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Research Article

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Desalination technology for energy-efficient and low-cost water production: A bibliometric analysis

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Abstract: Over the last few decades, steady growth in desalination literature has been observed. However, conducting a quantitative analysis of this literature is still a novelty. This study aimed at carrying out a quantitative analysis of desalination literature published during the last 30 years, using bibliometric and content analysis techniques, based on the Web of Science database. The bibliometric analysis revealed that desalination has received much attention after the year 2000, as 95.4% of literature has been published in two decades after 2000. The text mining analysis showed that the hot themes of desalination research are reverse osmosis optimization, graphene implications, interfacial polymerization, capacitive deionization, carbon nanotube implications, and antifouling techniques. Furthermore, it was observed that many desalination technologies have emerged recently that make it a challenge to choose the right desalination technology for industrialization. Therefore, this study also contributed to identifying the factors that are important for the industrialization of desalination technologies and, based on these identified factors, this study has compared different desalination technologies to unearth the energy-efficient and low production cost technology. Analytical hierarchy process was used for comparing existing desalination technologies based on eight different parameters and it demonstrated that reverse osmosis is the best available technology for desalination.

Keywords: trends in desalination, low-cost water, comparative analysis, analytical hierarchy process, bibliometric analysis

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1 Introduction

Desalination is referred to as a potable water recovery method that removes dissolved solids/salts from brackish or saline water [1]. Desalination is a nature-inspired process of salt removal [2] as water evaporation over the sea surface and ice formation are some examples. Owing to a lower density of ice than water, excessive salt gets expelled during the ice-formation process (referred to as desalination) [3]. Plant and animals also provide some examples of desalination. Mangroves and Willows are some well-known plant examples. Mangroves grow in the sea, absorb seawater, and expel salt through their leaves and roots [4]. Willows are intentionally grown in seawater or other salty lands. These plants have the capability to absorb salts and other contaminants [5]. Some animals, especially seabirds like gulls and pelicans, have a gland that distils water. These seabirds drink seawater and sneeze the brine [6].

There are various types of desalination processes but the basic principle of operation is similar. The desalination process can be divided into three compartments: intake, processing, and output. The intake compartment specifies intake design and preprocessing of raw water. It consists of a pipe structure, a congregation of pumps, and valves to supply raw water to the processing unit. Its design depends upon the distance of the processing unit from the raw water supply. Preprocessing is sometimes necessary if the raw water has a high amount of turbidity or fouling agents. The processing compartment is the main compartment, in which desalination is performed by any of the methods described in Figure 1. In the output compartment, there are two main products – fresh water and brine. Freshwater may require some post-processing, based on water quality and application of desalinated water. The segregated brine has a high concentration, hence requiring proper disposal [7–10]. In modern systems, various types of sensors are employed to control the output and examine the output of every compartment [11,12]. Figure 1 describes the general principle of desalination.

To cope with the increasing water demands, desalination has been a substantial contributor as evident from the increasing research and installed capacity all over the globe. Starting from the day of the introduction of the desalination plant in the market in 1928, desalination has become a pivot to provide potable water to water-deficient areas. Moreover, the globally installed capacity of desalination has steadily increased at a rate of 7% per annum since 2010. The importance of desalination can be accessed from the fact that within a year from 2019 to 2020, 155 new plants have been installed globally that possess a cumulative capacity of producing 5.2 M·m^3 per day [13]. In recent years, desalination has gotten much attention as a potential technology to meet the growing water demands. There is a wide range of different technologies available within the domain of desalination, and this study compares them quantitatively to find out the most favorable and significant desalination technique.

Conducting a detailed quantitative analysis of desalination literature is still a novelty. Almulhim et al. [14] conducted a bibliometric analysis of water planning and management scenario in Saudi Arabia based on the

