Desalination 519 (2022) 115305

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Worldwide research trends on desalination

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HIGHLIGHTS

- This manuscript explores the whole literature related to desalination.
- The top 3 most productive countries are China, USA, and India.
- Six main clusters were detected.
- The top 3 clusters: Reverse osmosis, Renewable energy, Thermal desalination
- Membrane was the main keyword from 2015 to 2020.

ARTICLE INFO

Keywords:
Desalination
Reverse osmosis
Forward osmosis
Membrane
Distillation
Optimization
Brine
Capacitive deionization
Electrodialysis
Microbial desalination cell
Freeze desalination
Corrosion
Electromigration
Electroosmosis
Bibliometric
Scopus

ABSTRACT

It is a fact that the world's population has increased twofold in the last 50 years, which has meant that the availability of freshwater for all required activities, industrial use, agriculture, and domestic use, has become increasingly scarce. In addition to these factors, 40% of the world's population lives less than 100 km from the coast. All these factors make desalination a key factor for the sustainability of the world's population. In this study, a bibliometric study has been carried out on all publications related to desalination. An exponential growth has been detected since 2008. The top 4 categories are environmental sciences (28%), engineering (27%), chemical engineering (11%), and chemistry (10%). The top 3 most productive in this scientific field have been China, USA, and India. Within the top 20 institutions, 8 are from China and 4 from Saudi Arabia, the top 3 being Ministry of Education China, Chinese Academy of Sciences, and Regarding international collaboration, US authors stand out, noting that there are many different groups that collaborate with many authors from different countries and are therefore at the core of international collaboration. Massachusetts Institute of Technology. On the other hand, the institutions with the highest scientific production tend to collaborate little with the rest of the institutions in their own country. The analysis of the evolution of the top 10 keywords shows that the top keywords were: from 2000 to 2001 reverse osmosis, 2002 membranes, from 2003 to 2007 sea water, from 2008 to 2014 water filtration, and from 2015 to 2020 membranes. An analysis of the scientific communities in which these works are grouped, and which represent the world trends in research in this field has found: Reverse osmosis (27%), Renewable energy desalination (26%), Thermal desalination (14%), Brine (13%), Electrodialysis (8%), Membrane distillation (7%), and less than 2% Microbial desalination and Freeze desalination.

1. Introduction

One of the major problems affecting people around the world is inadequate access to safe drinking water [1]. Water scarcity can be considered a natural phenomenon, but it may also be human-induced. There is an estimated amount of freshwater on the planet to meet the needs of the world's population of about seven billion people. The problem is its distribution in time and space. Moreover, much of it is wasted, polluted, and unsustainably managed. About one third of the rural population in developing countries lives in arid and semi-arid regions and faces recurrent water scarcity [2].

In the world in 2017, the last year with known data, 3881 billion cubic metres of freshwater were extracted [3], of which 71% was for agricultural use, 17% for industrial use and 12% for domestic use (see Table 1). If this classification is made according to the wealth of the country, see Table 1, a great imbalance in water use is observed, where the most striking feature is that domestic use is almost three times higher in high-income countries than in low-income countries.

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https://doi.org/10.1016/j.desal.2021.115305
Received 2 May 2021; Received in revised form 5 August 2021; Accepted 14 August 2021
Available online 25 August 2021
0011-9164/

Table 1
Water distribution (%) by sector according to the country's level of wealth [3].

Country					
Sector	High income	Upper middle income	Lower middle income	Low income	Average
Agriculture (%)	43.3	71.2	88.1	90.6	71
Industry (%)	40.5	15.4	4.0	2.7	17
Domestic (%)	16.2	13.4	7.9	6.7	12

If one examines the World Bank's data on Renewable internal freshwater resources per capita (cubic meters), Fig. 1, one can see that in the last 50 years, freshwater per capita has fallen by half [3], from 12,000 m^3 in 1967 to 5732 m^3 in 2017. Although it is not the purpose of this paper to analyze the causes of this water shortage, it should be noted that in 1967, there were 3462 million people and in 2017, there were 7509 million, i.e. the world population has doubled in 50 years.

The UN Human Development Report 2006 and the World Health Organization [4] recommend that 50–100 l per capita per day (l/c/d) of water should be piped into households for human development [5] and to maintain adequate health [6] E.g. For South Africa, the goal is 'households with at least 25 l of potable water per person per day within 200 m of a household, not interrupted for more than 7 days per year' [7].

More than 40% of the world's population (more than 2.8 billion people) live within 100 km of the coast [4]. This means that a large part of the world's population faces water scarcity, and another large part of the world's population faces water supply constraints due to lack of infrastructure to take water from rivers and aquifers or the desalination of seawater and brackish water. In view of the data, short-term solutions must be searched for and desalination may therefore be a major contribution in view of the high population density close to the coasts.

The aim of this work is to examine all the scientific literature on desalination worldwide to analyze research trends in this field. To this end, a bibliometric study will be carried out, analyzing the evolution of publications by year, the countries and affiliations that contribute most to this scientific field, and through the key words of the articles, analyzing the scientific communities in which these works can be grouped.

In the literature, some bibliometric studies on desalination can be found. Some of them based on WoS between 1997 and 2012.The main conclusion was that the seven major industrialized countries (G7) USA, Italy, Japan, Germany, UK, Canada, and France published the majority of the world articles [8]. Regarding the WoS categories, these publications were centered on Engineering Chemical (53%) and Water Resources (44%). And the five most frequently used keywords, excluded desalination, were: "reverse osmosis", "seawater", "solar energy", "electrodialysis" and "nanofiltration".

Another study based on Scopus but limited to Arab world research productivity from 1976 to 2015 [9]. This is for Saudi Arabia, Egypt, Jordan, Palestine, Lebanon, Qatar, Bahrain, Kuwait, Morocco, Tunisia, Syrian Arab Republic, UAE, Iraq, Sudan, Yemen, Algeria, Comoros, Djibouti, Libya, Mauritania, Oman, and Somalia. Among these, the top 3 were Saudi Arabia, Egypt and UAE. The main categories found were Chemical Engineering (57%), Engineering (43%), and Environmental Science (40%). Regarding the main institutions, the top 3 were from Saudi Arabia: King Saud University, King Fahd University of Petroleum and Minerals, and King Abdullah University of Science and Technology. There are also bibliometric papers on desalination that focus on a single country such as Korea [10].

Other bibliometric studies focus on a single technology such as forward osmosis [11]. This study was based on Scopus and for the period 1967 to 2018, and they analyze 1462 article records. They found that the top 5 countries were: China, USA, Singapore, Australia, and South Korea. The top 5 most productive institutions in forward osmosis were: National University of Singapore (Singapore), Nanyang Technological University (Singapore), University of Technology Sydney (Australia), Yale University (USA), King Abdullah University of Science and Technology (Saudi Arabia). Another example is related to brine production.

2. Methodology

This analysis was based on searches of Scopus databases. Although the historical content of Scopus dates to 1788, the search was limited from 2000 to 2020. The search was conducted using the search term desalination: "TITLE-ABS-KEY (desalination)". The Scopus API was used for automatic data retrieval. Data processing was carried out with different tools. Microsoft Excel, Gephi and ArcGIS for the analysis and representation of the results, see Fig. 2. The analysis of scientific communities, both in terms of keywords and in terms of the relationship between authors or between countries, was carried out with the Gephi software. The problem of community detection arises from a common feature inherent to all complex systems. This characteristic is the presence of patterns of nodes that are more densely connected to each other than to the rest of the nodes in the network [12]. Nodes that exhibit such connection patterns are called communities. They are expected to share

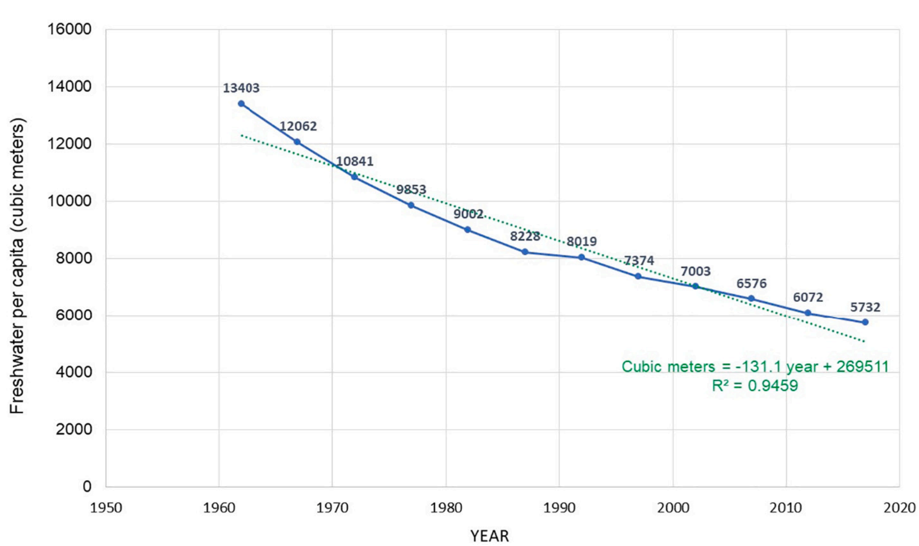

Fig. 1. Renewable internal freshwater resources per capita (cubic meters) from 1962 to 2017.

certain properties that allow the detection of new features or functional relationships in the network [13]. The search for these patterns or community structures is known as the community detection problem. To this end, a multitude of algorithms and objective functions have been proposed to solve the problem. Among them, evolutionary algorithms and the modularity index have stood out as the main solutions accepted by the scientific community [14]. The employed tool Gephi uses an algorithm for community detection based on modularity in large networks (Fig. 2).

