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Mapping the desalination journal: A systematic bibliometric study over 54 years

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HIGHLIGHTS

- The evolution of the *Desalination* journal from 1966 to 2020 has been analyzed using scientometrics analysis.
- A comprehensive analysis has been carried out using Web of Science and Scopus databases.
- The review examined key fields, including research trends, the most cited papers, the number of publications , and the most publishing countries.
- An outlook for the upcoming research directions in desalination is provided.

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ABSTRACT

Desalination is one of the most important techniques that can provide potable water to meet the ever-growing demand for fresh water in many regions. Over the years, desalination techniques have been significantly improved to be an economically viable option to meet the increasing demand. In 1966, the *Desalination* journal was founded as a research platform to assess the progress and evaluate novel techniques in water desalting. This review follows the evolution of the *Desalination* journal from 1966 to 2020 by utilizing scientometrics analysis. A comprehensive analysis has been carried out to review bibliometric data for the journal over the specified period using Web of Science and Scopus databases to identify the research trend. The analysis covers seven main research indicators: growth trends, productive countries and institutions, productive authors, mostly used keywords, citation and co-citation. The study explored more than 14,500 articles published in the *Desalination* journal. Furthermore, it examined key fields in the journal, including research trends, the most cited papers, the number of publications in each year, the most publishing countries. Finally, the review offers an overview of future research trends. This bibliometric analysis helps the readers to identify the active areas in water desalination and increase the visibility of the published papers. The findings of this review can provide the desalination researchers a comprehensive overview of the research direction in the field as well as an outlook for the upcoming research directions.

1. Introduction

Nowadays, freshwater reserves are getting exhausted around the world [1], making the access to potable clean water severe and pervasive problem that is afflicting people [2]. Water is one of the essential natural resources for living and sustaining life on earth [3]. However, water scarcity related issues are expected to grow and become worse, even in water-rich countries [4]. With the continuous increase of water demand in different anthropogenic activities such as agriculture, industrial and domestic use, given the depletion of groundwater, desalting seawater attracted attention as a potential candidate for fulfilling different water needs [5]. Desalination or desalting is referred to as the process by which the dissolved salts, ions, minerals and contaminants are removed from seawater, brackish water, or wastewater [6]. The process purifies salty water and produce fresh water that can be utilized in several anthropogenic activities [7]. In England 1869, the first patent regarding desalting technique was granted as well as the first desalination plant was built in Aden by the British government [8]. Fasting forward to the 21st century, desalination is considered as a pivotal process to meet water demands in the Middle East, Singapore, Maldives,

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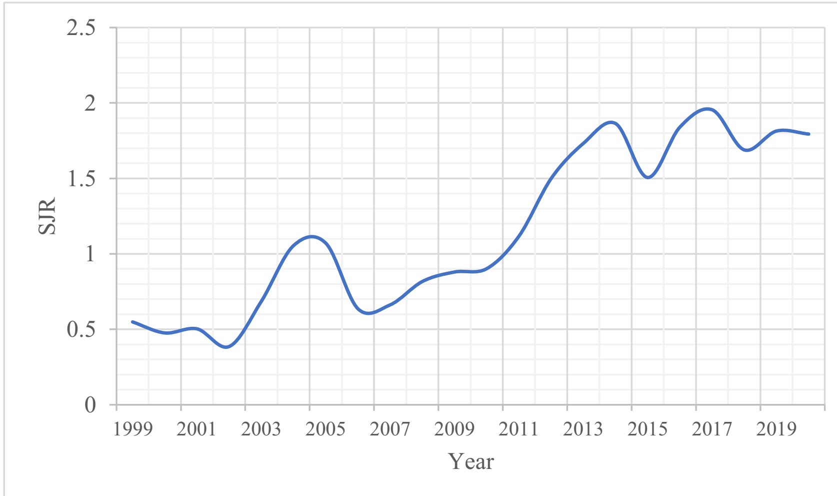

Fig. 1. SJR of Desalination journal over (1999–2020) [41].

and other countries [9]. The total number of fully equipped desalination plants worldwide reached 18,000 plants by the end of the same year [10]. Almost 44% of desalination plants around the world are located in the Middle East and North Africa, with an annual growth rate of 7–9% [11]. From an economic point of view, the global desalination industry is expected to reach US$ 32.1 billion by 2027 [12].

Many scholars direct their focus to water research studying the different technologies for clean water production to identify the most technically and economically feasible process [13]. In addition, the United Nations encouraged the developed countries to impose water policies in order to manage the demand of different sectors and to explore cooperation opportunities between countries [14]. This international collaboration can provide the financial support to promote the private companies investing in water projects just as ACP-EU organization in Africa, Caribbean and Pacific areas [15]. Water industry was revolutionized over past few decades by adopting technologies that can produce clean water using different process [16]. These processes include adsorption, thermal desalination, desalination using membranes and biological processes [16]. In the last decade, two leading desalination technologies that were widely used required either thermal or mechanical energy [17]. Multi-effect boiling and multi-stage flashing utilize thermal energy. On the other hand, mechanical vapor compression and freezing (phase change process) operate by the direct use of mechanical energy [18]. Membrane desalination processes such as reverse osmosis utilize indirect mechanical energy by the employment of electrically powered pumps [19]. Yet, desalination with all of its different technologies is considered as an energy-intensive technique [19] which is contributing to global warming substantially if fossils fuel continued to be used as the main energy source [20]. This reveals the trade-off between the energy consumption of this process and its crucial importance in supplying freshwater, given the freshwater scarcity issue [21].

Due to the global importance of desalination as a water desalting process, the *Desalination* journal was incepted in 1966 by Miriam Balaban [22]. The journal is now one of the most leading journals that is dedicated to research in water industry. It promotes high-quality research in different areas of water desalination and purification fields including theoretical and applied research. The journal accepts publications that discuss the-state-of-the art in all aspects of the field and welcomes the original works and literature in advanced and novel water treatment and desalination processes. The journal covers all desalination technologies and related issues, such as thermal desalination, distillation, membrane technologies (reverse osmosis, electrodialysis, ion exchange and forward osmosis), brine management, energy efficiency as well as integrated systems for water reuse. Recently, the journal has become more accessible to a wider portion of readers, scientists and students through offering open access publications and providing free abstract viewing [23].

1.1. Bibliometric analysis

Periodical content analysis of a certain discipline provides openings and opportunities to evaluate the harmony and dynamicity of the professional literature. In addition, it can provide an overview of the field's interests, objectives, values and hotspot areas [24]. Bibliometric analysis can achieve this through quantitative assessment to evaluate various academic parameters of previously published peer-reviewed literature. It is based on metrics, such as the number of publications, citation and co-citation. Then each metric can be analyzed based on the country, institution and individuals in addition to the interrelations between them. It is an effective method to understand past and future research in journals by mapping the historical progress and ongoing trends [25]. Bibliometric analysis can be applied to the academic literature in different forms. It can be carried out for investigating a certain topic or research area for a certain period by analyzing all related journals based on a predetermined criterion. Examples of bibliometric analysis include: the study carried out by Yang et al. (2018) on desalination research over 16 years by reviewing all related journals of the Science Citation Index (SCI) [26]; the study of global research trends of forward osmosis, which was carried out by Ang et al. (2019) over 51 years [27]; global research on rainwater harvesting for agricultural purpose conducted by Velasco-Munoz et al. (2019) [28]; and the study on the posterior cruciate ligament in Annals of Medicine and Surgery journal by Rhatomy et al. (2020) [29]. Also, it can be used to carry out a comprehensive mapping study for a single journal over a specific period. Mapping of The Journal of Vocational Behavior was carried out through three scientometric studies in three different time spans. The first study was published in 1989 by Fitzgerald and Round [30]; another one was published in 1995 by Buboltz et al. [31]; and the most recent study was carried out in 2019 by Byington et al. [32].

In this work, a rigorous and detailed analysis was conducted systematically on the bibliometric data of the Desalination journal over 54 years. This was accomplished by reviewing all published papers over the period from 1966 to 2020. This methodology aims to analyze massive amounts of data related to the Desalination journal publications over the 54 years and facilitate richer reviews accompanied by informative, broader scope and less biased science maps [26]. The outcomes of this bibliometric study are expected to help scholars in the desalination field

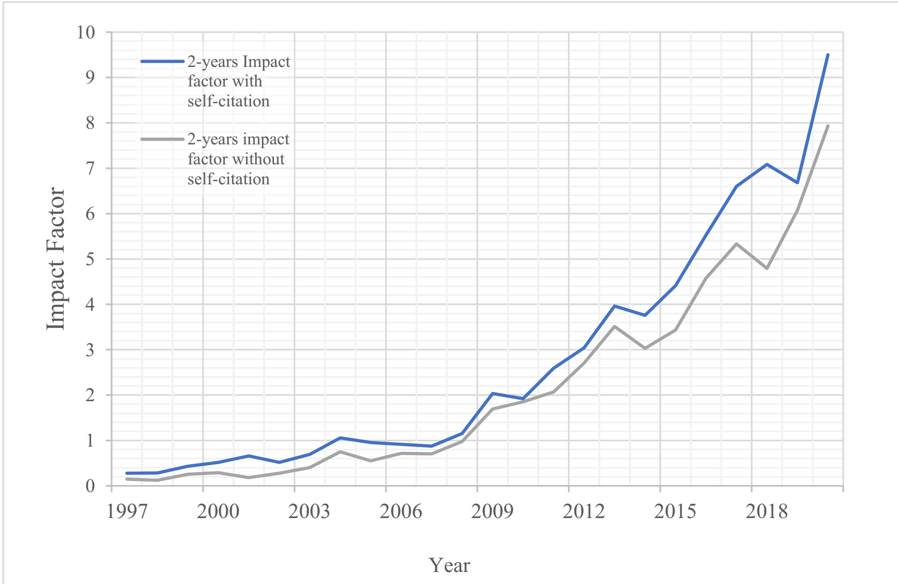

Fig. 2. 2-years impact factor with and without self-citation [44].

find out the places where flowers are blooming the most [33], bearing in mind that the desalination journal is one of the leading platforms in desalination and water studies [34]. This bibliometric study provides a road map to the past, ongoing and future research in the journal considering the growing interest in desalination [35]. To the best of the authors' knowledge, there has not been any bibliometric study on the Desalination journal. The main objective of this paper, therefore, is to map out the research in the Desalination journal through carrying a comprehensive review of the trends, interconnections in the studies, authors and co-citations along with future research directions. VOS-viewer was used in this bibliometric review to carry out network mapping.