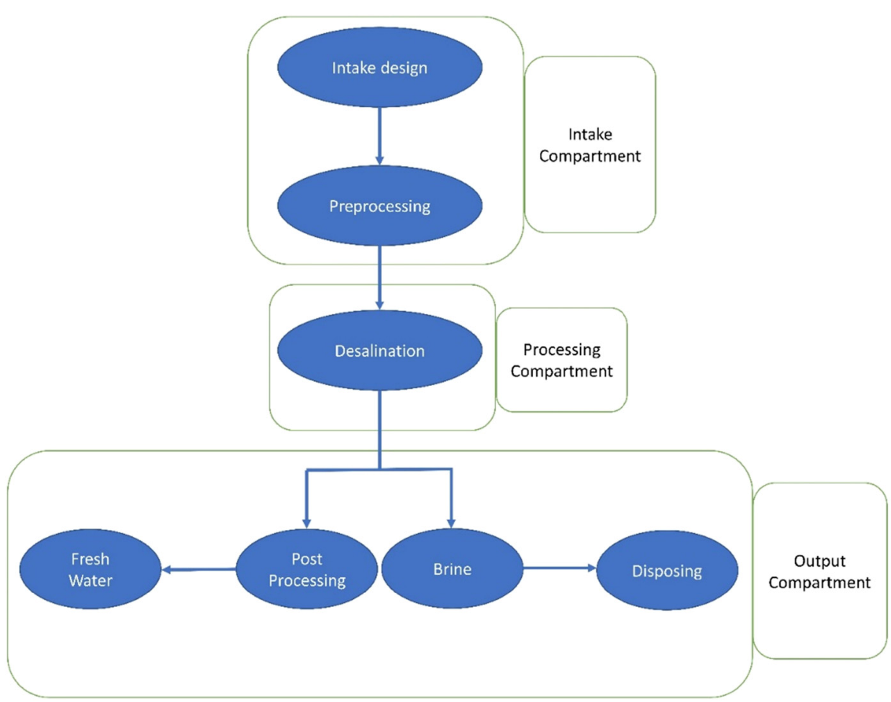

Figure 1: General principle of the desalination process.

literature published during 1981–2020 using the Web of Science (WoS) database. In this study, the year 2020 was observed as the most productive year, while the maximum citation count was observed in 2016. Most prolific countries, organizations, and authors were also highlighted. Ang et al. [15] conducted a similar study for highlighting evolution in forwarding osmosis research using bibliometric analysis of literature published between 1967 and 2018 that were indexed in Scopus. Reverse osmosis (RO) was observed as a widely applied process in desalination and wastewater treatment. In the case of desalination, finding such studies that use bibliometric and text mining techniques to quantitatively review desalination literature published in the last 30 years and indexed in WoS is still rare. Therefore, herein, an initiative has been taken to fill the literature gap by conducting this study that has the following aims:

- to map the history of desalination research, so that emergence of various research tracks can be highlighted;
- to unearth hot research topics of the field;
- to compare existing desalination technologies using analytical hierarchy process (APH), so that a cost-effective and less energy-intensive desalination technology can be identified.

2 Research methodology

This study is divided into two sections. In the first section, a quantitative literature analysis technique, bibliometric analysis, is applied to highlight research trends, whereas in the second section, available desalination technologies are compared using a quantitative technique called AHP.

2.1 Bibliometric analysis

This section evaluates the impact and research trends of desalination technology. For this purpose, a quantitative literature analysis technique, bibliometric analysis, was applied. Published literature related to desalination was retrieved from WoS using relevant keywords, and was followed by the content analysis technique. Detailed methodology to conduct this analysis can be found elsewhere [16]. It must be noted here that different studies, using this technique, to map research fields are widely available in the literature [15–20].

2.2 Analytical hierarchy process for comparative analysis

2.2.1 Technology selection

There is a multitude of desalination technologies available in the literature. All of these technologies can be grouped into three categories: thermal desalination, membrane desalination, and other emerging technologies, as depicted in Figure 2 [21]. The basic principle of operation in thermal desalination is evaporation and condensation, in which seawater is first evaporated by either providing thermal energy, lowering of pressure, or both. In the membrane separation technology, seawater is forcefully passed through a semipermeable membrane that allows only water to pass through.

In multistage flash distillation (MSFD), raw water is passed through multiple chambers, called stages, in the direction of decreasing pressure. This raw water was vaporized at low pressure and allowed to enter chambers. As a result, vapors of pure water get condensed and separated. In multieffect distillation (MED), seawater is sprayed over heated steam that converts the falling sea water to pure water steam. Steam is then condensed and separated. Vapor compression is similar to MED, except that the former involves compression of steam to ensure salt removal to a higher extent. In RO, electrodialysis (ED), and membrane distillation (MD), seawater is passed through a semipermeable membrane that allows only water molecules to pass, but these methods differ in terms of the operating force. For example, in RO, the pressure difference and the concentration gradient are the driving force, while in ED, electricity performs this task. On the other hand, in MD, the temperature difference is the driving force. There are many other methods proposed, but these are in the developing phase or are not widely used at the industrial level. Detailed working principles of these methods can be found in the literature [22,23].