3. Results

3.1. Evolution trend

All the scientific production data collected in the Scopus database with the search term “Desalination” has been retrieved. So, 35,845 results have been obtained. Fig. 3 shows the evolution of all publications related to desalination in the period between 2000 and 2020. Two periods are highlighted. The first one from 2000 to 2008, where the scientific production was below 1000 publications per year. The second period from 2009 to 2020 with more than 1000 publications per year has an exponential growth but reaches its maximum in 2016 with more than 3000 publications per year, a rate that is reached again in the last year studied, 2020.

3.2. Subjects from worldwide publications

The scientific categories in which the research is classified are important to determine from which point of view the problem to be solved or the problem to be solved is approached. The scientific categories are assigned by the classification made by the Scopus database itself; this is done according to the category in which the journal that publishes these works is indexed.

Fig. 4 shows the distribution by categories of all this scientific output. The two top categories are environmental sciences (28%) and engineering (27%). The third, fourth and fifth are chemical engineering (11%), chemistry (10%) and materials science (9%). In sixth position is the energy category (5%), and the other categories are not very relevant as they are below 2%. The evolution of the scientific categories is also shown in Fig. 4. As expected, the first two, environmental sciences and engineering, follow a parallel growth. However, the next three, chemical engineering, chemistry, and materials science, show how materials science is catching up with the other two. Finally, the category of energy is increasing a lot, especially in the last 5 years.

The most cited article in the engineering environmental sciences category is a review on reverse osmosis desalination [15]. The most cited article in the engineering category is a review on membrane distillation [16] which in turn is the third most cited in the environmental sciences category. For the categories of Chemical Engineering and Energy the most cited article is also a review but in this case about solar thermal collectors and applications [17]. Finally for the categories of chemistry and materials science the most cited article is the same, and it is also a review, about forward osmosis [18]. Note that if a journal is indexed in two categories, the work will be indexed in both categories. Although they are not among the main categories found, it is worth noting two articles that are from the multidisciplinary category and are by far the two most cited in relation to desalination. The most cited is about increasing water supply through safe reuse of wastewater and efficient desalination of seawater and brackish water [1]. The second most cited article reviews possible reductions in energy demand through state-of-the-art seawater desalination technologies [19].

The type of publication is an index of the maturity of the technology studied, where a high percentage of books would indicate that the topic is well known, and a high percentage of conference publications would indicate the opposite, a very new technology. In this study, book chapters account for only 2%, conference papers 9% and articles 87% (article 83% and review 4%). Therefore, it can be considered that desalination is a mature technology.

3.3. Journals

In the previous section the scientific categories have been discussed, but it should be pointed out that these are determined by the indexation of the journals where they are published, and therefore it is appropriate to mention at least the first 20 in order to understand the classification of the scientific categories. Table 2 lists top 20 journals related to desalination according Scopus database. It shows the number of publications (N), SJR Category and Rank SJR, SJR Indicator, and CiteScore Scopus. It can be observed that all journals listed keep the quartile rank whatever the indexation category. These top 20 journals focus, as one would

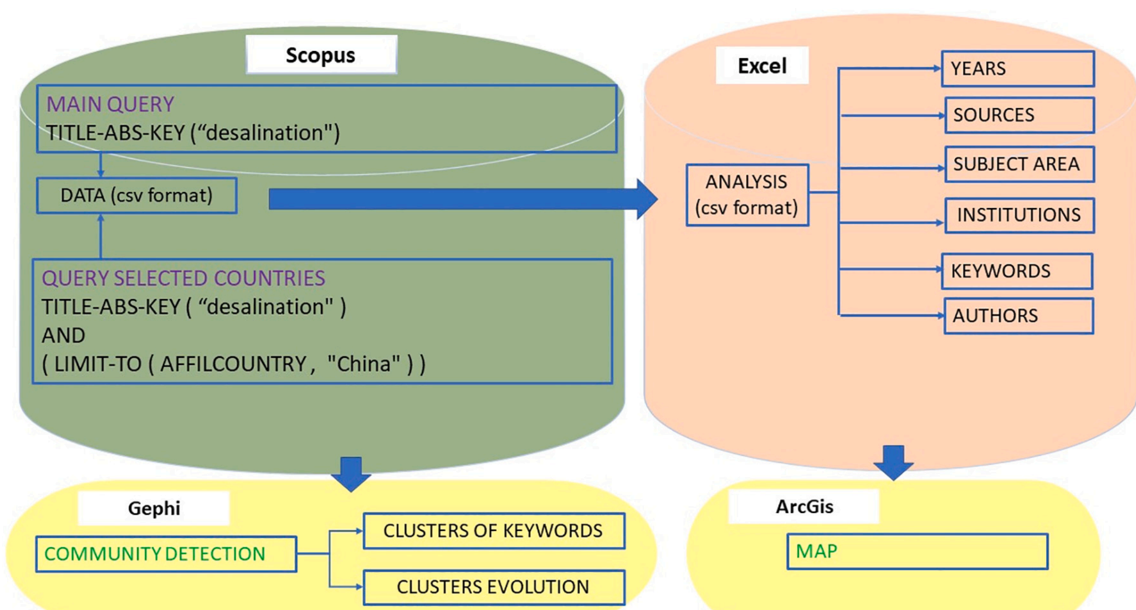

Fig. 2. Methodology.

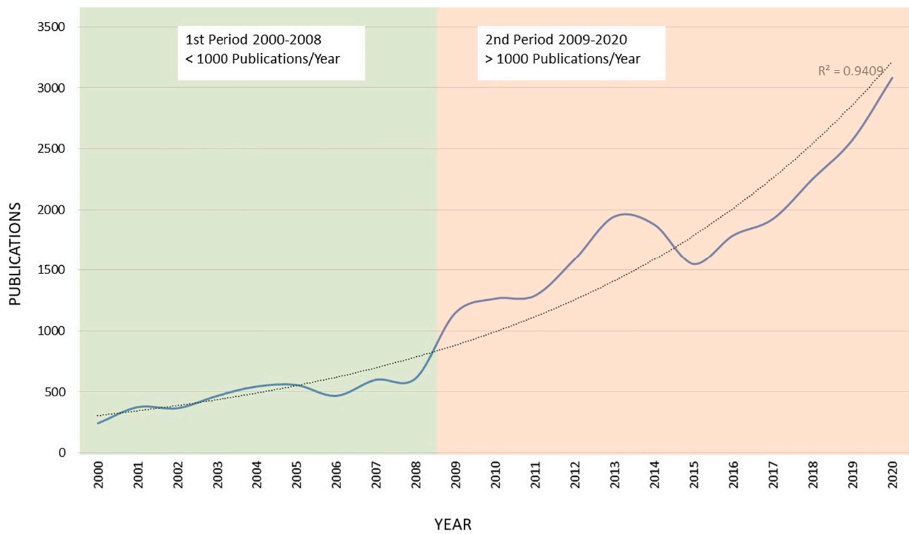

Fig. 3. Evolution of the worldwide scientific production in desalination.

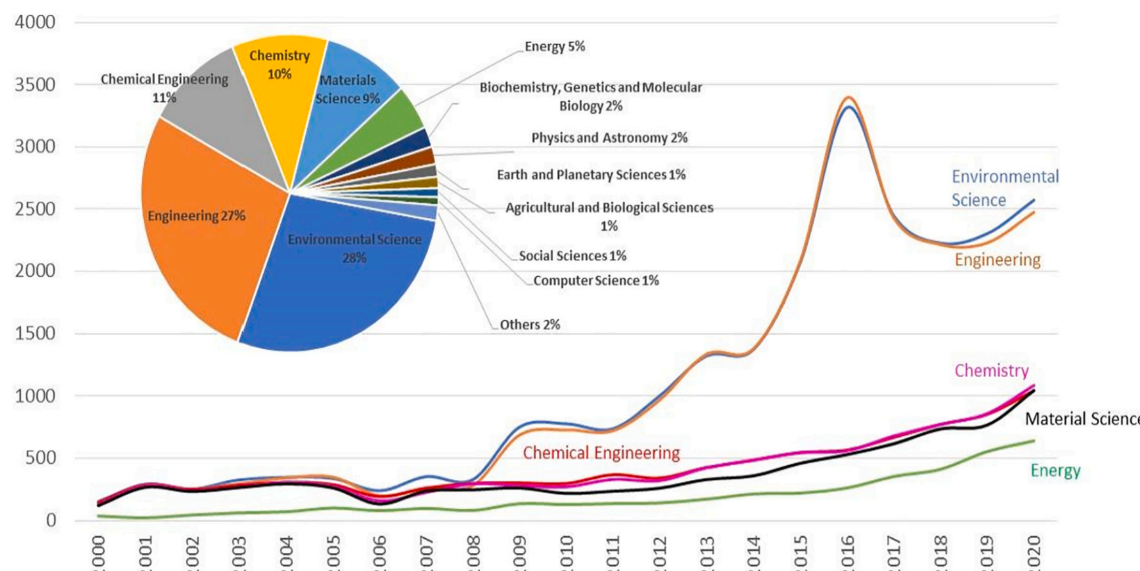

Fig. 4. Distribution and evolution of Scopus categories on Desalination.

expect, on the three main categories found in the previous section: Environmental Science, Engineering, and Chemical Engineering.

Fig. 5 shows the evolution of articles in the 10 journals that publish the largest number of articles on desalination. It can be seen that all of them have a certain continuity over time except for the journal ACS Applied Materials and Interfaces, which has an exponential growth. This journal began publishing 401 articles in 2009, and by 2020 it had published 6266. Fig. 6 shows the citation evolution of the top 10 journals. The exponential growth of the journal ACS Applied Materials and Interfaces can be observed, probably due to the large number of articles published. The other journals show a linear growth. Environmental Science and Technology stands out as it has not significantly increased the number of articles published per year.