1.2. Desalination journal and its influence

The Desalination journal is a peer-reviewed scientific journal published by Elsevier in the Netherlands. The journal is devoted to water desalting and purification and covers different aspects, such as water treatment and reuse, novel technologies in desalination, renewable energy sources and others [36]. As stated earlier, the journal was established in 1966 by Miriam Balaban [37]. In 2009, Miriam Balaban was succeeded by Nidal Hilal as Editor-in-Chief of the journal [38]. Today, the Desalination journal reflects the growing water industry from research to pilot plants and strives to be an efficient forum for communication between scholars and industry.

The academic prestige of a scientific journal is often determined over time. This can be quantitively measured by using a set of metrics, such as scientific journal rankings (SJR), journal impact factor (JIF), H-index, CiteScore and article influence score [39]. For journals ranking, Desalination journal is considered as first quartile journal (Q1) using the (SJR) citation index. SJR citation index weighs the quantity and the quality of references cited in publications of the journal based on the idea that "citations are not equal". It is based on 3 years period citations and uses quartiles from (Q1 to Q4) to rank journals based on sub-

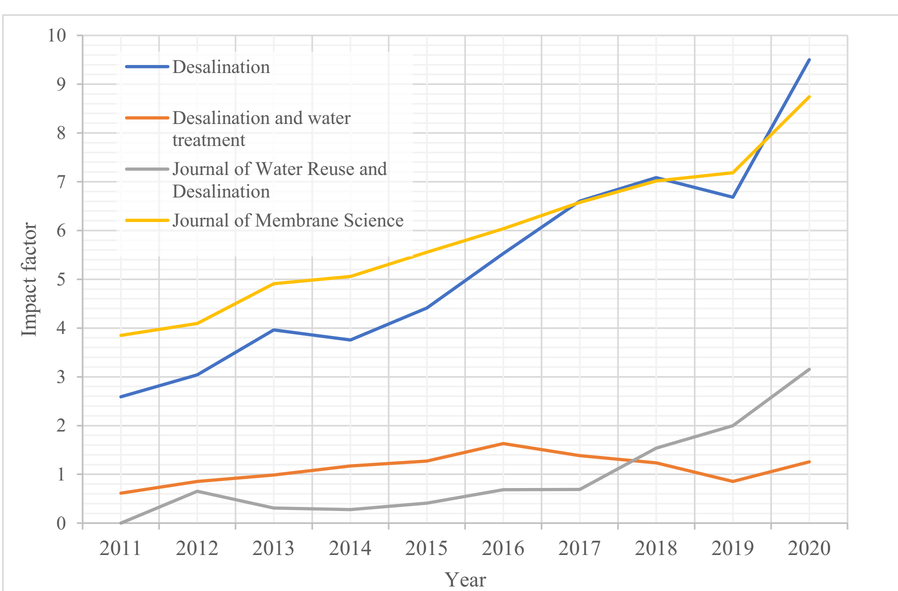

Fig. 3. Comparison of 2-years impact factor of Desalination journal and similar journals in the field of desalination [45].

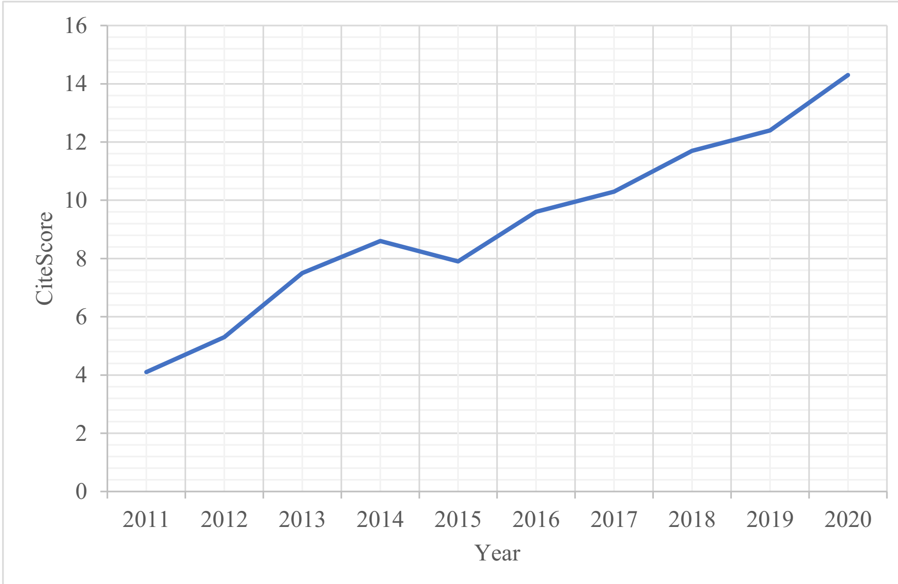

Fig. 4. CiteScore of Desalination journal (2011–2020) [46].

categories, where Q1 is referred to the top 25% of journals [40]. The variation of SJR for the Desalination journal over the years is shown in Fig. 1.

To track the evolution of the journal, it is a rather difficult task to quantify the overall impact by depending only on one matrix. Therefore, a set of matrices are used to determine the influence and the quality of a journal. Some of these matrices are journal impact factor (JIF), H-index and CiteScore. The 2-years JIF of Desalination is the metric that shows the average number of citations of recent articles per papers that have been published over the two preceding years. This reveals the importance of the journal in its field; the higher the impact factor of the journal, the more citations it has with respect to the number of published papers. Citations reveal the quality and novelty of the articles and the contribution of the articles in grabbing the researchers' attention. Fig. 2 shows the historical data for the 2-year impact factor trend from 1997 to 2020 with and without self-citation (data available for impact factor and other metrics from 1997 only). It is noticed that the impact factor over the specified period using a moving average trend line is increasing reaching an all-time high of 7.576 in 2019. The impact factor decreased to 6.240 over 2019–2020 [42], but recently increased to 9.501 ranked as the 3rd out of 98 most popular journal in water resources [43]. JIF without self-citations excludes any citations from articles in the journal itself. This indicates that the direct influence of the journal on its citations has been removed, thus, highlighting the citations of the journal by its peers. This is expected to be lower than the 2-years impact factor for each year.

The journals in Fig. 3 are all peer-reviewed journals related to water science and technology. Fig. 3 shows a comparison of the 2-year impact factor of three desalination journals and the Journal of Membrane Science, which publishes a 55% similar content to the Desalination journal. From 2011 to 2019 Membrane Science had a higher impact factor than that of the Desalination journal. However, in 2020 the Desalination journal achieved higher IF than the Journal of Membrane Science.

Hirsch index (H-index), which is (H) number of papers which are (at

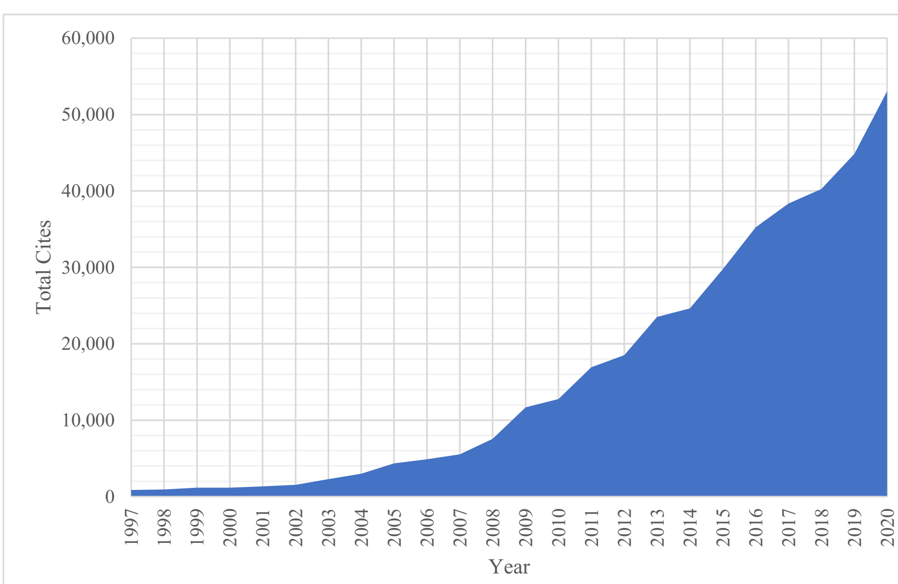

Fig. 5. Total citations of Desalination journal (1997–2020) [44].