Among all the mentioned technologies of desalination, the industrially appreciable technologies are RO (from the category of MD) and MED and MSFD (from the category of thermal distillation) [13,24]. All other technologies are still categorized as “emerging technologies” or “lab technologies,” owing to no substantial applications in the industrial sector [13,24]. Therefore, the RO, MED, and MSFD technologies have been selected here for the comparative analysis, as depicted in Table 1.

The main objective of this study was to evaluate desalination techniques based on energy requirements, as 60% of the desalination cost owes to it [25]. RO is an

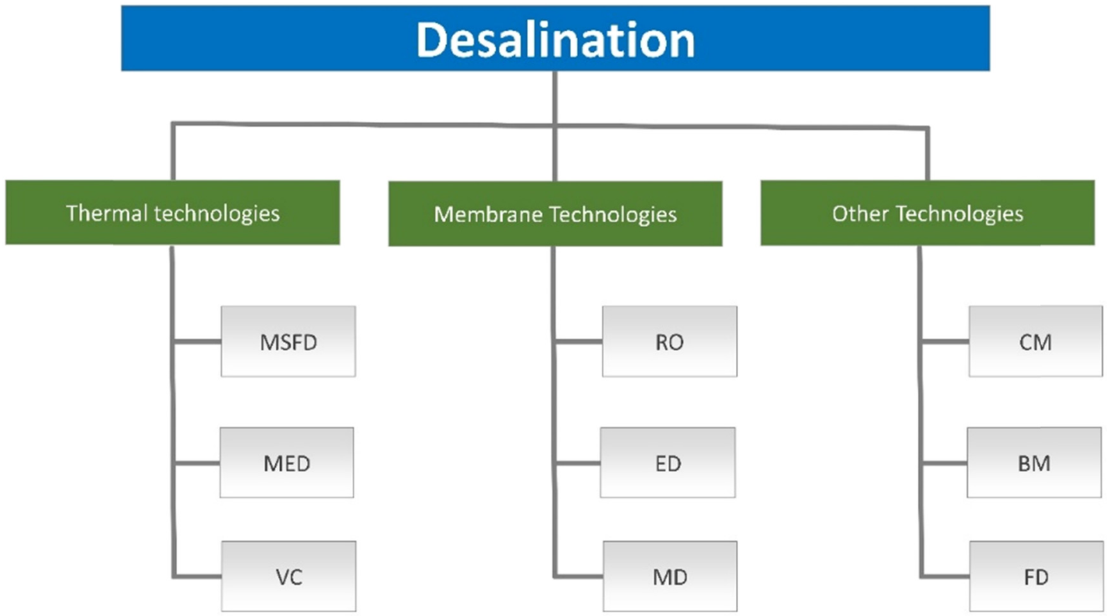

Figure 2: Classification of the widely used desalination techniques. MSFD, MED, vapor compression, RO, ED, MD, CM (chemical methods), BM (biological methods), and FD (freezing distillation).

Table 1: Comparison of RO, MED and MSFD [29,37–42]

Parameters	RO	MED	MSFD
Energy demand (kW·h·m^{-3})	0.8	20.2	24.6
Global installation (%)	69	7	17
CO_2 release (kg·m^{-3})	3.8	5.5	6.9
Potable water cost ($·m^{-3})	0.75	0.86	0.96
Potable water salinity (ppm)	10	10	10
Feed water salinity (10^3 ppm)	45	45	70
Typical plant capacity (10^3·m^3 per day)	128	5–91	23–528
Operating temperature (°C)	Ambient	70–75	90–110

energy-intensive process, as the energy required for this process is 8–10 times more than the surface water treatment technologies. These energy requirements owe to the osmotic pressure of the seawater. RO's energy requirement is defined as the osmotic pressure multiplied by the volume of the seawater. The osmotic pressure is normally 2.8 MPa, depending upon the salt concentration of seawater [26,27]. Therefore, the treatment of 1 L of seawater thermodynamically requires 0.85 kW·h·m^{-3} of energy density. Despite the technological advancements and emergence of various membrane technologies, the energy density requirement for RO is still as high as 1.5–4 kW·h·m^{-3} [28]. On the other hand, the thermal desalination process requires even more energy than is required by RO. Therefore, about 69% of the total installed desalination capacity worldwide is based on RO technology, while MED and MSFD contribute 7% and 17%, respectively [13]. Additionally, the new projects are also preferring to adopt RO, as it is referred to as the lowest cost and the lowest energy consuming water desalination system [29].