3.4. Countries and their main topics

The scientific distribution by country is important to show which countries are making the greatest scientific efforts in this field. Fig. 7 shows a world map with the ranking according to the number of publications on desalination. In a first comment, it can be stated that all countries in the world have studies on desalination, except for some African countries, and in Asia, Mongolia, which is landlocked.

With more than 2000 publications in order of rank are China, USA, India, Iran, and South Korea. With more than 1000 publications the following countries can be found: Saudi Arabia, Australia, Spain, Egypt, and United Kingdom. In this top 10, Egypt must be included in last place.

The international collaborations of these top 10 most productive countries are shown in Table 3. The 5 countries with which each of them collaborates most are shown in order. This data is deduced from the co-authorship of the articles. It can be seen that the USA is the only country that is listed as a main partner for all of these top 10 countries.

Another important aspect of scientific collaboration between countries is that established by the authors themselves. To this end, the co-authorships of the articles are analyzed. Fig. 8 shows the total number of articles published on desalination. It can be seen that there are a large number of articles that are not connected to the core, i.e. they are by authors who do not collaborate with authors from the core. It could be said that their manuscript is occasional or isolated. If the core is

Table 2
Top 20 Journals and their metrics. (Year 2020).

Journal	N	SJR category. Rank SJR	SJR indicator	CiteScore Scopus
Desalination and Water Treatment	4374	Ocean Engineering. 60/156 – Q3 Pollution. 92/162 – Q3 Water Science and Technology. 160/277 – Q3	0.251	1.6
Desalination	4135	Chemical Engineering (miscellaneous). 19/394 – Q1 Chemistry (miscellaneous). 44/446 – Q1 Mechanical Engineering. 24/1016 – Q1 Water Science and Technology. 11/277 – Q1 Materials Science (miscellaneous). 57/638 – Q1	1.794	14.3
Journal of Membrane Science	861	Biochemistry. 58/438 – Q1 Filtration and Separation. 1/20 – Q1 Physical and Theoretical Chemistry. 11/167 – Q1 Materials Science (miscellaneous). 50/638 – Q1	1.929	13.5
Separation and Purification Technology	273	Filtration and Separation. 2/20 – Q1 Analytical Chemistry. 12/121 – Q1	1.279	9.9
Water Research	235	Civil and Structural Engineering. 3/513 – Q1 Ecological Modeling. 2/36 – Q1 Environmental Engineering. 1/211 – Q1 Pollution. 2/163 – Q1 Waste Management and Disposal. 1/145 – Q1 Water Science and Technology. 2/277 – Q1	3.099	15.6
Energy Conversion and Management	231	Energy Engineering and Power Technology. 7/905 – Q1 Fuel Technology. 4/246 – Q1 Nuclear Energy and Engineering. 2/98 – Q1 Renewable Energy, Sustainability and the Environment. 12/486 – Q1	2.743	15.9
Energy	192	Energy Engineering and Power Technology. 11/905 – Q1 Energy (miscellaneous). 8/119 – Q1 Fuel Technology. 7/246 – Q1 Renewable Energy, Sustainability and the Environment. 20/486 – Q1 Building and Construction. 5/314 – Q1 Civil and Structural Engineering. 11/513 – Q1 Electrical and Electronic Engineering. 39/2032 – Q1 Industrial and Manufacturing Engineering. 13/593 – Q1 Mechanical Engineering. 21/1016 – Q1 Management, Monitoring, Policy and Law. 17/389 – Q1 Pollution. 9/163 – Q1 Modeling and Simulation. 9/660 – Q1	1.961	11.5
Environmental Science and Technology	189	Chemistry (miscellaneous). 25/446 – Q1 Environmental Chemistry. 6/128 – Q1 Medicine (miscellaneous). 81/2447 – Q1	2.851	13.8
Applied Thermal Engineering	178	Energy Engineering and Power Technology. 18/905 – Q1 Industrial and Manufacturing Engineering. 19/593 – Q1	1.714	10.1
ACS Applied Materials and Interfaces	165	Materials Science (miscellaneous). 41/638 – Q1 Nanoscience and Nanotechnology. 13/79 – Q1 Medicine (miscellaneous). 103/2447 – Q1	2.535	14.0
Journal of Materials Chemistry A	150	Chemistry (miscellaneous). 22/446 – Q1 Renewable Energy, Sustainability and the Environment. 8/486 – Q1 Materials Science (miscellaneous). 25/638 – Q1	3.637	19.7
Applied Energy	137	Energy (miscellaneous). 3/119 – Q1 Building and Construction. 2/314 – Q1 Mechanical Engineering. 10/1016 – Q1 Management, Monitoring, Policy and Law. 7/389 – Q1	3.035	17.6
Industrial and Engineering Chemistry Research	128	Chemical Engineering (miscellaneous). 53/394 – Q1 Chemistry (miscellaneous). 88/446 – Q1 Industrial and Manufacturing Engineering. 59/593 – Q1	0.878	5.6
Renewable and Sustainable Energy Reviews	128	Renewable Energy, Sustainability and the Environment. 9/486 – Q1	3.522	30.5
Chemical Engineering Journal	120	Chemical Engineering (miscellaneous). 11/394 –Q1 Chemistry	2.528	17.2

(continued on next page)

Table 2 (*continued*)

Journal	N	SJR category. Rank SJR	SJR indicator	CiteScore Scopus
		(miscellaneous). 30/446 – Q1 Industrial and Manufacturing Engineering. 5/593 – Q1 Environmental Chemistry. 8/128 – Q1		
Renewable Energy	120	Renewable Energy, Sustainability and the Environment. 26/486 – Q1	1.825	10.8
Solar Energy	118	Renewable Energy, Sustainability and the Environment. 36/486 – Q1 Materials Science (miscellaneous). 76/638 – Q1	1.337	8.9
International Journal of Nuclear Desalination *from 2003 to 2011	117		N/A	N/A
Advanced Materials Research *from 2005 to 2014	113		N/A	N/A
Journal of Cleaner Production	112	Strategy and Management. 35/513 – Q1 Renewable Energy, Sustainability and the Environment. 21/486 – Q1 Industrial and Manufacturing Engineering. 14/593 – Q1 Environmental Science (miscellaneous). 15/340 – Q1	1.937	13.1

analyzed, each point is an author, and the size indicates the number of collaborations or, in other words, co-authors. Thus, it is remarkable that the most centered authors in this graph, and therefore those who are at the center of the collaboration, are Australian authors. In China, one author stands out above all others in terms of the number of co-authors. On the other hand, the US authors are very spread out, which indicates that there are many different groups collaborating with many authors from different countries. Another curious example is Spain, where there is clearly an independent cluster, indicating that it is a group of co-authors who almost all work with each other and collaboration with the core is very weak. In fact, it is established through a single author.

3.5. Affiliations and their main topics

Once the countries have been studied, it is important to pay attention to the institutions that carry out this research, to identify which are the main centres of research and, if possible, to determine which are the priority lines of this research. Fig. 9 shows the institutions with more than 200 scientific contributions to the field of desalination. The first two are from China and stand out from the rest: Ministry of Education China and Chinese Academy of Sciences. The third is from the USA, Massachusetts Institute of Technology. The fourth and fifth are from Saudi Arabia: King Abdullah University of Science and Technology and King Saud University. Note that Saudi Arabia is the world's first country in seawater desalination, with an estimated four out of every five liters of water consumption in the country coming from desalination.

Table 4 shows the top 4 keywords of the top 20 affiliations. Among the top 20 affiliations 8 are from China and 4 from Saudi Arabia. In overall terms, there is little difference between the objectives of these institutions, as the first four keywords are almost the same for all of them: Seawater, Membrane, Reverse Osmosis, and Water Filtration. The only differences detailed that may be of interest are from MIT (Massachusetts Institute of Technology) for Energy Efficiency, from Tsinghua University for Capacitive Deionization, from King Fahd University of Petroleum and Minerals for the keywords of Humidity Control and Humidification-dehumidification; from University of Tehran for Exergy, Solar Energy and Distillation, from University of Chinese Academy of Sciences for Hydrophilicity.

For the two main countries, China and the USA, the goal was to analyze the internal collaboration between their own institutions. For this purpose, the co-authorships of each of these countries have been illustrated. Fig. 10 shows the relationships between institutions in China. Tsinghua University has the most internal collaborations with 5.14%. Of the two main affiliations of China Ministry of Education China and Chinese Academy of Sciences, only the latter appears in the internal collaborations with 2.5%. In general, there is little internal collaboration, as the groups of authors are not related to each other, sometimes not even within the same institution, perhaps because they work on different research topics (Fig. 10).

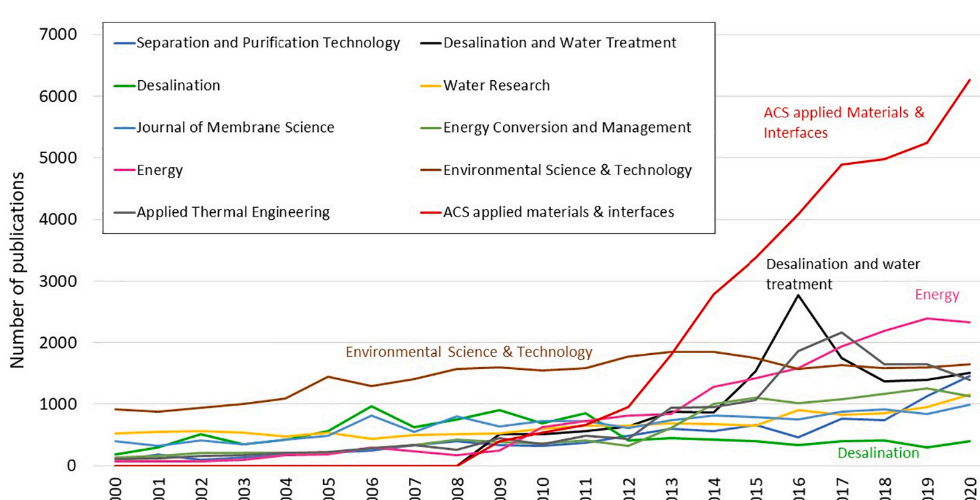

Fig. 5. Evolution of manuscripts for the top10 journals.

