as *Ceramics International*, *Journal of the European Ceramic Society*, and *Journal of the American Ceramic Society* appeared in the table, because these journals deal with the research on ceramic science. *Separation and Purification Technology* and *Separation Science and Technology* are directly related to separation, reflecting the most important function of ceramic membranes. It is worth noting that there are many journals obviously related to chemistry or chemical engineering, including *Industrial & Engineering Chemistry*, *Catalysis Today*, *AICHE Journal*, *Chemical Engineering Journal*, *Chemical Engineering Science* and *Chinese Journal of Chemical Engineering*. This phenomenon indicates that ceramic membranes are widely used materials in chemical engineering. The appearance of *Desalination*, *Desalination and Water Treatment*, *International Journal of Hydrogen Energy*, *Water Research*, *Journal of Power Sources* and *Journal of Food Engineering* may reveal that the most pervasive application fields of ceramic membranes are water resource, energy, environmental science and food engineering.

3.4. Keywords analysis

10195 kinds of keywords were found from the collected records, however, only 552 kinds of them appeared more than 10 times. Fig. 8 shows the co-occurrence network of the top 100 keywords with the most frequent occurrence, where each circle represents a keyword and each curve represents the co-occurrence relationship between the two keywords connected. It is noted that some keywords are hidden in the figure because of the label optimization for the clear description of figure. As is shown in the figure, the keywords appearing in the picture are divided into 3 clusters with different colors:

Cluster 1(in red): this cluster mainly includes the keywords related to the topic of membrane filtration especially in water treatment, such as “ultrafiltration”, “microfiltration”, “filtration”, “nanofiltration”, “cross-flow microfiltration”, “membrane filtration”, “microfiltration membranes”, “reverse-osmosis”, “waste water”, “water”, “fouling” and “recovery”.

Cluster 2(in green): this cluster mainly includes the keywords related to the topic of oxygen permeation, such as “oxygen permeation”, “partial oxidation”, “oxidation”, “mixed conductor”, “methane conversion”, “syngas”, “dense ceramic membrane”, “oxides”, “perovskite”

Table 3
Top 20 most productive journals during 1998–2016.

Rank	Journal	N	IF2016	Rank	Journal	N	IF2016
1	Journal of Membrane Science	623	6.035	11	Journal of the European Ceramics Society	59	3.454
2	Desalination	247	5.527	12	AICHE Journal	54	2.836
3	Separation and Purification Technology	185	3.359	13	Chemical Engineering Journal	46	6.216
4	Desalination and Water Treatment	113	1.631	14	Microporous and Mesoporous Materials	36	3.615
5	Ceramics International	86	2.986	15	Journal of the American Ceramic Society	33	2.841
6	Industrial & Engineering Chemistry Research	85	2.843	16	Water Research	33	6.942
7	Solid State Ionics	81	2.354	17	Journal of Power Sources	31	6.395
8	International Journal of Hydrogen Energy	68	3.582	18	Chemical Engineering Science	27	2.895
9	Separation Science and Technology	66	1.106	19	Journal of Food Engineering	27	3.099
10	Catalysis Today	61	4.636	20	Chinese Journal of Chemical Engineering	26	1.174

N number of publications; IF2016 journal impact factor in 2016, obtained from Journal Citation Reports from Web of Science.