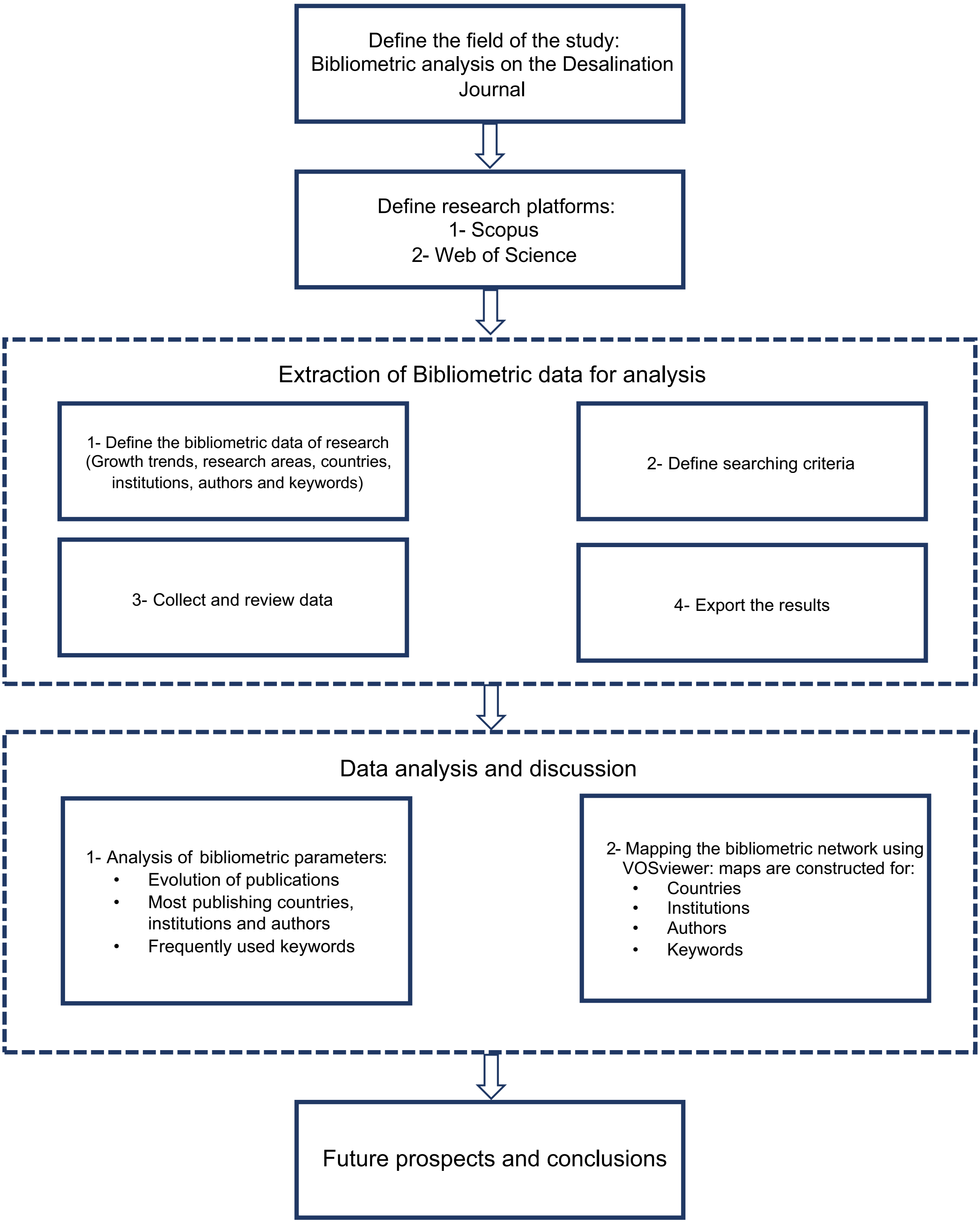

Fig. 6. Methodology of the review.

least) cited (H) number of times, gives a better indication in terms of measuring the impact of the scientists and the journal. The H-index for the Desalination journal is 184 [41]. The CiteScore of Desalination can be easily calculated by dividing the number of citations in a three-year period per the documents in that period; thus, it reflects the average number of citations just as JIF. This metric was extracted from Scopus for (2011–2020) and is shown in Fig. 4. [46]. CiteScore [47] trend is almost linear from (2011–2014), and the same trend from 2016 to 2020; however, a drop of citations is observed between (2014–2015) which was also shown in Fig. 2 in terms JIF and Fig. 5 for the total citation.

2. Data collection and methodology

Using Web of Science and Scopus databases, the academic literature was extracted from 1966 to 2020. The selected documents were limited to the English language. A total of 14,582 publications were found.

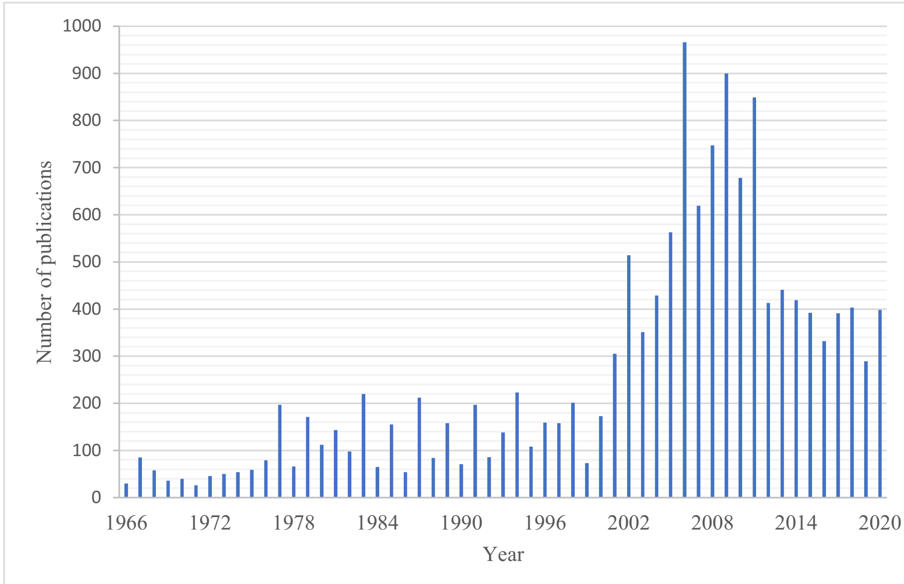

Fig. 7. Growth of publications in Desalination journal over the years (1966–2020).

Among these, 95.8% of the publications were full-length articles, 1.790% were review papers and the balance was distributed between conference papers, editorials, erratum and others such as conference review, letters and notes. The bibliometric analysis was limited to review papers and full-length articles for more reliable results [48], and this decreased the number of analyzed literature to 14,231 records. Out of the collected documents, 98.16% were scientific articles and the balance was review papers. Each of the selected records was scanned (title and abstract) before downloading its related bibliometric information for final screening purposes. The bibliographical information for selected records was downloaded for further analysis using Microsoft Excel and VOSviewer software. VOSviewer is a software for creating and visualizing bibliometric maps based on the data gathered either from bibliographic database files such as Scopus and Web of Science or reference manager files like RIS and Endnote. Different types of analysis can be performed based on bibliographic data imported to the software. The analysis could be co-authorship, co-occurrence, citation, bibliographic coupling and co-citation. While the unit of analysis could be authors, organization, countries, documents, or cited references. Simple statistical analysis was carried out using Microsoft Excel just as the number of records per year, while bibliometric maps were visualized using VOSviewer software such as co- citation networks and others. The overall methodology is shown in Fig. 6.

3. Results and discussion

All the compiled records are analyzed in this section, and the analysis is divided into seven main sections: number of publications over the

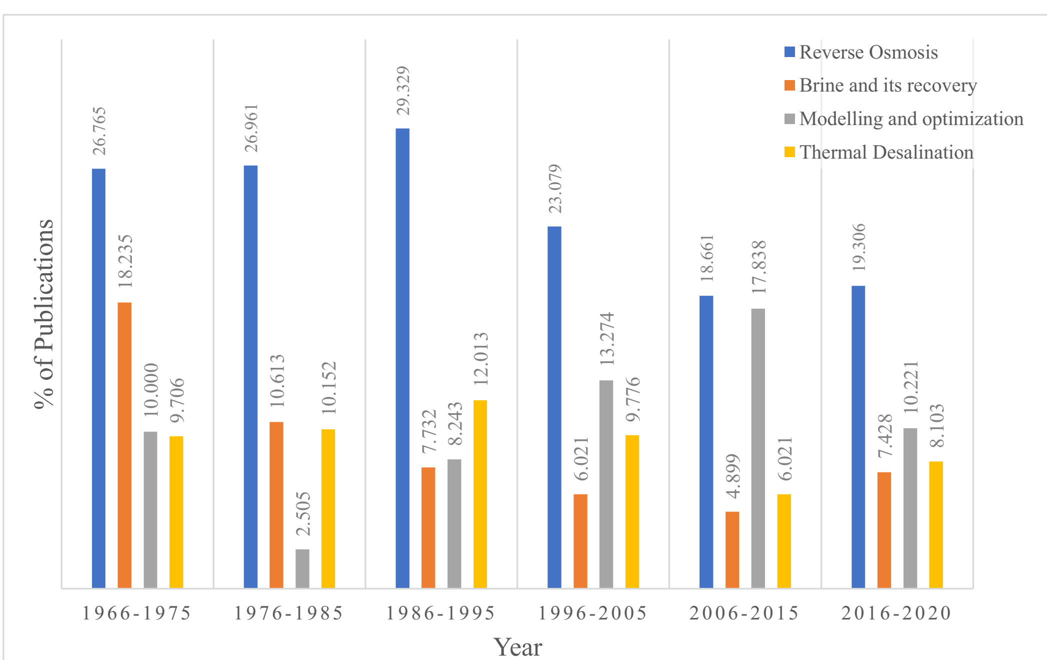

Fig. 8. The progress of top four research categories of the Desalination journal per period.

Table 1
Publications (%) of each research category in the Desalination journal per period.

Research category	1966–1975	1976–1985	1986–1995	1996–2005	2006–2015	2016–2020
• Forward osmosis	1.77	0.527	0.831	1.61	3.40	7.12
• Renewable energy	1.18	16.7	5.18	7.60	6.58	7.09
• Environmental issues	1.18	2.11	2.56	5.59	6.90	3.10
• Hybrid and novel systems	0.294	0.791	1.73	2.87	5.44	6.66
• Sustainability in desalination	0	0	0.319	1.81	2.90	2.67
• Electrodialysis desalination process	1.77	1.65	1.53	1.61	1.55	1.90
• Energy consumption and recovery	2.94	5.34	5.88	7.34	8.32	11.3

year, research categories, keywords analysis, and contributions of countries, institutions and authors.