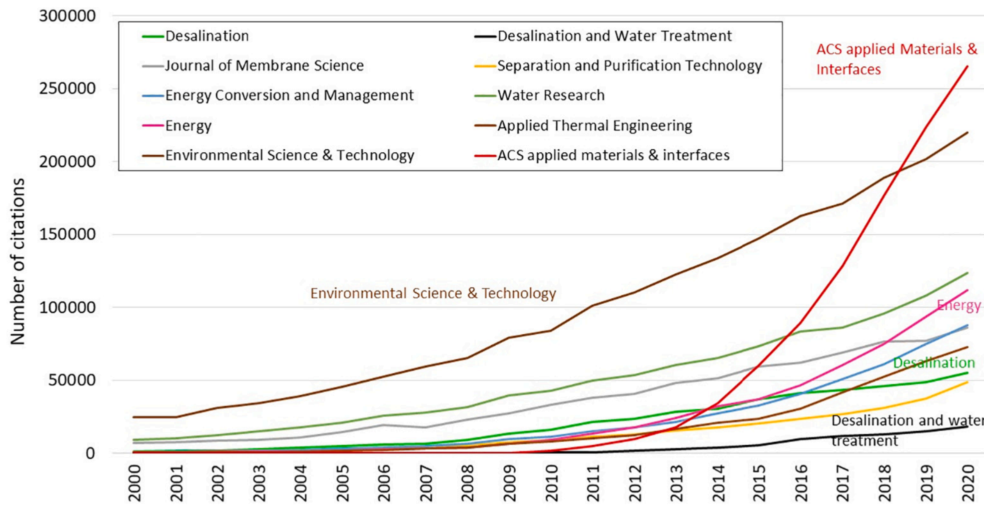

Fig. 6. Citation evolution for the top10 journals.

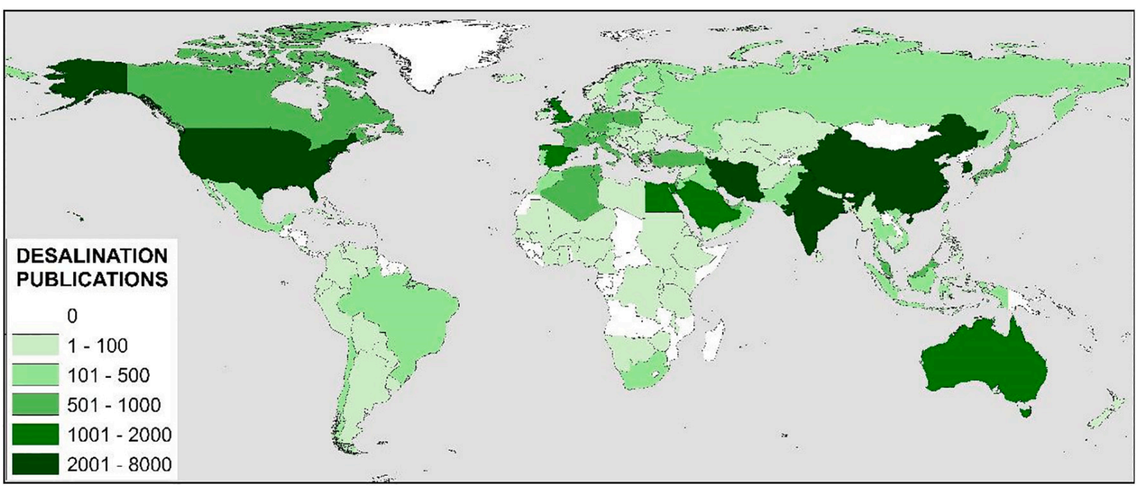

Fig. 7. Worldwide geographical distribution of the scientific production on desalination.

Table 3
Top 10 countries and their international collaboration (2000–2020).

Country	N	Collaboration				
		1	2	3	4	5
China	5176	United States	Australia	Singapore	UK	Japan
United States	4374	China	Saudi Arabia	South Korea	Australia	Singapore
India	1516	United States	Malaysia	Egypt	Saudi Arabia	Australia
South Korea	1446	United States	Australia	Saudi Arabia	Singapore	Italy
Australia	1400	China	South Korea	United States	UK	Saudi Arabia
Saudi Arabia	1326	United States	Egypt	South Korea	Singapore	Tunisia
Spain	1213	UK	United States	Italy	Germany	France
Iran	1138	Canada	United States	Malaysia	Australia	China
United Kingdom	1099	China	United States	United Arab Emirates	Spain	Australia
Egypt	941	Saudi Arabia	United States	United Arab Emirates	India	UK

The internal US collaborations are shown in Fig. 11. It is noted that the main US institution, Massachusetts Institute of Technology, is an independent cluster and has little relationship with the other US institutions. And from this analysis it is remarkable that in the centre of the graph is the Colorado School of Mines, which is not one of the most productive institutions in this field. Note that it is common in all scientific fields for smaller institutions to have greater collaboration with others than those considered more important, which tend to work independently, and even have several research groups that do not collaborate with each other [20] (Fig. 11).

3.6. Keywords from worldwide publications

Desalination systems can use different energy sources such as thermal, mechanical, electrical, and chemical, which has given rise to a first classification. They can also be classified according to the desalination process, and thus we have evaporation-condensation, filtration, and crystallization techniques. Some of the desalination technologies are

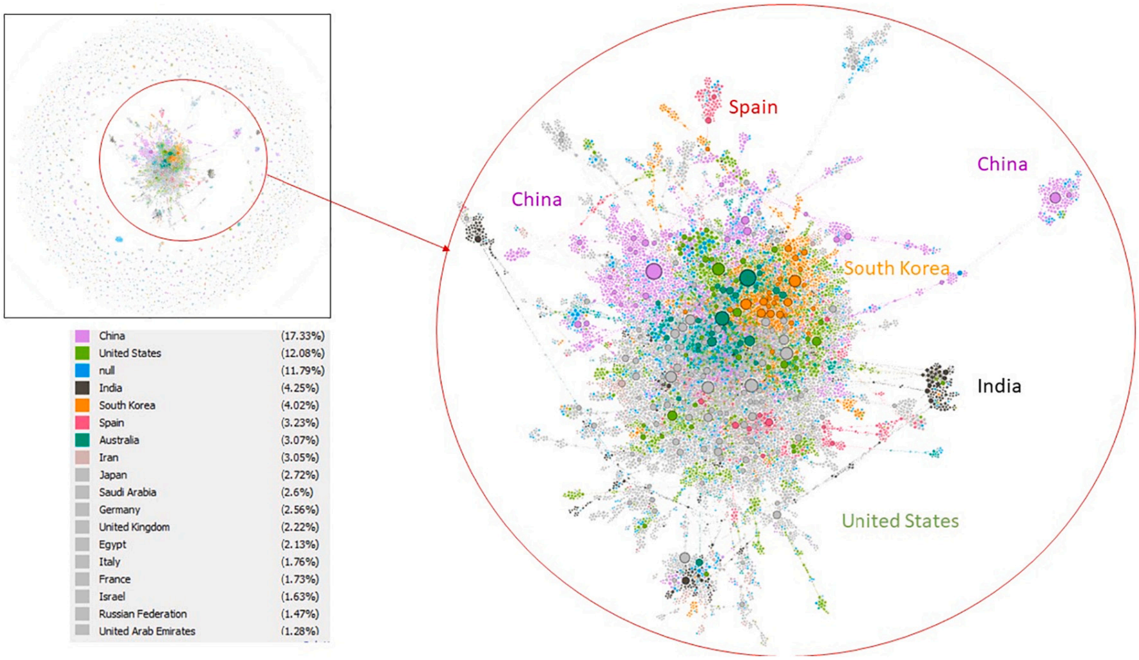

Fig. 8. Co-authorship of the authors from the different countries.

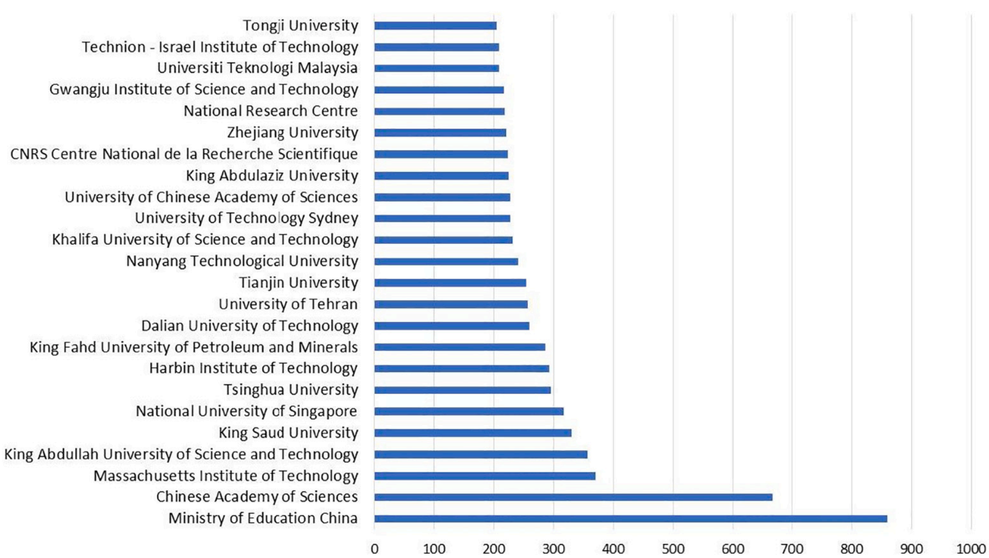

Fig. 9. Main institutions in the scientific production of the desalination.

still under development, such as solar chimney, greenhouse, natural vacuum, adsorption desalination, membrane distillation, membrane bioreactor, direct osmosis, and ion exchange resins [21]. At the commercial level, the most widely used technologies are reverse osmosis (RO), multistage flash desalination (MSF) and multi-effect distillation (MED). In these technologies, research seeks to exploit renewable sources such as wind, solar and biomass energy [22]. The top 20 keywords are listed in Table 5. The top 10 keywords related to desalination are, globally, as follows: Seawater; Water Filtration; Membrane; Reverse Osmosis; Water Treatment; Distillation; Water Supply; Sodium Chloride; Osmosis; Solar Energy. Note that same keywords were merged as they are the same concept, all the synonymous terms have been placed in the same position, although the authors express them with different key words.