2.2.2 Multicriteria decision making (MCDM)

For comparison of the above-mentioned technologies, MCDM was adopted. For this purpose, the values of various significant parameters were collected from the literature (Table 1); and AHP was selected as the quantitative method for comparison of the mentioned desalination technologies. The flow chart of AHP is depicted in Figure 3 [30].

For comparative analysis, eight parameters were selected and mapped for comparison by AHP (Figure 4), followed by the construction of the decision matrix (Table 2). All the parameters were ranked and prioritized for their importance by constructing a normalized comparison matrix (Table 3).

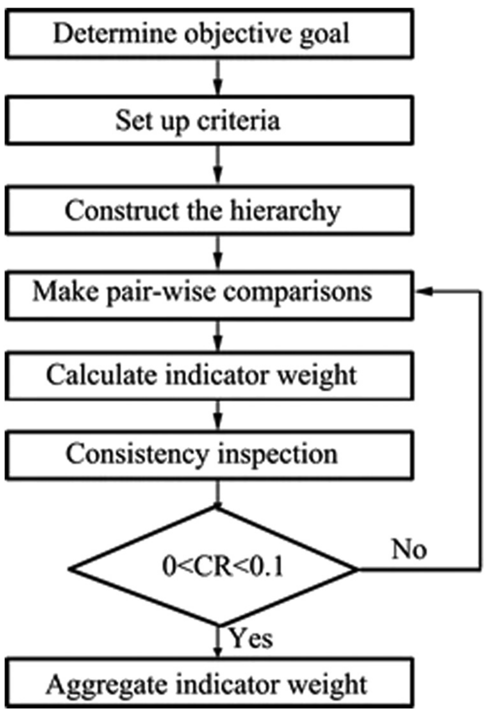

Figure 3: Flowchart for the AHP [30].

3 Results and discussions

Table 2: Decision matrix (pairwise comparison matrix)

	A	B	C	D	E	F	G	H
A	**1**	6	4	3	3	6	3	4
B	1/6	**1**	1/5	1/6	1	2	1/2	1/4
C	1/4	5	**1**	½	4	4	1	3
D	1/3	6	2	**1**	3	5	1	4
E	1/3	1	1/4	1/3	**1**	3	1/5	1/2
F	1/6	½	1/4	1/5	1/3	**1**	1/4	1/3
G	1/3	2	1	1	5	4	**1**	2
H	1/4	4	1/3	¼	2	3	½	**1**

3.1 Comparative analysis of the available desalination technologies

The most important parameter to evaluate in AHP is the consistency ratio (CR) [31,32]. If CR is less than 0.1, the system is considered to be consistent, which, in turn, implies that the assigned weightage is correct. For the present case, the CR value is 0.0625. Therefore, it can be safely said that the system is consistent, and the assigned values are significantly true. As noted above, the analysis revealed that energy demand, potable water