3.1. Growth of publication number

The number of publications in a journal per year is an important parameter that reflects the activity of the journal and its dynamicity. Also, it gives an indication about the growth of the journal and the affinity of researchers towards it. This can be directly linked to the JIF which is shown in Fig. 2. In addition, there were more than 25 international conferences and conference reviews in water desalination that were published in the Desalination journal from 1966 to 1990 to raise the interest of researchers in the importance of water desalting. The number of publications in the Desalination journal per year is shown in Fig. 7. The journal started in 1966 with an insignificant number of publications (only 30 review papers and scientific articles were published). The number of publications showed a fluctuating trend of increasing and decreasing. After completing the first decade (1976 and 1977), the average number of articles started to increase with an average growth rate for the number of publications of about 9%. The considerable increase in the number of publications is noticed in the period of late 90's and the beginning of the 21st century 1997–2012. The number of articles increased to nearly five-folds in this period. The increasing number of publications can be attributed to the availability of resources, feasibility to commercialize plants, and diversification in desalination field research. In 2002 a drastic increase in the number of papers was noticed with an increase of 4.4% in annual publications than the previous year. The peak of the number of publications over the whole study period was shown in 2006 an annual increase of 5%. The number of total citations jumped from 860 in 1997 to 5550 in 2007. Both, the number of publications and the number of citations reveal the continuous interest of scholars in the Desalination journal. During the same time span 1997–2012, many important global events took place. For example, in 2004, the first pilot greenhouse desalination plant was built in Oman [49]; in 2006 the first reverse osmosis plant began operating in Perth [50]; in 2010 Minjur desalination plant in India was inaugurated [51]. The main interest drivers towards desalination in this period could be population increase, rapid global urbanization industrialization and economic growth. Overall, the growth trend of publications number in the journal is directly linked to breakthroughs in the research field in desalination, enhancement and developments to the technology and diversification.

3.2. Research categories

The Desalination journal is an inter-disciplinary journal in which desalination and water related papers are published. The journal accepts papers in different fields just as thermal desalination, membrane distillation and membrane fabrication, hybrid processes, brine and its recovery, sustainability in desalination and life cycle assessments, clean energy sources for desalination and other related fields. Some of the fields in the journal are analyzed based on the growth of publication number as a function of time as shown in Fig. 8. The different categories for this analysis are chosen based on the fields considered by the journal. The trends for each specified period are highlighted in Fig. 8 for the top four research fields, while the evolution of other fields is given in Table 1. The number of publications was gathered from Scopus for each time span and topic. It is obvious that new research topics, such as sustainability, energy efficiency as well as environmental issues, such as brine recovery seem to appear in recent years, especially during the last decade.

Reverse osmosis (RO) is one of the hot spots in the desalination field, and it can be considered one of the mature and well-developed processes. It is noteworthy that reverse osmosis is one of the most published fields since 1966–1975 followed by technical design of full-scale plants field. In the first decade of the Desalination journal, 91 publications were related to reverse osmosis field to entering a booming phase in 2006–2015 to have 998 publications. The increased interest in RO can be attributed to the improved efficiency and economics of the technology. It is considered to be cost-effective and one of the most efficient methods for water softening [52] with less energy usage. In fact, the United States Environmental Protection Agency (EPA) considered reverse osmosis as one of the best available technologies for water desalting and treatment in 2009 [53]. Also, reverse osmosis is preferred over distillation as it is a faster process and it is more accessible with a lower operating costs [54]. The compact modular design of RO process attracted the attention of scholars, as it requires less footprint compared to other processes in the desalination market and less regular maintenance [55].

Most countries in the Middle East and GCC region lack natural freshwater resources and hence rely heavily on water desalination for potable water. Over 70% of desalination plants in the GCC depend on thermal desalination either multi-stage flash (MSF) or multi-effect distillation (MED). This is due to the quality and nature of intake seawater and its salinity which cause membrane fouling issues. Other reasons for thermal desalination dominance are the red tides and lack of research in membrane technology in such seawater quality [56]. However, membrane technologies could be applied in GCC countries for seawater desalination if feed pre-treatment is applied [57]. The main drawback of thermal desalination is the intensive use of power and electricity besides the brine production and disposal issues [58]. After the considerable advancements in different desalination processes, scholars are currently directing their efforts to address major economic and environmental challenges such as reject brine and its recovery. A good number of articles were directed towards this issue, increasing from 62 articles in (1966–1975) to 242 articles in (2016–2020). Reject brine is the highly concentrated water stream that is rejected from the last stage of the desalination process and discharged as wastewater [59]. The continuous disposal of brine into seawater bodies lead to an increase in contaminants concentration to multiple folds which could ravage marine ecology and cause mutations to marine creatures [60]. The management of brine instead of disposal is one of the best options in saving the environment. Some brine management techniques include the recovery of some of value-added products and chemicals from brine just as heavy-metals and other techniques such as minimization and reuse methods which include membrane and thermal based methods [61].

The transition to advanced desalination processes occurred due to the industrial revolution in Europe and the United States which caused huge rates of urbanization and population growth [58]. This resulted in

Table 2
Top 50 most used keywords from Scopus (1966–2020).

Rank	Keyword	Frequency	Rank	Keyword	Frequency
1	Membrane	4789	26	Separation	716
2	Desalination	4758	27	Optimization	714
3	Water Treatment	2482	28	Osmosis membrane	714
4	Membranes	2433	29	pH	638
5	Reverse Osmosis	2294	30	Aqueous solution	680
6	Wastewater Treatment	1589	31	Membrane Fouling	653
7	Wastewater	1563	32	Water Treatment Plants	633
8	Water Filtration	1528	33	Effluents	608
9	Seawater	1478	34	Pollutant Removal	596
10	Ultrafiltration	1434	35	Chemicals Removal (water Treatment)	593
11	Fouling	1323	36	Drinking Water	572
12	Filtration	1308	37	Energy Utilization	569
13	Distillation	1256	38	Mathematical Models	567
14	Adsorption	1084	39	Wastewater Reclamation	563
15	Osmosis	1080	40	Scanning Electron Microscopy	555
16	Concentration (composition)	982	41	DESALINATION	553
17	Nanofiltration	910	42	Electrodialysis	545
18	Microfiltration	904	43	Solutions	532
19	Water Supply	887	44	Membrane Technology	527
20	Polymer	820	45	Sodium Chloride	520
21	Potable Water	808	46	Numerical Model	514
22	Water Quality	805	47	Chemical Oxygen Demand	509
23	Ion Exchange	770	48	Bioreactor	508
24	Experimental Study	767	49	Evaporation	502
25	Performance Assessment	765	50	Mass Transfer	499

huge pollution issues such as air, water and thermal pollution due to the increased usage of fossil fuel in the operation of desalination plants. The use renewable energy sources to control environmental pollution and improve the quality of the desalination process draw scientists' interest, with the number of publications increasing from 4 in (1966–1975) to 352 in (2006–2015). In additions, publications related to environmental issues also increased to 92 folds to 369 in (2006–2015) as compared to 4 in (1966–1975) [62]. At this time, publications in energy consumption and energy recovery also started and from 10 publications in (1966–1975) to reach 8 times in (1976–1985). Energy consumption is one of the key parameters impacting the economic side of different desalination techniques. Energy recovery and reuse from currently available desalination techniques such as reverse osmosis is becoming a viable topic [63]. Energy recovery by work exchangers using variable frequency drive (VFD) at high pressure feed stream pumping system is one of the solutions for water and energy recovery [64]. Two stage brine conversion seawater reverse osmosis system was developed and commercialized in 1999 producing 4500 m^3/day in Spain for fresh-water, energy and brine recovery [65]. This configuration of the plant recovers up to 22% energy in one stage reverse osmosis unit [66]. Meanwhile, new research areas such as sustainability seem to draw some attention in recent years. These areas are mainly related to coupling the membrane process with the renewable energy sources [67].

Reverse osmosis, forward osmosis and hybrid systems are all research fields related to the membrane process. There are many integrated advantages to RO desalination, including the complete purification of water from all ions and salts and having a compact footprint and design [68]. Economic factors related to energy and power consumption are still under study and only few studies have been conducted especially on process economics and sustainability of RO [69].

Forward osmosis desalination has appeared on the stage in late 80's. The main difference between RO and FO is that the RO process uses hydraulic pressure while, FO utilizes the natural osmotic pressure for water flow through the membrane [70]. Thus, it requires lower energy consumption. In addition, it can contribute to zero liquid discharge and it has less fouling problems [71]. Nowadays, the research trend in the Desalination journal is moving towards new areas, such as sustainability of desalination plants which is at the forefront of research, energy recovery, optimization of different processes (hybrid systems and FO), environmental issues related to desaliantion and finally energy recovery. Sustainability in desalination is very important as the increase in water desalination will increase the salinity of oceans and seas which as a result will decrease the amount of water to be desalted in coming years [72]. It is worth mentioning that desalination plants consume considerable amounts of energy, which accounts for at least 35% of the total operating costs. Therefore, the gap between water and electricity

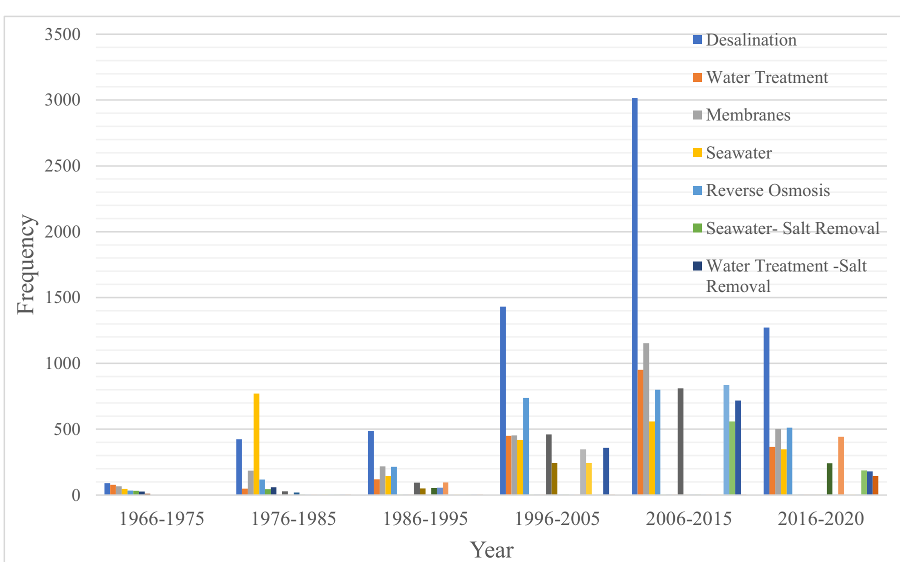

Fig. 9. Keywords frequency chart.