Fig. 12 shows the evolution of the top 10 keywords over the last 20 years, from 2000 to 2020. At the beginning of the period, in 2000, all these concepts were in a similar ratio, with less than 100 articles published. The top position was assumed by Reverse Osmosis in 2000, although, as mentioned above, without much difference with the others, at the end of the studied period this concept is in fourth place and has had an upward evolution. From 2003 onwards, the Sea water concept was consolidated in first place until 2008, moving upwards to occupy second place at the end of the period. The concept of Water filtration starts to be significant in the year 2007 reaching the top position, which it maintains until the year 2014, in this period the great prominence of this concept is very significant; from 2014 onwards, it is maintained as what should have been a regular upward trend. Finally, it is worth highlighting the Membrane concept, whose upward trend has been regular and continuous, being the most used concept since 2015 and maintaining the top position until the end of the period.

Table 4
Top 20 affiliations and their main keywords.

Affiliation	N	Country	Keywords (desalination excluded)			
			1	2	3	4
Ministry of Education China	860	China	Water filtration	Seawater desalination	Seawater	Membranes
Chinese Academy of Sciences	668	China	Membranes	Water filtration	Membrane	Sodium chloride
Massachusetts Institute of Technology	371	USA	Water filtration	Reverse osmosis	Seawater	Energy efficiency
King Abdullah University of Science and Technology	357	Saudi Arabia	Seawater	Membrane	Reverse osmosis	Water filtration
King Saud University	330	Saudi Arabia	Seawater	Distillation	Saudi Arabia	Reverse osmosis
National University of Singapore	317	Singapore	Water filtration	Seawater	Membranes	Osmosis
Tsinghua University	296	China	Water filtration	Seawater	Seawater desalination	Capacitive deionization
Harbin Institute of Technology	293	China	Water filtration	Membrane	Seawater desalination	Water treatment
King Fahd University of Petroleum and Minerals	287	Saudi Arabia	Water filtration	Reverse osmosis	Humidity control	Humidification-dehumidification
Dalian University of Technology	260	China	Distillation	Water filtration	Seawater	Heat transfer
University of Tehran	257	Iran	Water filtration	Exergy	Solar energy	Distillation
Tianjin University	254	China	Seawater	Water filtration	Membranes	Reverse osmosis
Nanyang Technological University	241	Singapore	Membrane	Water filtration	Reverse osmosis	Osmosis
Khalifa University of Science and Technology	232	United Arab Emirates	Water filtration	Distillation	Membranes	Seawater
University of Technology Sydney	228	Australia	Membrane	Forward osmosis	Seawater	Osmosis
University of Chinese Academy of Sciences	228	China	Membrane	Sodium chloride	Water filtration	Hydrophilicity
King Abdulaziz University	225	Saudi Arabia	Distillation	Water filtration	Saudi arabia	Membranes
CNRS Centre National de la Recherche Scientifique	224	France	Reverse osmosis	Membrane	Water filtration	Seawater
Zhejiang University	221	China	Water filtration	Membranes	Reverse osmosis	Seawater
National Research Centre	218	Egypt	Reverse osmosis	Membranes	Water filtration	Seawater

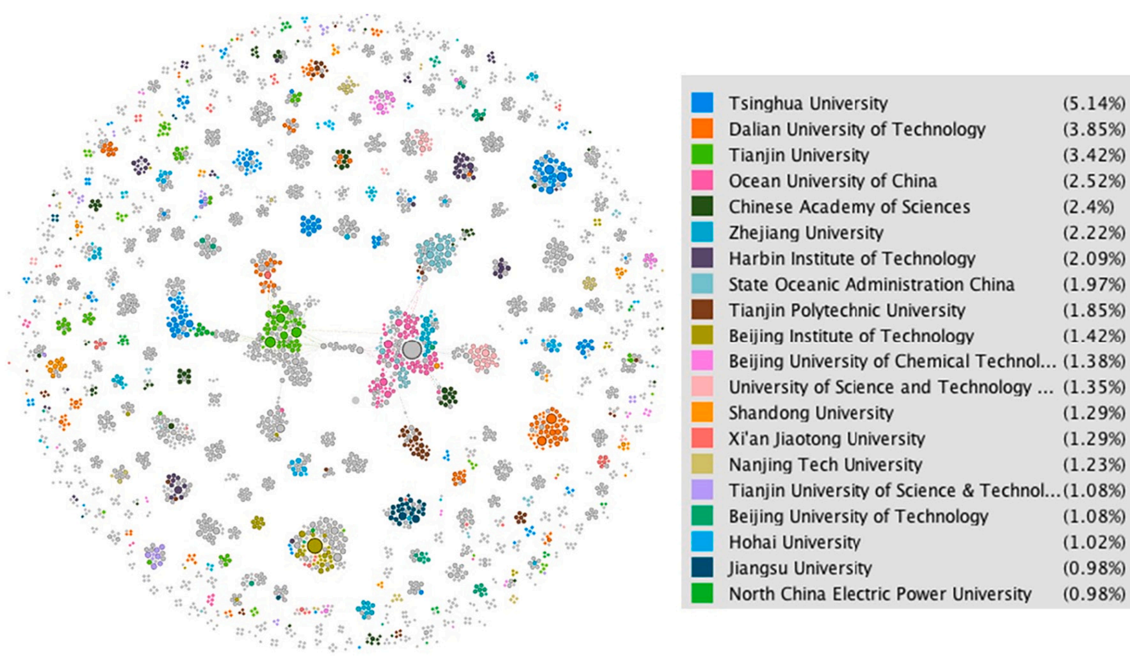

Fig. 10. Links between China's institutions.

4. Worldwide research trends: cluster analysis

However, the previous analysis of the key words would not be exhaustive if it were not done accurately and considering the relationship between all the published works. For this purpose, the clusters in which all the publications can be grouped have been detected by using the Gephi software. Fig. 13 shows the clusters found and the relationship between them, Table 6. Of these, only 8 clusters are meaningful since their relative importance is greater than 1%, and among these they account for 99.1% of the studies. The names of the clusters have been set according to the most frequent or representative key words of each cluster. The 20 key words of each cluster are listed in Table 7, 8 and 9.

The cluster 1 designated as *Reverse osmosis* is the most important in terms of size with 27.16% of the total output. This cluster is located between the brine and membrane clusters. In addition, two other clusters of lesser importance can be observed: Microbial desalination and electrodialysis. Table 7 lists the main keywords of this cluster. As an important note, it is observed that it leads the first 20 keywords of its

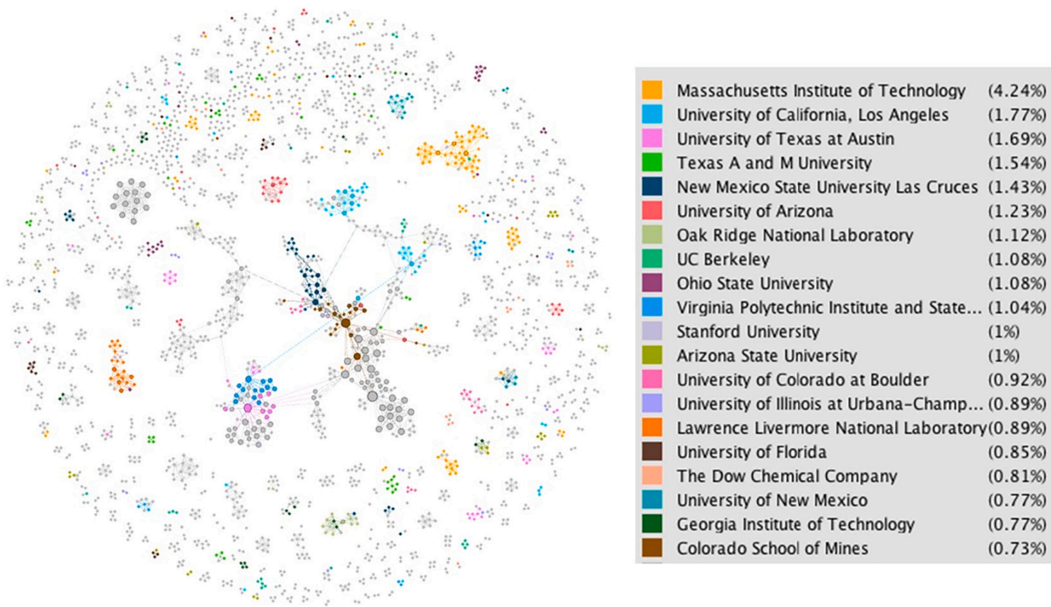

Fig. 11. Links between USA's institutions.

Table 5
Top 20 keywords related to desalination.