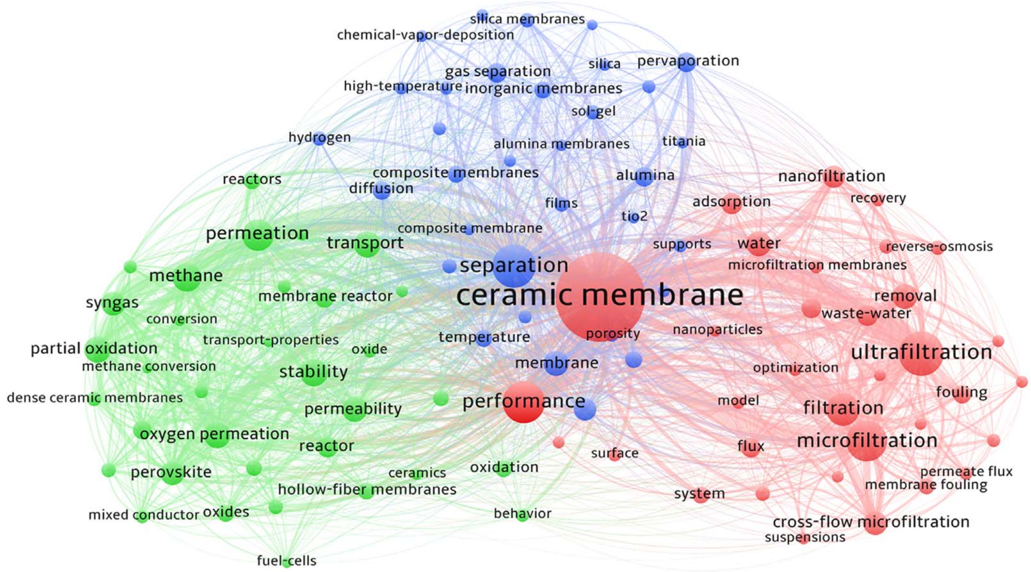

Fig. 8. Co-occurrence network of the top 100 keywords with the most frequent occurrence.

and “membrane reactor”.

Cluster 3(in blue): this cluster mainly includes the keywords related to the topic of fabrication, such as “fabrication”, “sol-gel”, “chemical-vapor-deposition”, “titania”, “alumina”, “silica” and “inorganic membrane”.

The three clusters revealed the major research directions of the research on ceramic membranes. In order to give a deeper but accessible analysis of keywords, the three clusters were discussed below.

3.4.1. *Cluster 1- membrane filtration*

The keyword “filtration” may be the core of cluster 1, revealing one of the main research directions of ceramic membranes. Membrane filtration is a process to separate the different components in liquid relying on the pressure difference across the membrane and suitable pore size in membrane [23]. Compared with organic membranes, ceramic membranes have many advantages in filtration technology, such as stronger chemical resistance, better thermal stability, higher mechanical strength and longer operation life [24]. Therefore, the filtration technology based on ceramic membranes has attracted many researchers to do related studies.

The keywords “microfiltration”, “ultrafiltration”, “nanofiltration” and “reverse-osmosis” just shows four common membrane filtration technologies [25]. Because of the difference of pore size, the 4 technologies can intercept the specific substances with different size. For instance, microfiltration can intercept the particles with the diameter larger than 0.1 μm such as suspended solids and large bacteria, but reverse-osmosis can remove the salt and small organic molecules.

The appearances of “water” and “waste-water” reveals the main object applying membrane filtration technology. Compared with the traditional water treatment technology, ceramic membrane filtration technology has many advantages, such as no chemical addition, lower energy consumption, lower operation temperature, better selectivity and smaller floor area. Therefore, ceramic membrane filtration technology has been widely used in the water treatment. Nowadays, in addition to the seawater desalination, ceramic membranes have been widely used in the treatment of oily wastewater [26], petrochemical wastewater [27], domestic wastewater [28], river water [29] etc.

The keywords of “fouling” and “recovery” in this cluster reflected the research on membrane fouling, which is a unavoidable problem in the process of membrane filtration. Membrane fouling results from the particle deposition on the membrane surface or in membrane pores [30]. The membrane flux will decline with the operation time going, until seriously affect the membrane quality. Therefore, it is necessary to take effective measures to make the performance of membranes recovery [31].

3.4.2. *Cluster 2- oxygen permeation*

The keyword “oxygen permeation” is the core of this cluster, and almost all keywords in this cluster are related to this topic. Oxygen separation is a vital process for many chemical industries, and the basic target of this process is usually to obtain oxygen from air [32]. Because of the excellent material properties of ceramic membranes, the research on ceramic membranes for oxygen separation has been active for decades.

Some keywords in this cluster indicates the materials or types of ceramic membranes for oxygen separation, such as “dense ceramic membrane”, “mixed conductor”, “perovskite” and “oxide”. Dense ceramic membrane made from mixed ionic-electronic conductor (MIEC) is an excellent candidate for the oxygen separation from air because of the high electronic and ionic conductivity at elevated temperature [32]. Due to the structure with oxygen defect, the conductivity of oxygen-ionic and electron in perovskite oxides can be achieved without electrodes or external electrical circuitry [33]. Therefore, as the promising compounds, perovskite oxides and their derivatives have been the most widely studied MIEC compounds [34–36].

The keywords “methane” and “methane conversion” may reveal the most important application area of oxygen separation membranes. Furthermore, the keyword “syngas” and “partial oxidation” indicates target product and approach of membrane conversion respectively which are in extensive research. Some ceramic reactors made from dense ceramic membranes integrated in catalytic materials can realize the oxygen separation and partial oxidation of methane to syngas in a single step [37]. This technology is safe in management and is promising to reduce the capital costs of methane conversion [38], thus it has been a research focus for many years.