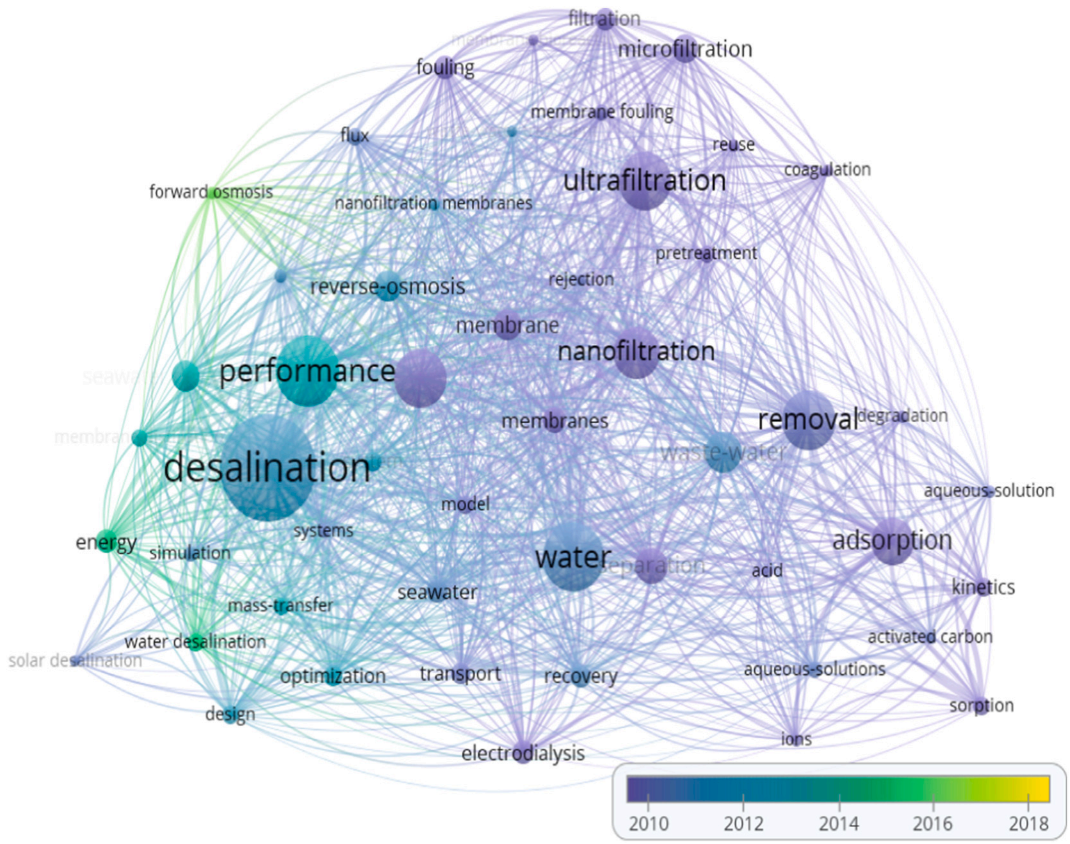

Fig. 10. Keywords frequency map based on the time.

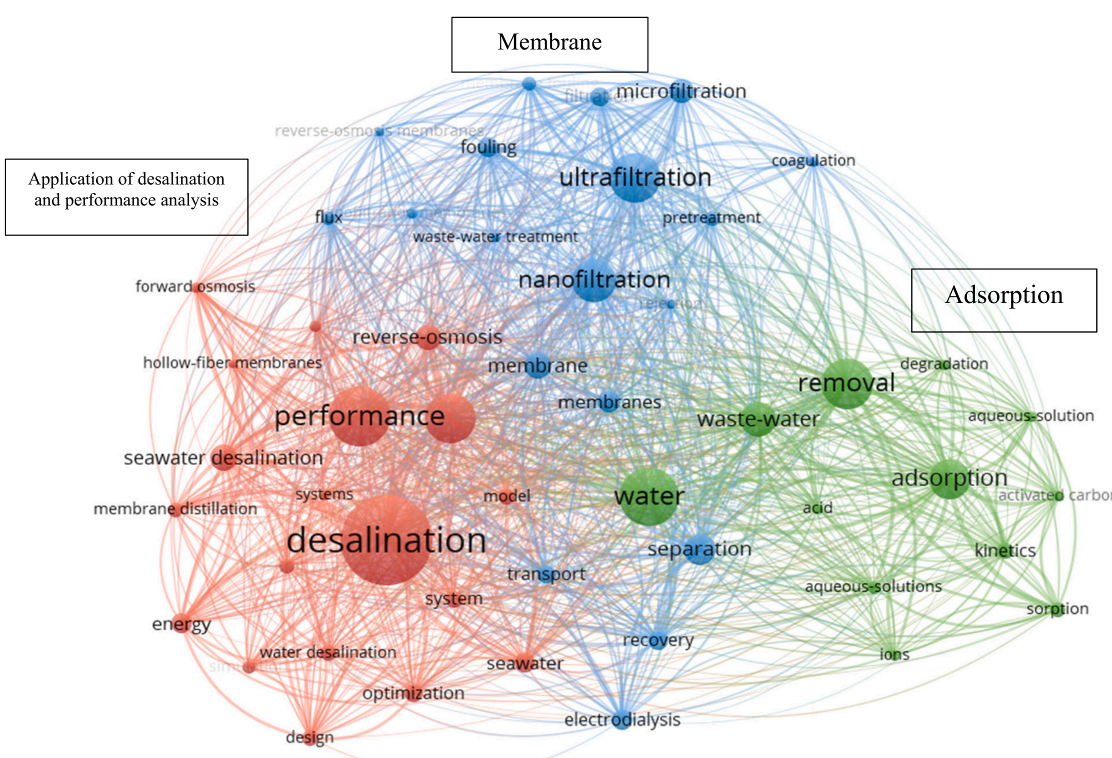

Fig. 11. Top 50 most co-occurrence of all keywords map (1968–2020).

Table 3
Top 20 most cited countries, number of publications and citations per publication extracted from VOSviewer (1968–2020).

Country rank	Country	Citations/ publication	Citations	Number of publications
1	Malaysia	84	23,853	284
2	Iran	48	24,591	508
3	Turkey	47	18,357	387
4	United Arab Emirates	42	11,763	281
5	India	41	28,704	703
6	Egypt	40	14,532	362
7	Canada	38	10,549	276
8	Greece	37	9842	263
9	Algeria	35	8902	253
10	Australia	35	21,548	614
11	China	35	59,791	1709
12	South Korea	35	22,542	653
13	Tunisia	34	7523	222
14	Spain	33	22,395	679
15	France	30	20,772	691
16	Saudi Arabia	29	13,821	477
17	Poland	27	9413	344
18	Netherlands	27	8760	326
19	United States	26	45,825	1731
20	Germany	26	19,278	731
21	Israel	24	8997	376
22	Italy	23	12,757	555
23	Japan	21	12,465	593
24	England	18	11,971	666
25	Kuwait	17	3940	238

demand and the sustainable supply need to be reduced by 2030 [70]. Therefore, today's water resources should be used wisely to maintain the availability of water for the future generation.

3.3. Keywords analysis

Keywords are one of the important parts of a research paper, as they highlight the contents of the article. The frequency of a keyword indicates hotspot areas of science. Also, keywords help in increasing the visibility of the research papers by assisting the research engines and indexers to figure out the relevant papers to the search. In the Desalination journal, a total of 162 most used keywords were extracted which have been used more than 300 times. The top 50 used keywords extracted from Scopus during the period from 1966 to 2020 are listed in Table 2. An interesting point to notice is that “Membrane” is the first most used keyword, while “Membranes” is the 4th. Therefore, the selection of proper keywords is as important in the visibility of the paper as its title. Thus, it is crucial to include the most relevant keywords in the paper

In addition, this analysis can be used to pinpoint the emerging novel technologies or hotspot in desalination in upcoming years. This is performed by analyzing keywords based on the time they appear in the field. The keywords frequency is illustrated in Fig. 9.

Both Figs. 9 and 10 show the frequency of the most used keywords. Fig. 9 shows some selected keywords from the top 20 most frequently used keywords in each period as a function of time. This analysis gives an indication about the areas and their time of appearance which reflects the period of scholar's interest. It is worth noting that some keywords such as “brine” have disappeared from the top 20 after the first decade, but they are still being used at a limited scale. Some new keywords such as mathematical models, solar power and performance have appeared in the last 3 decades. Fig. 10 shows keywords frequency map. Performance, forward osmosis and energy are among the most recently used keywords, while membranes were mostly used in earlier periods.