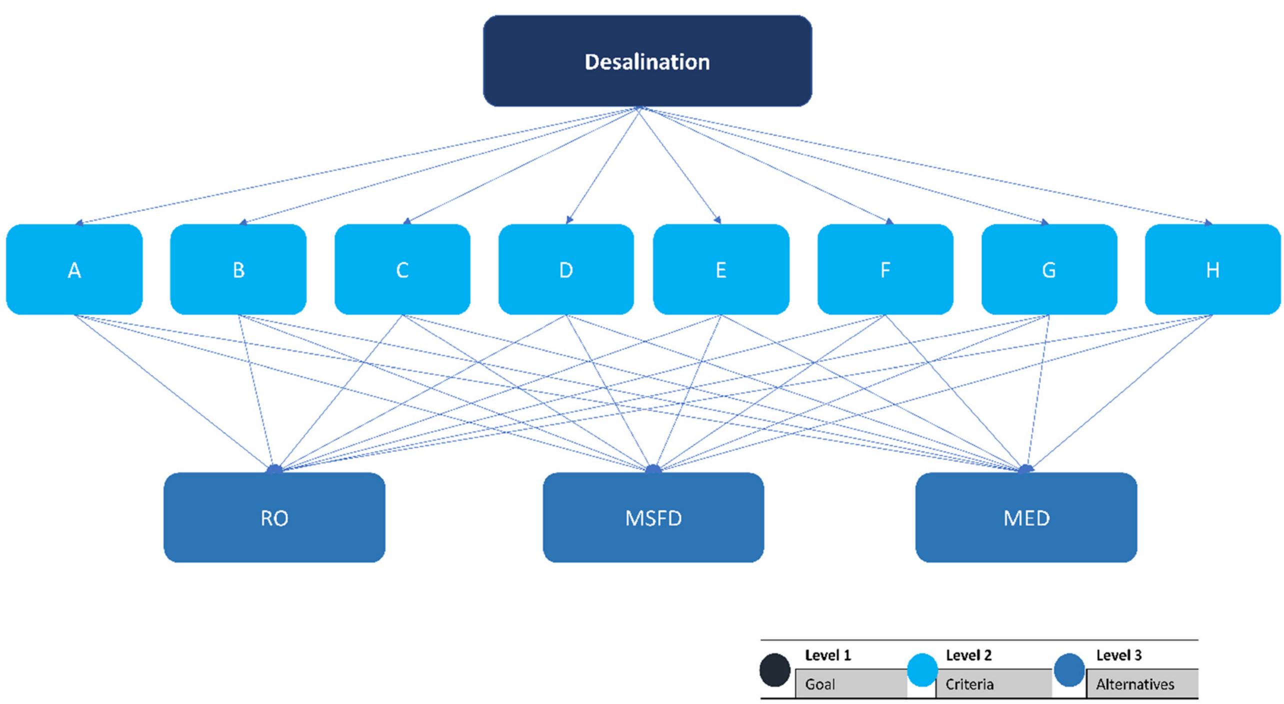

Figure 4: Analytical hierarchy for comparison of the desalination technologies.

Table 3: Normalized pairwise comparison matrix

	A	B	C	D	E	F	G	H
A	0.352941	0.235294	0.442804	0.465116	0.155172	0.214286	0.402685	0.265193
B	0.058824	0.039216	0.02214	0.02584	0.051724	0.071429	0.067114	0.016575
C	0.088235	0.196078	0.110701	0.077519	0.206897	0.142857	0.134228	0.198895
D	0.117647	0.235294	0.221402	0.155039	0.155172	0.178571	0.134228	0.265193
E	0.117647	0.039216	0.027675	0.05168	0.051724	0.107143	0.026846	0.033149
F	0.058824	0.019608	0.027675	0.031008	0.017241	0.035714	0.033557	0.022099
G	0.117647	0.078431	0.110701	0.155039	0.258621	0.142857	0.134228	0.132597
H	0.088235	0.156863	0.0369	0.03876	0.103448	0.107143	0.067114	0.066298

Table 4: AHP priority weightage for selected parameters

Category	Priority	Rank
A	0.316687	1
B	0.044108	7
C	0.144426	3
D	0.182818	2
E	0.056885	6
F	0.030716	8
G	0.141265	4
H	0.083095	5

cost, and CO_2 released are the top three factors that decide the selection of a desalination technique (Table 4).

The consolidated results obtained from the comparative analysis of desalination technologies are depicted in Figure 5. It can be realized from the figure that energy demand is the highest priority parameter, followed by water cost and CO_2 emission. Based on this comparison, it was deduced that RO is the best available method for desalination, which lies in line with the findings of previous studies [33,34]. As stated above, although desalination of seawater thermodynamically requires only 0.85 kW·h·m^{-3} of energy density, plants still employ >1.5 kW·h·m^{-3} of operational energy density; therefore, there is a serious need to reduce the energy requirements of desalination. This can be done either by upgrading the membranes or by integrating other technologies, like microbial fuel cell (MFC), to produce low-cost water [35,36].

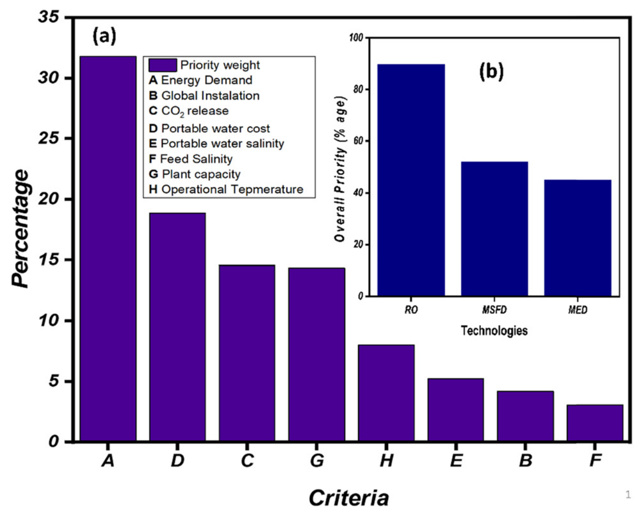

Figure 5: Consolidated results of the AHP (a) priority weightage of parameters (b) overall priority weightage of compared technologies.