The keywords “stability” and “permeability” may reflect the requirements for the performance of the ceramic membranes for oxygen separation. It is merited that oxygen permeability is an important indicator to evaluate the performance of ceramic membranes because of the production demand. However, in most of oxygen separation industries, the ceramic membranes have to tolerate high operating temperature and severe chemical potential gradients across the membranes [37]. Some reducing gas and CO_2 can also cause the phase change of membrane materials then lead to the degradation of performance [39]. Therefore, in addition to the permeability, the stability of ceramic membranes also should be considered for industrial application.

Considering the two aspects, future research will focus on the new ceramic membrane materials with high oxygen permeability as well as sufficient stability.

3.4.3. Cluster 3- fabrication

The keyword "fabrication" is the core of this cluster, since most of the keywords in this cluster are relevant to the fabrication of ceramic membranes directly or indirectly. Because of the differences in materials and fabrication techniques, the ceramic membranes will exhibit various characteristics and the cost is different. Therefore, how to fabricate the ceramic membranes with high performance but low cost has been a hot topic for decades [40–42].

It is identified that the keywords "sol-gel" and "chemical vapor-deposition" appearing in this cluster are two common fabrication methods of ceramic membranes. More specifically, both of them are the popular modification techniques for the surface of ceramic membranes. The sol-gel process is a traditional but practical method for producing the ceramic membranes with small pore size and narrow pore size distribution [43]. In the sol–gel method, the sol is obtained after the hydrolysis and condensation reactions of precursor, followed by drying and firing at high temperatures. Chemical vapor-deposition is also an effective method to fabricate membranes with micropore [44]. In the process of chemical vapor-deposition, the predecessors react in the gas state and deposit on the surface of membrane supports, thereby reducing the pore size of membrane and obtaining the dense ceramic membranes. Although the gas permeances are lower, chemical vapor-deposition can make the membranes better stability and durability compared with sol-gel [45].

The keywords "alumina", "titania" and "silica" in cluster 3 revealed the most popular raw materials for the fabrication of ceramic membranes. Because of the great mechanical strength chemical resistance, alumina is widely used in the industrial production of porous ceramic membranes [46]. Compared with the alumina, titania has some unique features such as low sintering temperature and good photocatalysis activity. Therefore, besides the raw material of ceramic supports, titania is also used as the sintering aid [47] and catalytic material [48]. Silica is a low-cost material which is mainly focused on the fabrication of separation layer. Nowadays, the microporous silica membranes can be applied in hydrogen purification, carbon dioxide capture, and alcohol dehydration [49].

3.5. Citation bursts detection

The most active area of research during a certain period can be revealed by citation burst, which is an indicator for the cited reference obtaining dramatic increase of citations during a period of time [21]. The metrics for a citation burst mainly includes the burst strength and burst period. In this study, 278 citation bursts were detected from the 62,402 valid references cited by the 3796 publications. Table 4 lists the top 20 references with the strongest citation burst, which can be divided into five groups according to their research topics:

Group 1: The references in this group are related to oxygen separation, including #1, #3, #4, #5, #6, #8, #12, #15 and #16.

Group 2: The references in this group are related to methane conversion, including #2, #10, #13, #14, #17 and #20.

Group 3: The reference in this group is related to solid-oxide fuel cells, including #7.

Group 4: The references in this group are related to water treatment, including #9 and #11.

Group 5: The references in this group are related to the preparation and characterization of ceramic membranes, including #18 and #19.

It is worth noting that topics of the five groups above are highly consist with the topics of three keywords clusters in 3.4, verifying the main research directions of ceramic membranes analyzed by keywords are reasonable.

In order to analyze the evolutions of the five citation bursts groups,

Table 4
Top 20 references with the strongest citation burst.