Further analysis of keywords was carried out using VOSviewer to generate co-occurrence map of the top 50 most frequently used keywords out of a total of 25,632. Each keyword has a minimum co-occurance of 197 to be represented in the network. Co-occurrence refers to the frequency of simultaneous occurrence of keywords in all papers in the Desalination journal including all keywords (not only author's keywords) in order to close the proximity of similar keywords. In Fig. 11. each keyword is represented as a circle or a node, while the size of the circle reflects the frequency of the occurrence. The larger the circle, the more a keyword was used in analyzed scientific articles. The connection between any two keywords is represented by a curve, the stronger the connection (link strength), the thicker the line. From Fig. 11. keywords can be classified into three clusters. Cluster 1, 2 and 3 which are shown in red, green and blue, respectively. In each cluster, the closer the circles, the relevant the keywords in the cluster. The first cluster is related to the application of desalination and performance analysis, as it can be figured out from keywords, such as desalination, performance, energy, reverse and reverse-osmosis. While cluster 2 is related more to membrane analysis which is represented by words, such as ultrafiltration, nanofiltration and fouling. Cluster 3 represents adsorption field which is related to water treatment using adsorbent; the most representative keywords are separation, removal and adsorption. These three clusters reveal the major fields of research from 1968 on going in the Desalination journal based on co-occurrence and visibility of keywords. The connections of each of the keywords to other keywords is shown for keyword “desalination”; it is connected strongly with keywords, such as performance, water, seawater and energy, whereas it is weakly connected with adsorption. It is important to mention that the analysis can also show the new areas in the field. It can be noticed that words such as “optimization”, “system”, “design” and “model” are appearing recently to be used with considerable frequencies to appear in the top 50 keywords.

3.4. Countries analysis

Table 3 shows the top 20 most productive countries based on data extracted from Scopus (1968–2020). This table is based on most productive countries in the Desalination journal, while the country rank is based on the citations per publication. This analysis gives an overview about the research interest and the areas that each country supports. This is directly proportional to the resources and deficits of each country. The top 12 countries, which are shown in Table 3, contributed to publishing more than 500 publications. The leading countries in the Desalination journal are the United States followed by China then Germany and India. It is worth noting here that a publication can be related to more than one country due to collaborations in different institutions, and this has already been taken into consideration.

For the two leading countries in terms of number of publications (the United States and China), the interest in water desalination research can be attributed to huge urbanization, large populations, governmental policies, financial incentives, and the availability of technological innovation. Also, the economic growth and the industrial evolution have an important role in this interest. A large number of industries in both countries use an enormous amount of water (desalinated or deionized water). The migration of people in China from rural areas to mega cities led to a steep increase in freshwater and power production requirements. According to the Ministry of Earth Surface Process of China, the urbanization rate will reach almost 65% by 2030 [73]. Therefore, China is facing water scarcity and pollution problems which need to be addressed [74]. It is worth mentioning that by now, almost 400 cities out of 668 in China face challenges in water supply [73]. Also, the policies that were introduced by the Chinese government to support research in water and membrane technologies in order to remedy water pollution is another reason [75]. The incentives and the funding provided to different research institution are other reasons that led to more investments in research. This can be noticed from the institutional analysis that 16% of the most productive institutions in the Desalination journal are from China. In the United States, the economic growth and large population, in addition to the shrinking water resources and drought

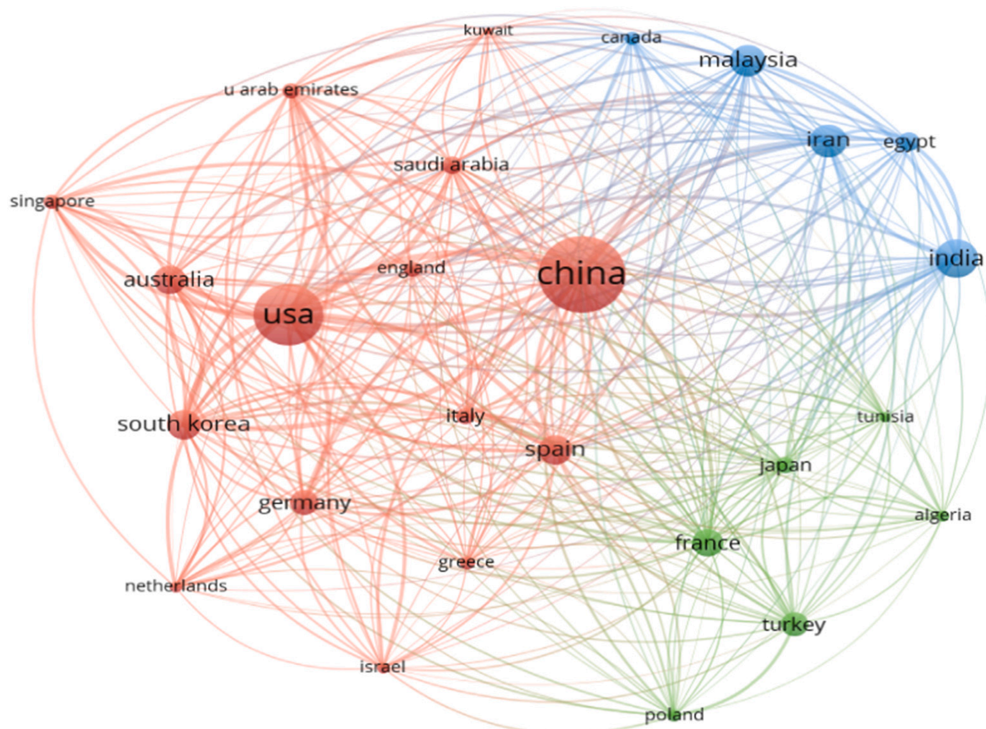

Fig. 12. Most cited countries in the Desalination journal (1968–2020).

Table 4
Most productive institutions in the Desalination journal (1966–2020).

Institution ranking	Institution	Documents	Country
1	Ministry of Education China	175	China
2	Chinese Academy of Sciences	172	China
3	Technion - Israel Institute of Technology	132	Israel
4	Tsinghua University	124	China
5	UNSW Sydney	124	Australia
6	University of Technology Sydney	123	Australia
7	Swansea University	120	United Kingdom
8	Nanyang Technological University	120	Singapore
9	Universiti Teknologi Malaysia	112	Malaysia
10	Kuwait Institute for Scientific Research	106	Kuwait
11	Gwangju Institute of Science and Technology	105	South Korea
12	CNRS Centre National de la Recherche Scientifique	103	France
13	King Fahd University of Petroleum and Minerals	102	KSA
14	Tianjin University	102	China
15	Kuwait University	102	Kuwait
16	Università della Calabria	100	Italy
17	Rheinisch-Westfälische Technische Hochschule Aachen	93	Germany
18	Massachusetts Institute of Technology	93	USA
19	Université des Sciences et de la Technologie Houari Boumediene	92	Algeria
20	Wrocław University of Science and Technology	91	Poland
21	Korea University	87	South Korea
22	Universitat Politècnica de València	87	Spain
23	Institut Européen des Membranes UMR5635	86	France
24	Silesian University of Technology	85	Poland
25	National University of Singapore	85	Singapore

problems in many regions of the country led the US to adopt desalination since 1950 as a viable solution for water shortage [76]. The United States established programs based on the governmental policies for supporting water infrastructure by providing federal funds. EPA, department of Agriculture and Department of Housing and Urban Development are the major sources of funds in water research [77]. Based on Water World, EPA announced to invest $2.7 Billion in water research in 2021 to ensure the access to clean water especially for underserved communities [78]. Even though there are other productive countries such as India in desalination research (703 publications), this did not translate into high rate of implementation as India currently suffers from the worst water crisis in its history [79]. This can be attributed to the high cost of the desalination processes compared to the country's economy and population. In terms of the impact (citation/publication), Malaysia, Iran and Turkey have the most impact among the top 25 countries.

Based on citations, China showed a total of 59,791 citations in the specified time span, followed by the USA with 45,825 total citations. Each country is represented by a circle with the variation of sizes based on the total number of citations. The circles of different countries are linked by a curve with others; the thickness of this curve shows the strength of collaboration between countries. While the color of the circles represents the research clusters that these countries contributing to the most. Red represents countries publishing in desalination applications and performance analysis, while blue represent countries with more records in membrane technology and green countries have more publications in adsorption [80]. Fig. 12. shows the network of the highly cited countries in the Desalination journal.

3.5. Institutions analysis

From Scopus records, out of 160 different institutions, the top 25 most productive institutions in terms of number of publications were analyzed in the period of (1966–2020) and displayed in Table 4. The top 15 institutions have published more than 100 articles in the specified time span. It can be noticed that most of the organizations are from

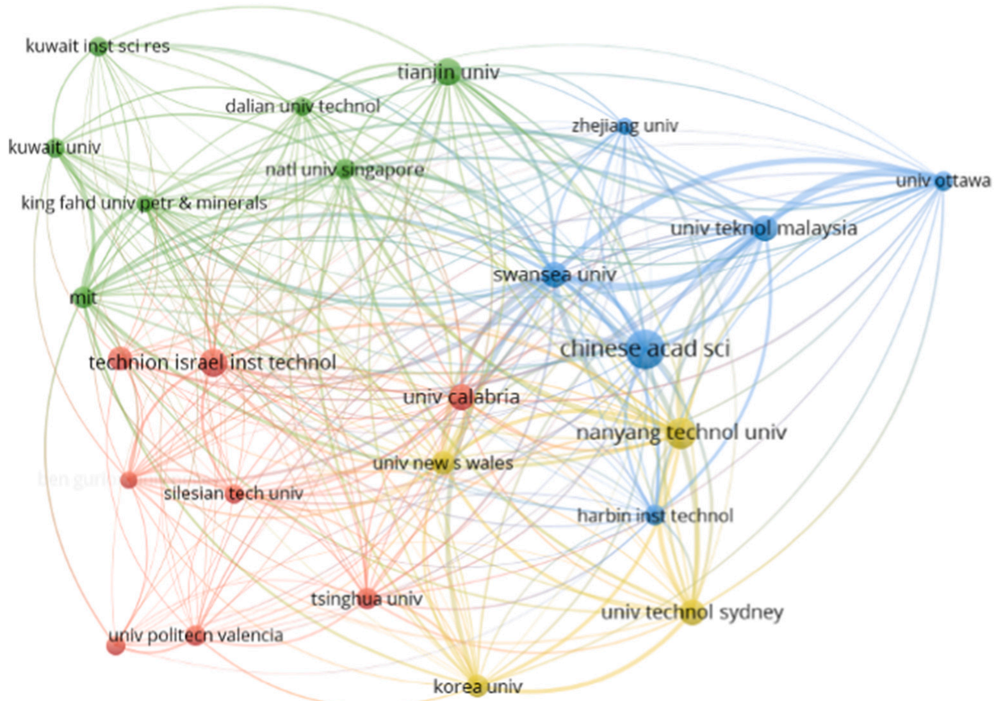

Fig. 13. Most cited institutions map from VOSviewer (1968–2020).