3.2 Impact analysis and research streamline of desalination

To determine the research trend in the field of desalination, a quantitative analysis of literature was conducted in this study. According to WoS, 19203 documents are available in the database ranging from 1970 to 2021. The data analysis of yearly publications revealed that desalination has got much attention after 2000. The era of three decades before 2000 and two decades afterwards have contributed 5.25% and 95.4%, respectively, of the total publications on the topic of desalination. Therefore, owing to the significant research concentration after 2000, the literature from 2000 to 2020 was evaluated here to find the research trend within the subject.

The region-based distribution of publications is presented in Figure 6. For this purpose, out of 116 countries, only those who produced a minimum of 100 research documents and 1,000 citations were selected. The size of the bubble, in Figure 6, shows the impact of a country in terms of published documents, while the strength of the links denotes citation and cooccurrence of two countries. Again, colors indicate the prominent era of publications and citations. It has been realized from this analysis that China leads the records (in the number of publications) by contributing 22.5%, followed by the USA and South Korea (contributing 17.36% and 6.8%, respectively), as depicted in Figure 6b. On the other hand, in

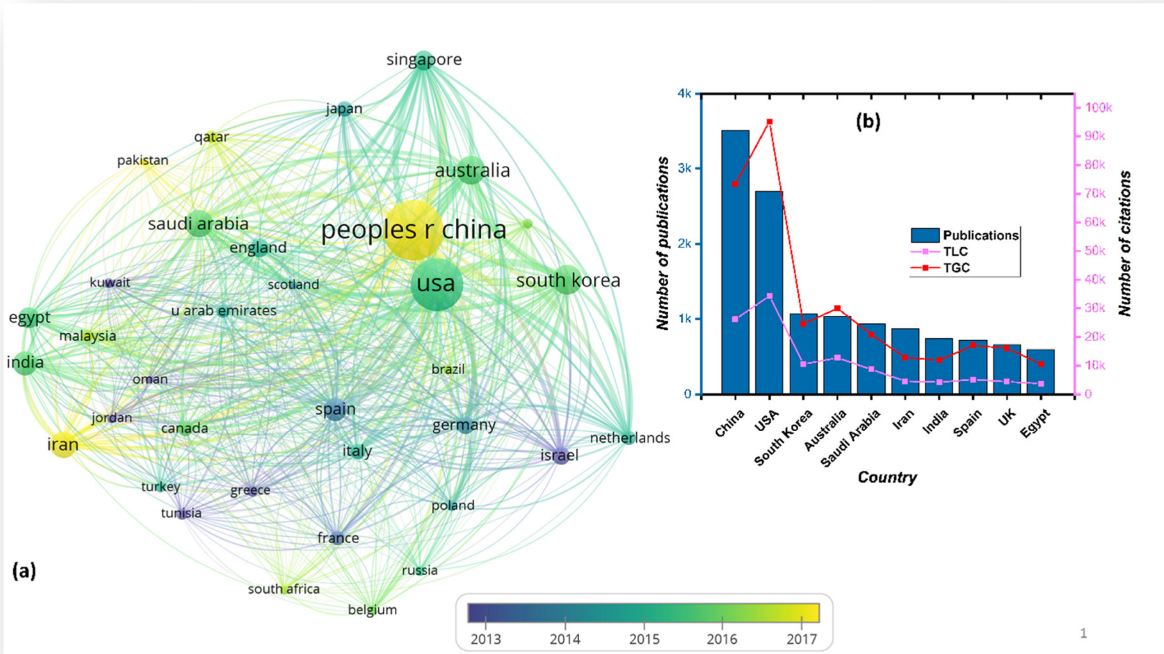

Figure 6: (a) Region-based distribution of desalination publications between 2000 and 2020; (b) top 10 contributing countries and their TLC and TGC.

terms of citations, the USA leads China in both total local citations (TLC) a nd total global citations (TGC).