#	References	Title	Year	Strength	Begin	End
1	SUNARSO J, 2008, J MEMBRANE SCI, V320, P13, DOI	Mixed ionic–electronic conducting (MIEC) ceramic-based membranes for oxygen separation	2008	41.1297	2010	2016
2	BOUWMEESTER HJM, 2003, CATAL TODAY, V82, P141, DOI	Dense ceramic membranes for methane conversion	2003	33.4894	2005	2011
3	BAUMANN S, 2011, J MEMBRANE SCI, V377, P198, DOI	Ultrahigh oxygen permeation flux through supported $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ membranes	2011	22.7888	2013	2016
4	DYER PN, 2000, SOLID STATE IONICS, V134, P21, DOI	Ion transport membrane technology for oxygen separation and syngas production	2000	22.1646	2003	2008
5	ARNOLD M, 2007, J MEMBRANE SCI, V293, P44, DOI	Influence of CO_2 on the oxygen permeation performance and the microstructure of perovskite-type $(Ba_{0.5}Sr_{0.5})(Co_{0.8}Fe_{0.2})O_{3-\delta}$ membranes	2007	19.3829	2011	2016
6	SHAO ZP, 2000, J MEMBRANE SCI, V172, P177, DOI	Investigation of the permeation behavior and stability of a $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ oxygen membrane	2000	18.9343	2002	2008
7	SHAO ZP, 2004, NATURE, V431, P170, DOI	A high-performance cathode for the next generation of solid-oxide fuel cells	2004	17.9906	2007	2011
8	LUO HX, 2011, ANGEW CHEM INT EDIT, V50, P759, DOI	CO2-Stable and Cobalt-Free Dual-Phase Membrane for Oxygen Separation	2011	17.0284	2012	2016
9	HOFS B, 2011, SEP PURIF TECHNOL, V79, P365, DOI	Comparison of ceramic and polymeric membrane permeability and fouling using surface water	2011	16.4866	2013	2016
10	ZENG Y, 1998, J MEMBRANE SCI, V150, P87, DOI	Perovskite-type ceramic membrane: synthesis, oxygen permeation and membrane reactor performance for oxidative coupling of methane	1998	16.2288	2000	2006
11	ABADI SRH, 2011, DESALINATION, V265, P222, DOI	Ceramic membrane performance in microfiltration of oily wastewater	2011	15.6994	2014	2016
12	ZHU XF, 2012, CHEM COMMUN, V48, P251, DOI	Novel dual-phase membranes for CO_2 capture via an oxyfuel route	2012	15.5892	2013	2016
13	WANG HH, 2003, CATAL TODAY, V82, P157, DOI	Investigation on the partial oxidation of methane to syngas in a tubular $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ membrane reactor	2003	15.5867	2005	2010
14	BALACHANDRAN U, 1995, APPL CATAL A-GEN, V133, P19, DOI	Dense ceramic membranes for partial oxidation of methane to syngas	1995	15.4028	1998	2003
15	ZHANG K, 2011, RSC ADV, V1, P1661, DOI	Research progress and materials selection guidelines on mixed conducting perovskite-type ceramic membranes for oxygen production	2011	15.1899	2014	2016
16	ZENG PY, 2007, J MEMBRANE SCI, V291, P148, DOI	Re-evaluation of $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ perovskite as oxygen semi-permeable membrane	2007	14.9745	2008	2011
17	TSAI CY, 1997, AICHE J, V43, P2741, DOI	Dense Perovskite Membrane Reactors for Partial Oxidation of Methane to Syngas	1997	14.9297	1999	2005
18	NANDI BK, 2008, APPL CLAY SCI, V42, P102, DOI	Preparation and characterization of low cost ceramic membranes for micro-filtration applications	2008	14.8849	2013	2016
19	DELANGE RSA, 1995, J MEMBRANE SCI, V99, P57, DOI	Formation and characterization of supported microporous ceramic membranes prepared by sol-gel modification techniques	1995	14.8356	1998	2002
20	PEI S, 1995, CATAL LETT, V30, P201, DOI	Failure mechanisms of ceramic membrane reactors in partial oxidation of methane to synthesis gas	1995	14.5413	1998	2003