Table 5
Top 25 most cited institutions and their total number of collaborations extracted from VOSviewer (1968–2020).

Institution rank	Institutions	Citations
1	Swansea University	9903
2	Universiti Teknologi Malaysia	9243
3	Chinese Academy of Science	6358
4	Nanyang Technology University	5640
5	University of Ottawa	5424
6	University of New South Wales	4876
7	NATL university of Singapore	4918
8	Indian Institution of Technology	4143
9	MIT	3849
10	Technion Israel Institute of Technology	3558
11	Harbin Institute of Technology	3556
12	Tianjin University	2952
13	University Calabria	3108
14	University of Technology Sydney	2923
15	Tsinghua University	2622
16	Korea University	2661
17	Ben-Gurion University of the Negev	2752
18	King Fahd University Petroleum and Minerals	2527
19	Kuwait University	2201
20	Silesian Technical University	2339
21	Dalian University Technology	1950
22	Université Montpellier	1830
23	Kuwait Institution for Scientific Research	1322
24	Universitat Politecnica Valencia	1915
25	Zhejiang University	2151

China, as four institutions out of 20 are Chinese institutions. Kuwait is the leading GCC country in publications in the Desalination journal by 106 records for Kuwait institute for scientific research proceeded by KSA. This can be linked to the history of desalination in Kuwait as it goes back to 1951 before all GCC countries [81]. It is worth mentioning that the ministry of electricity and water in Kuwait published a paper in April 1966 in the Desalination journal about the economics related to water production in Kuwait [82]. This paper was published in the first issue and volume of the journal, considered one of its kind.

The most cited institutions are represented in Fig. 13 using VOSviewer. Out of 5765 organization, 25 were chosen based on a minimum number of documents per organization of 67. The size of the circle for each of the institutions represents the number of its citations and the curves show the collaborations between the different organizations. Finally, the colors represent the field of research [80].

Table 6
Top 25 most cited authors normalized per publications extracted from VOSviewer (1968–2020). This includes all citations of papers published by the authors in the Desalination journal.

Author rank	Author's name	Citations/ publications	Citations	Number of publications
1	Ismail, A.F.	100	9522	95
2	Hilal, N.	93	12,149	131
3	Matsuura, T.	75	4726	63
4	Ghaffour, N.	68	2666	39
5	Tiwari, G.N.	64	2560	40
6	Mohammadi, T.	63	3226	51
7	Khayet, M.	63	2397	38
8	Madaeni, S.S.	55	1988	36
9	Kabay, N.	45	2223	49
10	Gao, C.	45	2631	58
11	Semiat, R.	40	2433	61
12	Cho, J.	37	1897	51
13	Lee, S.	37	1331	36
14	Hasson, D.	35	1654	47
15	Nyström, M.	35	1325	38
16	Fane, A.G.	34	2499	73
17	Drioli, E.	34	3377	99
18	Hong, S.	33	1440	43
19	Turek, M.	33	1215	37
20	Kim, I.S.	31	1164	37
21	Shon, H.K.	31	1724	56
22	Vigneswaran, S.	27	1654	61
23	Darwish, M.A.	22	1086	50
24	Rautenbach, R.	21	739	35
25	El-Nashar, A. M.	19	795	42

The top 25 most cited institutions and their total number of

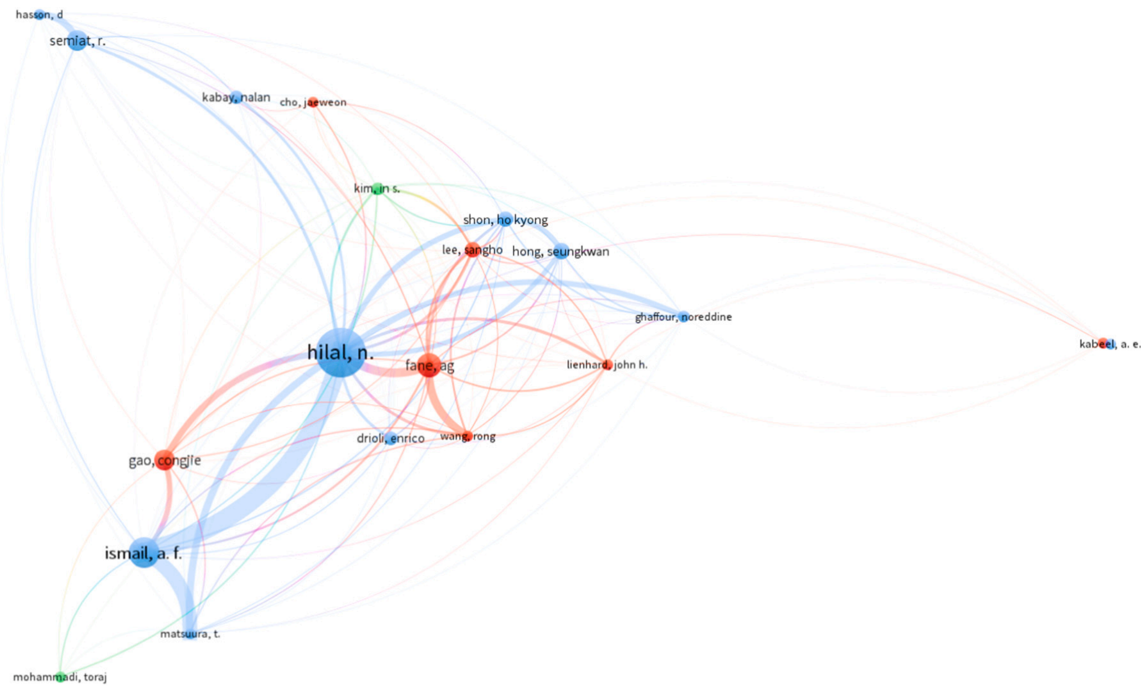

Fig. 14. Citation map of authors in the Desalination journal (1968–2020).

collaborations extracted from VOSviewer (1968–2020) can be shown in Table 5. As stated before, the collaborations are represented by the curves with thicker lines indicating stronger collaboration. Swansea University (UK) is the most cited institution with a total of 9903 citations and it has very strong collaborations with other institutions. The highly cited records of Swansea University are mainly related to membrane technology.

3.6. Author analysis

The top 25 most productive authors in terms of number of peer reviewed publications in the Desalination journal are given in Table 6 based on data extracted from Scopus. The most prolific authors in the journal are Hilal, N., Drioli, E. and Ismail, A.F. and all of them are specialized in the membrane technology field. The most productive authors and the normalized citations per the number of publications in (1968–2020) are shown in Table 6. Ismail, A.F. has the highest citations/publication ratio followed by Hilal, N. and Fane, A.G..

Also, for a better understanding of the scholars' collaborations, the contributing authors were taken as a unit for analysis. The citation and co-citation networks were constructed using VOSviewer. The citation network shows the most cited authors in the Desalination journal which is shown in Fig. 14 below. The citation map is based on a minimum number of documents per author of 26 with minimum number of

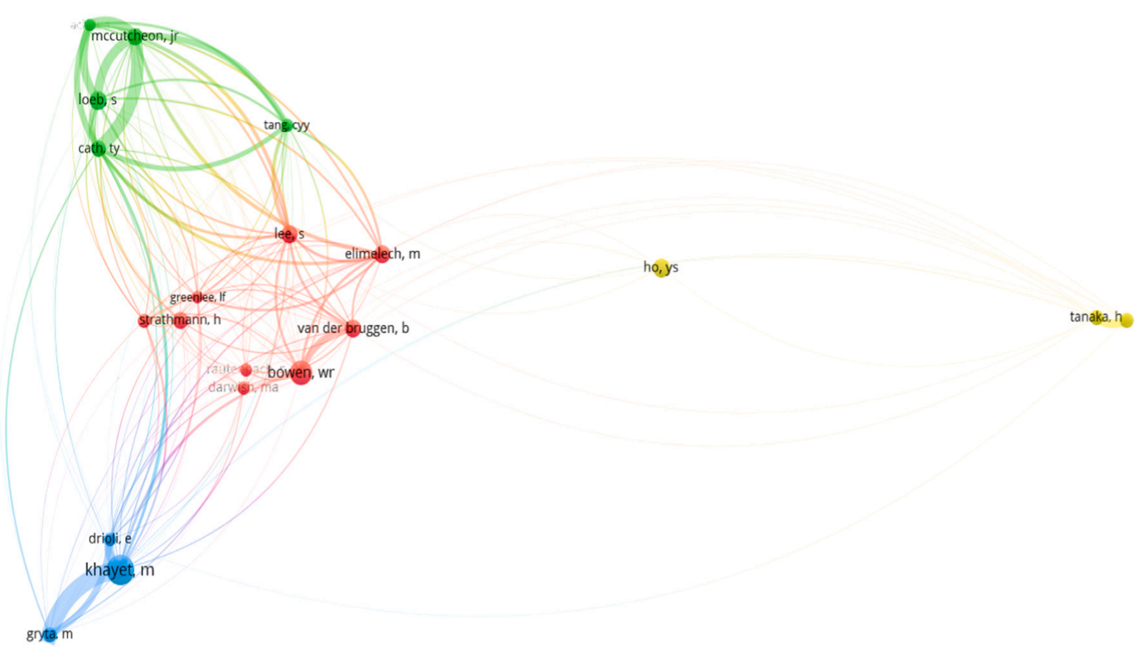

Fig. 15. Co-citation map of authors in the Desalination journal (1968–2020).

Table 7
Top 20 most cited papers in the Desalination journal over 54 years.