Next, the text mining technique was used to determine the most frequently used keywords by authors. These keywords help map the field. A total of 22,871 keywords were found. The basic criterion for the selection of the frequently occurring keywords was set to a minimum of 50 occurrences. By employing this filter, only 0.5028% (i.e., 115 keywords) of the total keywords was found to meet the criteria, as depicted in Figure 7. It is evident from Figure 7 that the period 2013–2020 represents the main era of desalination research concentration. From this analysis, it has been found that after desalination, the second most frequently used keyword is RO which signifies its importance over other methods. It is inferred from the keywords mining that the most emerging areas within the domain of desalination are graphene implications, interfacial polymerization, capacitive deionization, carbon nanotube implications and antifouling techniques. It should be mentioned here that the emergence of MFC-based technology is also notable. In 2014, it emerged as a microbial desalination cell (MDC), and has been actively studied by researchers since then It was also noted that the current trend of MFC/MDC research is its integration with capacitive deionization, water recovery and forward osmosis.

In the last two decades, the following 10 technologies have attracted significant attention for the desalination of water (arranged here in the descending order of their importance): (i) RO, (ii) forward osmosis, (iii) MD, (iv) nanofiltration, (v) capacitive deionization, (vi) ED, (vii) ultrafiltration, (viii) adsorption, (ix) direct contact MD, and (x) vacuum MD. However, the main challenges faced by desalination technology are membrane fouling, energy consumption, biofouling, pretreatment, water reuse, scaling, and concentration polarization. Further analysis of the literature revealed that among the various renewable energy sources, solar energy is the most attractive for desalination. In this regard, solar still and solar steam generation techniques for using the solar potential to desalinate water serve as the pivot to the research community.

Furthermore, to spot the most active journals in the field of desalination, a journal analysis has been conducted. For this purpose, journals have been classified based on the number of published documents and citations per year (Figure 8). A-type journals represent a high focus on desalination as well as a high impact factor,

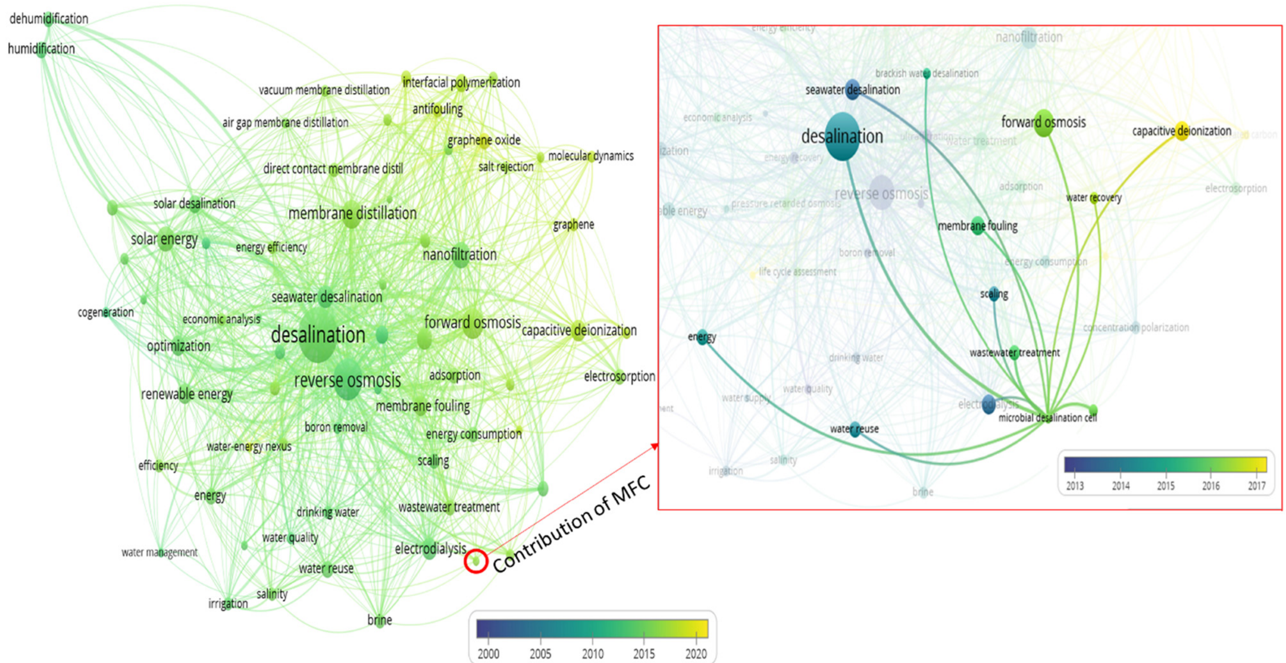

Figure 7: Frequently used keywords in desalination research between 2000 and 2020.