Rank	Keyword	N
1	Water filtration	5570
2	Membrane; membranes; membranes technology	5146
3	Seawater; seawater desalination; sea water	4905
4	Reverse osmosis; reverse osmosis desalination	4278
5	Water treatment	2835
6	Distillation	2750
7	Water supply	2233
8	Sodium chloride	1726
9	Osmosis	1689
10	Solar energy	1654
11	Capacitive deionization; membrane capacitive deionization; capacitive deionization (CDI); CDI	1508
12	Potable water	1476
13	Energy utilization	1429
14	Wastewater treatment	1372
15	Water management	1303
16	Water quality	1297
17	Adsorption	1288
18	Water desalination	1188
19	Energy efficiency	1173
20	Optimization	1159

cluster. In other words, these terms are more in this community than in any other community. It analyzes the problems associated with reverse osmosis. From membrane problems to energy demand. It is closely related to other communities, especially with the membrane and brine community, as well as with the use of renewable energies. Occupies the center of the diagram. Reverse osmosis membrane technology has developed over the past 40 years to a 44% share in world desalting production capacity, and an 80% share in the total number of desalination plants installed worldwide [15]. Reverse osmosis (RO) is a pressure-driven process in which a semipermeable membrane rejects dissolved components present in the feed water. This rejection is due to size exclusion, charge exclusion, and physicochemical interactions between the solute, solvent, and membrane [23]. Reverse osmosis membrane technology has developed over the past 40 years to reach a share of 44% of global desalination production capacity and 80% of the total number of desalination plants installed worldwide [15]. Spiral wound elements can use any of four commonly defined membrane technologies, which are microfiltration (0.01–0 μm), ultrafiltration (500–100,000 Da), nanofiltration (100–500 Da), and reverse osmosis (up to 100 Da) [24].

Reverse osmosis membranes are formed by polymerizing polyamide thin films on pure polysulfone and nanocomposite-polysulfone support membranes [25]. Graphene oxide has also been explored to improve the performance of thin-film composite membranes [26]. In recent years, reverse osmosis membrane technology is the most widely used technology in new desalination facilities and has been developed for both brackish and seawater applications [27].

Promising experimental lines of work on the incorporation of nanoparticles as Copper and Aluminum Oxide Nanoparticles [28], carbon nanotubes or graphene show promise as innovative desalination technologies with superior performance in terms of water permeability and salt rejection. However, only nanocomposite membranes have been commercialized, while others are still under development [29]. Within this cluster it is worth highlighting Nanofiltration as one of the most recent developments [30]. This type of technique apart from desalination has also been used in water treatment for drinking water production as well as wastewater treatment [31]. In addition, they have been studied in other applications such as pharmaceutical, biotechnology, food, and non-aqueous types of application [30].

Cluster 2 is named *Renewable energy*. This is the second largest community, with 26.06% of the keywords. This cluster is located between the Thermal desalination and membrane clusters. Table 7 lists the main keywords of this cluster. Community focused on the use of renewable energy in water production. Almost all its keywords are specific to this community. It is mainly related to the thermal desalination, membrane, and brine clusters. The integration of renewable resources in desalination and water treatment is becoming increasingly attractive. This is justified by the fact that freshwater-scarce areas often have abundant solar energy, and these technologies have low operating and maintenance costs [32]. Solar-assisted desalination has proven to be technically feasible; however, combined solar and fossil fuel desalination and desalination using low-grade waste heat could be very interesting at this time [33].

Solar energy applications for desalination have been classified into four major areas: solar stills [34], solar pond water desalination plants [35], multi-effect solar desalination plants [36], and photovoltaic cells for water desalination plants [37]. Also, two or more of these techniques are being successfully integrated [38].

The seawater desalination technique using the dehumidification/

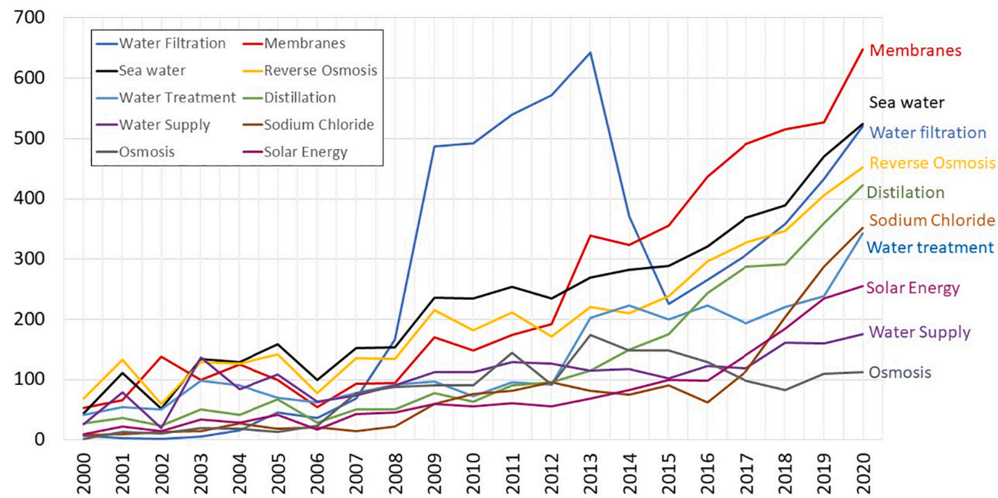

Fig. 12. Keywords evolution (2000 to 2020).

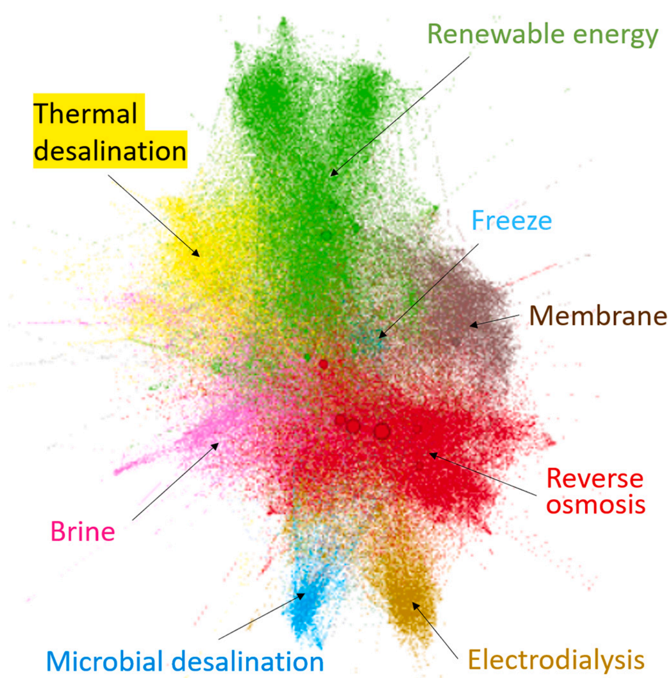

Fig. 13. Relationship between desalination publications.

Table 6
Main C=clusters (Fig. 13), weight and names.

Cluster name	Weight (%)	N
Reverse osmosis	27.16	1
Renewable energy desalination	26.06	2
Thermal desalination	14.34	3
Brine	13.07	4
Electrodialysis	7.62	5
Membrane distillation	7.19	6
Microbial desalination	1.73	7
Freeze desalination	1.62	8

humidification process is considered a promising method for small-capacity production plants [39]. It would be feasible to address the problem of water scarcity by desalinating seawater and brackish water; however, this operation requires large amounts of energy that, when

Table 7
Main keywords of clusters 1 (reverse osmosis), 2 (renewable energy) and 3 (thermal desalination).

Reverse osmosis		Renewable energy		Thermal desalination	
Keyword	N	Keyword	N	Keyword	N
Reverse osmosis	510	Solar desalination	291	Seawater desalination	78
Forward osmosis	264	Reverse osmosis	289	Reverse osmosis	68
Membrane	185	Solar energy	255	Multi-effect distillation	66
Seawater desalination	181	Solar still	222	Optimization	63
Nanofiltration	148	Renewable energy	149	Exergy	62
Seawater	119	Seawater desalination	131	Cogeneration	58
Pretreatment	114	Humidification-dehumidification	94	Solar energy	49
Fouling	89	Humidification	78	Med	49
Ultrafiltration	65	Water desalination	76	Msf	46
Interfacial polymerization	64	Photovoltaic	69	Exergy analysis	44
Water desalination	63	Optimization	64	Solar desalination	42
Biofouling	60	Dehumidification	61	Thermal desalination	38
Membrane fouling	59	Brackish water	55	Adsorption	38
Water treatment	58	Solar	45	Energy	29
Brackish water	55	Solar distillation	45	Simulation	28
Draw solution	48	Seawater	42	Seawater	27
Polyamide	46	Simulation	39	Modeling	25
Boron	44	Solar collector	39	Multi-effect desalination	24
Electrodialysis	42	Wind energy	37	Thermal vapor compression	23

produced from fossil fuels, can cause damage to the environment [40]. The integration of renewable resources in water desalination is becoming increasingly attractive. In addition, areas with a shortage of fresh water often have plenty of solar and wind energy available with low operating and maintenance costs [32].