No.	Title	Author(s)	Year	Cited by	Keywords	Document type	Focus field	Ref.
1	Membrane distillation: A comprehensive review	Alkhudhiri, A; Darwish, N; Hilal, N	2012	1455	Membrane distillation; AGMD; Membrane	Review	Membrane characteristi-cs	[90]
2	State-of-the-art of reverse osmosis desalination	Fritzmann, C; Lowenberg, J; Wintgens, T; Melin, T	2007	1271	Desalination; reverse osmosis	Article	Membrane	[91]
3	Cationic and anionic dye adsorption by agricultural solid wastes: A comprehensive review	Salleh, MAM; Mahmoud, DK; Karim, WAWA; Idris, A	2011	1010	Adsorption; Cationic dye; Agricultural solid wastes	Review	Adsorption	[92]
4	Advances in seawater desalination technologies	hawaji, AD; Kutubkhanah, IK; Wie, JM	2008	928	Seawater desalination technologies; Desalination; Solar evaporation desalination	Review	Desalination	[93]
5	A kinetics and thermodynamics study of methylene blue adsorption on wheat shells	Bulut, Y; Aydin, H	2006	928	Adsorption; Methylene blue; Wheat shells	Article	Adsorption	[94]
6	Nanofiltration membranes review: Recent advances and future prospect	Mohammad, A.W., Teow, Y. H., Ang, W.L., (…), Oatley-Radcliffe, D.L., Hilal, N.	2015	909	Desalination; Fabrication; Modeling; Nanofiltration	Review	Membrane	[95]
7	Thermodynamics of hyperfiltration (reverse osmosis): criteria for efficient membranes	Spiegler, K.S., Kedem, O.	1966	877	–	Article	Desalination	[96]
8	Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability	Ghaffour, N; Missimer, TM; Amy, GL	2013	862	Desalination cost; Desalination technologies development; Energy consumption	Review	Economics	[97]
9	Electrodialysis, a mature technology with a multitude of new applications	Strathmann, H	2010	852	Electrodialysis; Continuous electro-deionization; Electro-dialytic water dissociation	Article	Electrodialysis	[98]
10	Capacitive deionization (CDI) for desalination and water treatment past, present and future (a review)	Oren, Y.	2008	805	Capacitive deionization (CDI); Capacitive deionization technology (CDT); Electronic water purification (EWP)	Review	Water purification	[99]
11	A novel ammonia-carbon dioxide forward (direct) osmosis desalination process	McCutcheon, JR; McGinnis, RL; Elimelech, M	2005	780	Forward osmosis; Osmosis; desalination; Ammonium bicarbonate	Article	Forward osmosis	[100]
12	Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals	Snyder, SA; Adham, S; Redding, AM; Cannon, FS; DeCarolis, J; Oppenheimer, J; Wert, EC; Yoon, Y	2007	769	Endocrine disruptor; Pharmaceutical; Emerging contaminant	Article	Membrane	[101]
13	A review of the effects of emerging contaminants in wastewater and options for their removal	Bolong, N; Ismail, AF; Salim, MR; Matsuura, T	2009	648	Emerging contaminants; Environmental impact; Advanced wastewater treatment	Review	Nanofiltration	[102]
14	The forward osmosis membrane bioreactor: A low fouling alternative to MBR processes	Achilli, A; Cath, TY; Marchand, EA; Childress, AE	2009	644	Membrane bioreactor; Forward osmosis; Membrane fouling;	Article	Forward osmosis	[103]
15	Adsorption thermodynamics, kinetics and isosteric heat of adsorption of malachite green onto chemically modified rice husk	Chowdhury, S; Mishra, R; Saha, P; Kushwaha, P	2011	648	Rice husk; Malachite green; Kinetics;	Article	Adsorption	[104]
16	Trends in electro-Fenton process for water and wastewater treatment: An overview	Nidheesh, P.V., Gandhimathi, R.	2012	639	Degradation; Electro Fenton; Organic pollutant	Review	Wastewater treatment	[105]
17	Membrane technology enhancement in oil-water separation: A review	Padaki, M., Surya Murali, R., Abdullah, M.S., Misdan N., Moslehyani A., Kassim M.A., Hilal N., Ismail A.F.	2015	636	Fouling; Oily wastewater; Surface modification	Review	Membrane	[106]
18	Arsenic toxicity, health hazards and removal techniques from water: an overview	Choong, TSY; Chuah, TG; Robiah, Y; Koay, FLG; Azni, I	2007	627	Arsenic; Adsorption; Residual disposal	Review	Adsorption	[107]
19	Effect of membrane chemistry and coating layer on physiochemical properties of thin film composite polyamide RO and NF membranes. I. FTRI and XPS characterization of polyamide and coating layer chemistry	Tang, C.Y., Kwon, Y.-N., Leckie, J.O.	2009	614	Coating; Polyamide; Reverse osmosis	Article	Membrane	[108]
20	Environmental impact and impact assessment of seawater desalination	Lattemann, S., Höpner, T.	2008	595	Antiscalants; Environmental impact; Marine environment	Article	Environmental impact	[109]

citations per author of 95, and out of the 29,501 authors, only 28 met the threshold and the top 25 are shown in the map of Fig. 14. The size of the circles represents the citations per author, the curves represent collaborations between the authors, and the color of the circles refers to the field the authors: red is assigned to desalination field, blue for membranes and green for adsorption. It is worth noting that a good number of the most cited authors as shown in Fig. 14 are related to the membranes field which is one of the hotspots in the journal based on the most cited papers as shown earlier in the Keywords section and in the next section.

Co-citation analysis is a critical bibliometrics tool to examine the intellectual framework of a field based on the co-occurrence of different items. This analysis was introduced in 1973 [83] and can be defined as the frequency of citing two items of previous academic work together in a later work. Co-citation can be successfully applied on different items such as authors, keywords, or sources. In this section, the applied co-citation analysis took the author as the base for analyzing the frequency of co-occurrence "author co-citation analysis (ACA)" [84]. ACA map was constructed using VOSviewer which is based on a minimum number of co-citations of 300 which is shown in Fig. 15. The scholars are represented in 4 clusters based on the field of the study, while the size of the circles represents the co-citations of each author, the curves represent collaborations between the authors. Authors of the same cluster have a stronger collaboration sharing the same publication. The strongest the relatedness of authors in co-citation, the closer they are located from one another in the map. It is important to note that the link of each researcher to others and the strength of the link is not representing the real collaboration strength, as all authors in the Desalination journal are not included in Fig. 15. It is worth mentioning that VOSviewer in co-citation analysis looks at the frequency of cited works of an author appearing as the first author in the publications.

3.7. Most cited research papers in the desalination journal (1966–2020)

In this section, the highly cited papers in the Desalination journal are identified by means of H-classic methodology. This methodology is based on ranking papers depending on citation counts in descending order. For the collection of documents published in a specified time span in the Desalination journal, the H-index can be taken from Web of Science [85]. The H-index was found to be 180. Therefore, the first H highly cited papers should be listed. Table 7 shows only the top 20 highly cited publications in the Desalination journal from (1966–2020). The most cited papers in the Desalination journal could assist researchers to discover the dominant fields in the related science areas. In addition, highly cited papers can be used to increase the level of acceptability and visibility of papers especially for young researchers. This can be achieved by using similar keywords within the same field. The power of keywords is actually underestimated, as search engines often utilize the frequency of appearance of keywords in research papers for presenting top research results. Analysis of highly cited papers can be used further to demonstrate the gaps which need to be filled and identify areas in which developing new studies is possible. Keywords of highly cited papers can help in analyzing the gaps in related fields; high frequency of a keyword is an indication that the related field is saturated and explored sufficiently. However, scholars should be attentive, if a keyword was appearing frequently in a certain time period and then vanished, this could be a sign of literature exhaustion in that field [86]. As it can be noticed, 45% of the highly cited papers are related to the membranes field. That is because membrane technology has wide field applications. These applications vary from wastewater treatment, filtration and distillation to others beyond desalination such as food manufacturing and catalysts [87]. Another hotspot in the top 20 most cited articles is the adsorption field, which seems to account for 20% of papers published in wastewater treatment. Lower cost, easy operation and compact simple design are some of the factors that contribute to the attractiveness of adsorption processes [88]. In addition, a variety of organic, non-organic, toxic and persistent materials can be removed using this method, as it can offer low cost and high capacity binding solutions [89]. Table 7 is compatible with keywords analysis and shows the same result regarding the most used keywords. Keywords with high frequency have high co-occurrence in Table 7 in highly cited papers in the Desalination journal. Finally, it is worth mentioning that the citation of each paper in Table 7 is extracted from Scopus in November 2021.

4. Conclusions and future prospects

Based on this bibliometric study and different analyses, such as keywords, research categories and citation analysis, there has been tremendous evolution in the Desalination journal from 1966 to 2020. After reviewing 14,582 articles published over 54 years in the journal, the key research areas were identified. The growth of publications over the specified period was fluctuating showing a remarkable increase in the number of published documents from 2002. The growth of desalination field in the journal is due to the contribution of 163 top scholars from 145 countries with China and United States contributing the most Scopus, Web of science and VOSviewer software was used to gather the data and construct network maps. According to the analysis, more future research can be conducted in different fields of desalination such as sustainable integrated hybrid desalination plants that utilize renewable energy sources. This may also include synthesis of novel anti-fouling membranes for reverse osmosis, fabrication of doubled-skin FO membranes with different types of draw solutions. Energy and cost-effective desalination plant studies coupled with modeling and optimization will be increased to achieve current and future water demand while reducing the operating costs. Mathematical modeling and optimization are expected to contribute to the improvement of forward osmosis and microbial cells desalination. Moreover, increasing investments in membrane bioreactors and microbial desalination cells to enhance the sustainability of the desalination process and producing potable water while treating wastewater and producing renewable energy is a viable future research area. Assessments of the supply/value chains of the desalination process are growing to quantify and reduce CO_2 emissions, making the desalination plants more environmentally friendly. Finally, the implementation of hybrid desalination systems, coupled with nanomaterials to enhance the overall efficiency of the desalination process is another future direction to consider.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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