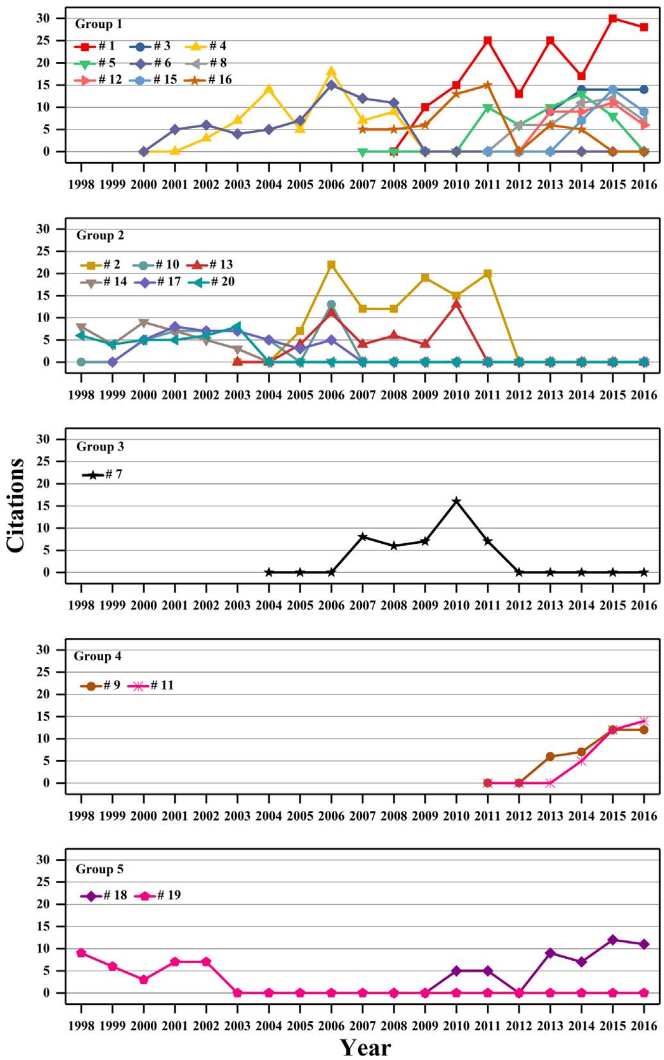

Fig. 9. Citation histories of the top 20 references with the strongest citation bursts.

the citation histories of the top 20 references with the strongest citation burst are showed in Fig. 9 according to different groups. It is evident that the references in group 1 have had a large number of citations since 2000, especially over the last several years. This phenomenon reveals that the research on ceramic membranes for oxygen separation is still a research focus. In contrast to the trend of group 1, the references in group 2 obtained some citations at the beginning of data collection period, then the citations peaked between 2006 and 2011, but decreased to zero in 2012. Similar to the trends of group 2, the citations of reference in group 3 increased in general from 2006 to 2010, then peaked in 2010 with the number of 17 but decreased to zero in 2012. The citation histories of group 2 and group 3 may indicate that the research on methane conversion and solid-oxide fuel cells in the field of ceramic membranes are not as popular as before. The citations of references in group 4 which are related to water treatment have increased since 2012, indicating the relevant research has been active in recent years. Group 5 includes two references related to the preparation and characterization of ceramic membranes, but the two references are entirely different in terms of citation history. The citation period of #19 is from 1998 to 2002, but another reference has obtained citations since 2010. This phenomenon perhaps indicates the recovery of related research.

4. Conclusions

Using the bibliometric analysis combined with visualization analysis, the research on ceramic membranes were summarized based on the publications extracted from Science Citation Index Expanded from 1998 to 2016. This study was conducted from five different aspects and a comprehensive and multi-perspective description of the research on ceramic membranes was presented. This paper can help the stakeholders to grasp the global characteristics and trends of the research on ceramic membranes. Moreover, this paper provided a unique combined analysis method, which can also be applied to analyze the global characteristics and trends of other research topic.

According to the increasing number of publications and authors, the growth trends of the research on ceramic membranes were positive from 1998 to 2016. The most productive country and institution were both from Peoples R China. Peoples R China. USA, Japan, Spain and UK had the most intensive collaboration with other countries, and the maximum collaboration intensity appeared between Peoples R China and Austria. The source institutions were distributed in Europe most densely, but the publications from Africa were very rare, indicating the research are influenced by the economic level. The top 20 categories with the largest number of publications were classified into 4 major discipline groups, including chemistry, physics, material, and application. The top 5 most productive journals were *Journal of Membrane Science*, followed by *Desalination*, *Separation and Purification Technology*, *Desalination and Water Treatment* and *Ceramics International*. Based on the journals analysis, the main application fields of ceramic membranes include water resource, energy, environmental science and food engineering. The top 100 keywords with the most frequent occurrence were divided into 3 clusters, including membrane filtration technology, oxygen permeation and the fabrication of ceramic membranes, which indicated three main research directions of ceramic membranes. 278 citation bursts were distinguished from the 62405 valid references, and the top 20 citation bursts with the maximum burst strength can be divided into five groups. The topics of the five groups are consistent with the research directions analyzed by keywords. Based on the citation histories analysis, it could be concluded that the research on oxygen separation has been flourishing and the research on water treatment used by ceramic membranes has attracted more attention in recent years.

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