Cluster 3 is named Thermal desalination. This cluster is located between the renewable energy and brine clusters. It is a community based on thermal desalination, mainly using the technique known as multi-effect distillation. Is the third largest community and concentrates 14.34% of the keywords, Table 7 lists the main keywords of this cluster, and is related to the renewable energy and brine communities, maintaining little relationship with the rest of the clusters. Has few specific keywords. Thermal desalination, or distillation, is one of the oldest ways of treating seawater and brackish water into drinking water. Thermal processes include the multistage flash, multiple effects boiling and vapor compression, cogeneration, and solar distillation, while the membrane processes include reverse osmosis, electrodialysis and membrane distillation [41]. Thermal desalination, also called distillation, is one of the oldest ways of treating seawater and brackish water into drinking water. It is based on the principles of boiling or evaporation and condensation. The water is heated to the evaporation state. The salt is left behind while the vapor condenses to produce fresh water. At present, much of the thermal energy required is produced in steam generators, waste heat boilers or by backpressure steam extraction from power plant turbines [41]. The main thermal desalination processes are of two types: Multi-Stage Flash Evaporation (MSF) and Multi-Effect Distillation (MED) [42]. Currently, the thermal desalination industry is dominated by MSF processes. Other thermal desalination processes, including MED and the mechanical vapor compression process [43], are on a very limited scale. The MED process is the oldest large-scale distillation method used for seawater desalination. Currently, 3.5% of the world's desalinated water is produced by MED plants. Its most obvious characteristics are high distilled water quality, high unit capacity, and high thermal efficiency [42]. In addition, MED has been traditionally used in the industrial distillation sector for the evaporation of sugar cane juice in sugar production and in salt production [44].

Conventional desalination techniques powered by fossil fuels consume large amounts of energy; have a high environmental impact, and high costs. Abundant cheap and clean renewable energy sources are therefore a promising alternative for powering modern desalination processes [45] Water production costs can be reduced by using a hybrid system consisting of two or more desalination methods [46] Recently, commercially available energy recovery devices based on the positive displacement direct pressure exchange method have proliferated. This growing interest is since the technology can significantly reduce the energy consumption of new and existing saline water reverse osmosis (SWRO) systems. Since energy costs are increasing and can consume up to 75% of the total operating costs of a SWRO plant, the dissemination of this technology throughout the industry is important [47].

Cluster 4 is concerned with the consequences of brine spills and proposes solutions to complete dewatering. This cluster is mainly in contact with reverse osmosis, and somewhat weaker with renewable energy and thermal desalination. They also deal with the process to reduce effluents and their concentration. It is closely related to the reverse osmosis and thermal desalination clusters. It groups 13.07% of the keywords cited. Table 8 lists the main keywords of this cluster. The production of brine, which is a concentrated salt solution, is a consequence of desalination plant operation and faces significant environmental challenges due to its high salinity [48]. Currently, several disposal methods have been practiced, such as surface water discharge [49], sewer discharge, deep well injection [50], evaporation ponds [51], and land application [52]. However, these brine disposal methods are unsustainable, are limited by high capital costs, and are not universally applicable [53].

Seawater desalination facilities continuously discharge brine into the coastal environment, which generally flows as a concentrated plume over the seafloor, eventually affecting benthic organisms [54]. The recovery of chemicals from brine [55], such as electrolysis of sodium chloride brine to produce hypochlorite, can be a significant economic [56] and environmental improvement. Brine disposal is one of the major concerns of many environmental issues associated with desalination. The production and growth of marine organisms is severely affected by discharge of brine in the desalination process [57]. In addition, the reject brine from inland desalination plants can alter the physical and chemical properties of the soil. The brine may also find its way to groundwater and can alter its properties [58].

The cluster 5, named Electrodialysis and Capacitive Deionization, is mainly concerned with the decontamination of water, not so much for the production of irrigation water, but for the extraction of elements from the water [59]. This cluster is mainly in contact with Reverse osmosis, and to a lesser extent with Microbial desalination. Table 8 lists the main keywords of this cluster. The concepts related to Capacitive Deionization stand out above all, although as we have seen above, the authors tend to express them in different ways in their keywords: Capacitive Deionization; Membrane Capacitive Deionization; Capacitive Deionization (CDI); or only CDI. With M. Faraday's [103] discovery of the dissociation of ions in solution under an electric field, and later J. Farmer's [104] discovery of carbon aerogel flux capacitors, to the use of new graphene and carbon nanotube materials as electrodes, Capacitive Deionization (CDI) and Membrane Capacitive Deionization (MCDI) technologies are progressively making their way into the desalination industry. But it should be noted that although Capacitive Deionization and Membrane Capacitive Deionization have demonstrated their feasibility and cost-effectiveness in brackish water treatment, the technology still lacks the final step of commercialization and this is still a challenge for the industry [60].

In electrodialysis, cation and anion exchange membranes are separated by a spacer gasket and form individual cells. If an electrolyte solution is pumped through these cells and an electrical potential is established between the electrodes, the overall result is that an electrolyte, i.e., a salt or an acid or a base, is concentrated in alternative compartments, while the other solutions are emptied of ionic components [59]. A major problem affecting the efficiency of almost all membrane separation processes is membrane fouling. However, in electrodialysis the problem has been largely eliminated by regularly reversing the polarity of the applied electrical potential, which results in

Table 8
Main keywords of clusters 4 (brine), 5 (electrodialysis) and 6 (membrane desalination).

Brine		Electrodialysis and capacitive deionization		Membrane desalination	
Keyword	N	Keyword	N	Keyword	N
Reverse osmosis	98	Capacitive deionization	154	Membrane distillation	268
Seawater desalination	90	Electrodialysis	117	Direct contact membrane distillation	67
Environmental impact	52	Water desalination	61	Seawater desalination	49
Brine	47	Electrosorption	53	Air gap membrane distillation	47
Nuclear desalination	40	Ion exchange membrane	37	Vacuum membrane distillation	45
Brine discharge	34	Activated carbon	23	Water desalination	37
Desalination plant	33	Brackish water	19	Solar energy	37
Salinity	31	Membrane capacitive deionization	18	Heat and mass transfer	24
Seawater	30	Energy consumption	17	Modeling	21
Electrodialysis	30	Ion-exchange membranes	17	Membrane	20
Brine disposal	26	Reverse osmosis	16	Solar desalination	20
Brackish water	25	Limiting current density	16	Seawater	17
Sustainability	23	Carbon nanotubes	15	Mass transfer	17
Life cycle assessment	21	Water treatment	13	Optimization	16
Water desalination	20	Capacitive deionization (cdi)	13	Electrospinning	16
Environment	18	Membrane	12	Hydrophobicity	16
Groundwater	17	Concentration polarization	10	Permeate flux	16
Wastewater	17	Cdi	10	Temperature polarization	16
Water management	15	Seawater desalination	9	DCMD	16

a removal of charged particles that have precipitated on the membranes [61]. This technique has achieved some importance in very specific industrial processes such as the production of acids and bases from the corresponding salts [62], the production of highly deionized water [63], the removal of ions from an aqueous solution [64], and the separation of acids and bases from mixtures with salts [65].

Cluster 6 is named, Membrane desalination. Table 8 lists the main keywords of this cluster. Membrane distillation is an emerging technology for desalination based on the vapor transport across the hydrophobic microporous membrane driven by the vapor pressure gradient across the membrane [16]. This cluster groups 7.19% of the cited keywords, is mainly related to the clusters of renewable energies, freezing, and reverse osmosis.

Among the thermal-based technologies, membrane distillation is the most promising for improving performance with the availability of a waste heat source [66]. Membrane distillation is a process in which hot water flows down one side of the membrane and evaporates through it due to a lower partial pressure of water on the other side [67]. It differs from other membrane technologies in that the driving force for desalination is the vapor pressure difference of the water across the membrane rather than the total pressure. Membranes for membrane distillation are hydrophobic. This allows water vapor to pass through, but not liquid water. The vapor pressure gradient is created by heating the source water, which raises its vapor pressure [16]. The four types of membrane distillation are:

- Direct contact membrane distillation. The cold condensing solution comes in direct contact with the membrane and flows counter current with the raw water. This configuration is the simplest to set up. It is best suited for applications such as desalination and concentration of aqueous solutions, e.g. juices [68].
- Membrane distillation with air chamber. It includes an air chamber followed by a cold surface. This configuration is the most general and can be used for any application [69].
- Membrane distillation with sweep gas. A sweep gas removes water vapor and/or volatiles from the system. It is useful when volatiles are to be removed from an aqueous solution [70].
- Vacuum membrane distillation. Vacuum is used to remove water vapor from the system. It is also useful when volatile products are to be removed from an aqueous solution [71].

Cluster 7 is also involved in water decontamination but as a differential note, it uses the activity of microorganisms on the organic matter dissolved in the water to produce the necessary energy [72]. This cluster is mainly in contact with Reverse osmosis, and somewhat weaker with Electrodialysis. Table 9 lists the main keywords of this cluster. This cluster groups 1.73% of the keywords cited and is a well-defined community with little contact with other clusters. It is close to the reverse osmosis and electrodialysis clusters but with no shared keywords. It has been demonstrated that microbial desalination cells can desalinate high-salinity water without any external energy source, but to date this process has not been systematically evaluated. Bioelectrochemical systems use electroactive microorganisms to degrade organic materials in waste to produce energy and/or chemicals [73]. These systems include applications such as microbial electrolysis cells, microbial desalination cells, and microbial electrosynthesis cells [74]. The idea starts from a basic microbial fuel cell that was modified by placing two membranes between the anode and cathode, thus creating an intermediate chamber for water desalination between the membranes [75]. In the anode chamber of the cell, microbes work as biocatalysts to generate electrons by oxidizing organic compounds (e.g., in wastewater) and transfer them to the anode electrode [76], desalinating the water in the intermediate chamber.

Cluster 8 is a very interrelated cluster, revolves around desalination by freezing, using different variants. It occupies a central location in the diagram and is difficult to separate from other clusters. This small cluster is between the Renewable Energy cluster and the Membrane cluster. It accounts of 1.62% of keywords and only a few ones are specific from this cluster. Table 9 lists the main keywords of this cluster. Freeze desalination is a well-known technique for water desalination [77]. The main advantages of this process are the low energy requirement and low temperature operation compared to thermal desalination. Other advantages are less fouling and corrosion problems, the possibility of using cheap plastics or low-cost material, and the absence of pretreatment [78]. However, it presents some problems, especially salt entrapment in ice [79]. Hydrate desalination can concentrate salts in saline water and produce fresh water through the formation of hydrate crystals. Hydrate desalination can produce desalinated water more cheaply than existing technologies [80] and is of great interest because the crystallization process can be operated at a much higher temperature compared with freeze desalination (usually slightly above the freezing point of water) and, therefore, the energy consumption for crystallization can be drastically reduced [81]. Although this technique has been known since ancient times, and there are several different processes that uses freezing to desalt seawater, however, the process has not been a commercial success in the production of fresh water. At this stage, freeze-desalting technology probably has better application in the treatment of industrial wastes than in the production of drinking water [82].