B-type journals are those with high focus but low impact factor, C-type journals include those with low focus and low impact factor, while D-type journals have low focus but high impact factor. The horizontal line represents the mean of the published articles, whereas the vertical line demonstrates the mean of the total local citations per year. In this analysis, only two journals, namely *Desalination* and *Journal of Membrane Science*, have been spotted as type-A journals, while the journals *Desalination and Water Treatment* stand in the B category. Furthermore, no journal is spotted in category C. Figure 8b is a zoom-in view of the D-type journals.

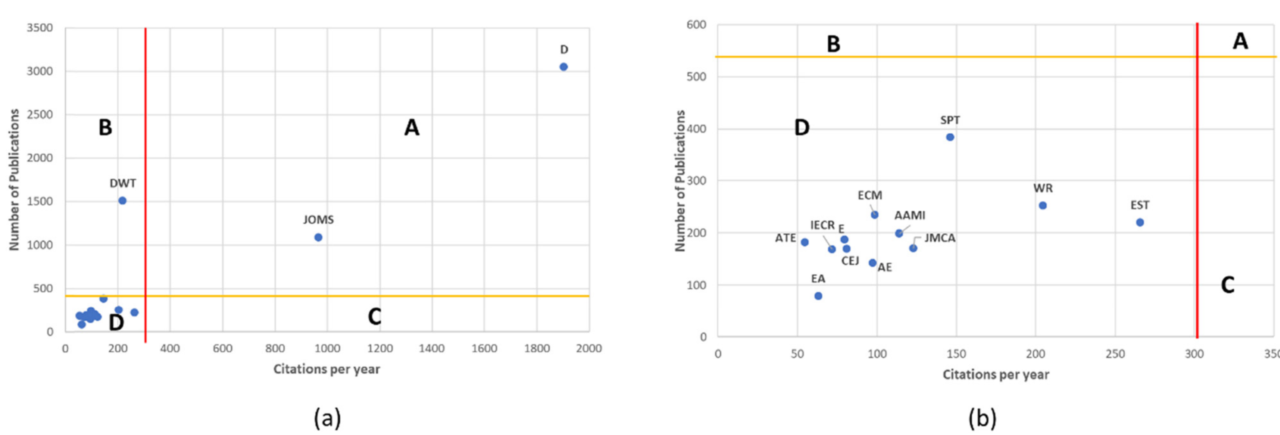

Figure 8: Classification of the top 15 contributing journals on desalination: (a) full view, (b) zoom-in view. EST: Environmental Science & Technology, WR: Water Research, SPT: Separation and Purification Technology, JCMA: Journal of Materials Chemistry A, EA: Electrochimica Acta, ATE: Applied Thermal Engineering, ECM: Energy Conversion and Management, AAMI: ACS Applied Materials & Interfaces, ICER: Industrial & Engineering Chemistry Research, AE: Applied Energy, CEJ: Chemical Engineering Journal, E: Energy, D: Desalination, JOMS: Journal of Membrane Science, DWT: Desalination and Water Treatment.

4 Conclusion

In summary, this study provided a deep insight into the research trends in water desalination. Based on articles published in WoS during the last 30 years, bibliometric analysis has been performed for desalination literature. Following are the main findings of this analysis:

1. Desalination has received significant attention after 2000, as about 94.5% of the total literature on this topic is published within the period 2000–2020.
2. About 116 countries are active in desalination research. China is the main research hub of desalination with the highest number of publications available in the literature, followed by the USA and South Korea. On the other hand, in terms of citations, the USA leads China.
3. The most attractive desalination techniques, in descending order of their importance, are (i) RO, (ii) forward osmosis, (iii) MD, (iv) capacitive deionization, (v) nanofiltration, (vi) ED, (vii) ultrafiltration, (viii) adsorption, (ix) direct contact MD, and (x) vacuum MD.
4. Membrane fouling, energy consumption, biofouling, pretreatment, water reuse, scaling, and concentration polarization are the main challenges associated with desalination technologies.
5. The hot topics of the desalination field are graphene implications, interfacial polymerization, capacitive deionization, carbon nanotube implications, and antifouling techniques.

Furthermore, various desalination technologies have been compared by employing a quantitative technique, analytical hierarchy process has been employed to find out the best desalination technology. This analysis revealed that RO is the best available technique for desalination, followed by MSFD and MED.

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