Table 9
Main keywords of clusters 7 (microbial desalination), and 8 (freeze desalination).

Microbial desalination		Freeze	
Keyword	N	Keyword	N
Microbial desalination cell	59	Gas hydrate	29
Desalination	47	Freeze desalination	18
Microbial fuel cell	19	Seawater desalination	10
Wastewater treatment	15	Seawater	9
Bioelectrochemical system	12	Water treatment	7
Bioelectricity	11	Cyclopentane	6
Power generation	8	Sea ice	6
Bioenergy	8	Cold energy	6
Electrodialysis	7	Kinetics	5
Forward osmosis	6	Freezing	5
Microbial desalination cell (mdc)	6	Reverse osmosis	4
Seawater desalination	5	Crystallization	4
Wastewater	5	Brine	4
Electricity generation	5	Thermodynamics	4
Microbial desalination	5	Hydrate	4
Biocathode	5	Refrigerant	4
Energy consumption	4	Produced water	3
Produced water	4	Carbon dioxide	3
Microbial electrolysis desalination and chemical-production cell	4	Water desalination	3

5. Discussion: challenges and perspectives

The new challenges of desalination can be summarised in this section. In recent years, desalination research has advanced at a considerable rate, especially since 2008, with new techniques and tools being developed that are already being used in many of the desalination facilities. The regions of the world best placed to adopt this technology are the gulf countries as they are the most water-scarce and have the most affordable energy [83,84], both conventional and renewable. Note that Arab countries have one of the highest per capita water consumption rates in the world, approximately more than 500 l/c/d, compared to less than 150 l/c/d in most developed countries, or the WHO minimum range of 50–100 l/c/d. Although in 1986 it was estimated that 1369 l/c/d are needed for the normal functioning of a modern society [85]. Rethinking the components of a minimum estimated water requirement for human health and for economic and social development suggests that a country needs a minimum of 135 l/c/d [86].

Until now, desalination has only been used in extreme circumstances due to the very high energy consumption of the process and, consequently, its high economic cost. The most advanced, multi-stage evaporative desalination plants have an energy consumption of more than 9 kW/h per m^3 of drinking water produced. Initially large desalination plants are built in locations where energy costs are very low, such as in the Middle East. Therefore, the use of renewable energies to achieve this goal is one of the greatest challenges in this scientific field.

The first will be to continue the search for a second life for desalination residues. This means producing useful chemicals from the concentrated brine, making desalination more cost effective [87]. The normal guideline for the drinking water we drink is usually 500 per million dissolved salts. Whatever the desalination process, the result is about 35% fresh water (up to 50% in very efficient plants) and 65% very salty brine. The desalinated water obtained is very pure. Water obtained by the distillation process has between 1 and 50 per million dissolved salts, while water obtained by reverse osmosis has between 10 and 500 per million per litre. Desalinated water is usually purer than the water we normally drink, which is why it is usually mixed with less pure water before distribution. The second challenge is to further develop desalination methods for providing safe drinking water to thousands of communities that currently have limited access to this resource and are relatively close to the coast [88]. Desalination plants collect water from the sea through intakes off the coast or in beach wells, where the salinity is significantly lower and therefore the cost of desalination is reduced.

The water treatment industry is very competitive, employing several techniques such as reverse osmosis, distillation, electrodialysis and vacuum freezing. Today only reverse osmosis and distillation are commercially viable. But reverse osmosis desalination plants built in the 20th century had an energy consumption of more than 6 kWh per cubic metre of drinking water produced, due to low membrane efficiency, pressure drop limitations and lack of energy recovery devices.

Desalination of seawater for food production, i.e. protected crops that can afford the cost of desalination, e.g. in SE Spain, for greenhouse crops. And brine denitrification produced during polluted groundwater desalination in fertigation areas of SE Spain [89,90]. The cultivation of the orange tree (*Citrus sinensis* (L.)) is considered the one of the most important fruits from a commercial point of view and the Mediterranean climate is especially suitable for its cultivation [91]. The Mediterranean climate is characterised by a scarcity of water resources that limits crop sustainability. In this sense, orange tree cultivation tends to be irrigated with deficit and controlled irrigation as a water conservation strategy with the aim of improving crop sustainability [92]. For this reason, the quality of the water provided is of vital relevance. For orange trees, a small amount of boron is necessary for growth and development, but boron becomes toxic if the amount is slightly higher than required. Orange it is considered very sensitive to borom, usually 0.5 to 0.75 mg/L of boron concentration in soil water [93]. Reverse osmosis, ion exchange with BSRs and adsorption membrane filtration are commonly used for boron removal [94].

As emerging technologies ceramic membranes should be mentioned. Red clay is an inexpensive and environmentally friendly material for the fabrication of ceramic membranes. Therefore, low-cost ceramic membranes for brackish water desalination are a promising technology for vacuum membrane distillation (VMD) [95]. Also, the advantages of the composite membranes must be highlighted. These allow a surface cleaning during electrocatalytic cleaning with hydrogen bubbles, and they have very good antimicrobial properties with low bacterial growth [105].

As research scenarios, it is worth mentioning that there are two close lines of research that may provide future opportunities for research regarding the desalination. The first one, the research around the problems generated by desalinated water and brine in the materials of the facilities, the corrosion. An important aspect related to desalination processes is the study of corrosion of materials, with special emphasis on metal pipes, evaporators, and other components of distillation facilities [96]. The chemically aggressive environment generated in some parts of SPS desalination plant equipment can cause corrosion problems. Proper selection of materials with higher corrosion resistance is considered one of the most prospective approaches for the smooth and efficient operation of plants [97]. The primary interest of plant designers and operators is to minimize corrosion to improve service life and reliability, and less emphasis has been placed on the effects of corrosion products on the environment [98]. Corrosion of positive electrodes, in capacitive deionization cells for water desalination processes, is a major problem that may prevent them from becoming usable on an industrial scale [99].

And the second one is related to the advantage of the effects of electricity to mobilize salts and other elements within porous materials. This was named electroosmosis. The technology generated for desalination can be used in other disciplines, as in the case of the technique known as electroosmosis. It consists of the movement of liquid through a microporous medium under the influence of an applied electric field [100]. The flow of water could be induced through a capillary by an external electric field. In other words, if soil is placed between two electrodes in a fluid, the fluid will move back and forth when an electromotive force is applied [101]. Electrokinetic remediation, variously referred to as electrochemical soil processing, electromigration, electrokinetic decontamination, or electroreclamation, uses electrical currents to extract radionuclides, heavy metals, certain organic compounds or mixed inorganic species, and some organic residues from soils and sludges [102].

6. Conclusions

Desalination is commonly adopted today to overcome freshwater scarcity in some areas of the world if brackish or salt water is available. Getting fresh water from the sea is, for everyone, the best technological opportunity to solve the water shortages that lie ahead. Over the last 20 years, much research has been carried out in this field and the different types of technologies applicable to desalination have been improved. The desalination research sector has been rising, especially since 2008. It has been seen that work is mainly focused on two main approaches, environmental sciences (28%) and engineering (27%). The other three relevant approaches are chemistry (11%), chemical engineering (10%) and materials science (9%), followed by energy (5%). The top 5 countries in this scientific field are China, USA, India, Iran, and South Korea. Among the top 20 affiliations, 8 are from China and 4 from Saudi Arabia. The study of international collaboration with other countries highlights above all that of the US authors. In the main countries, it has been observed that the most relevant institutions in terms of number of publications tend to collaborate little with those in their own country, indicating a certain specialisation in research within countries, perhaps to avoid competition for funding for research. There are few differences between the objectives of these institutions, as the first four keywords of their publications are similar in all of them: Seawater, Membrane, Reverse Osmosis and Water Filtration. It should be noted, however, that since 2015, membranes have been the most studied concept worldwide, followed by Seawater and, thirdly, Water filtration.

Eight main scientific clusters have been found in global research related to desalination: Reverse osmosis, Renewable energy desalination, Thermal desalination, Brine, Electrodialysis, Membrane distillation, Microbial desalination, and Freeze desalination.

Lines of research have been identified to improve brine management strategies, both to limit negative environmental impacts and to help reduce the economic cost of brine disposal. This may contribute to the development of new desalination facilities and contribute to the supply of water for generations to come.

For water-scarce countries, desalination may be the only viable means of providing the water supply needed to sustain agriculture and support the population, although energy costs and technological limitations must be considered, but it is research in this field that will allow its use to expand. Finally, it should be noted that when brackish water is collected from wells, there is a significant risk that groundwater salinity will increase due to marine intrusion. This study provides a benchmark in global description of scientific productivity in desalination research. It is therefore necessary to address the gaps and delays in desalination research in many coastal countries. The scientific output data reveal a good scientific output in this field of research worldwide. The combination of desalination technologies with renewable energy sources, especially solar energy, is opening up new perspectives or challenges for this field and increasingly opening up the possibility of its use in agriculture, which for the moment is only being used in high value-added agriculture such as intensive greenhouse agriculture.

Funding

This work was funded by EU under Project "Desalinated Seawater for Alternative and Sustainable Soilless Crop Production" with the acronym LIFE-DESEACROP for the period 2017–2020.

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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