

# A Bibliometric Analysis of Reverse Osmosis: How influential can it be?

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## Abstract

Reverse osmosis is a treatment process to produce highly purified water in wastewater management. This study was designed to assess the worldwide research trends of the reverse osmosis field in terms of publication output, keywords, journals, countries, institutions, collaboration, research areas, authors, document types, and languages. A bibliometric analysis was conducted on 6,939 research articles obtained from the Web of Science (WOS) database that were published from 1970 to 2019. The bibliometric map and network were generated using VOSviewer software. Results have shown that the most related keywords are desalination and nanofiltration. The most preferred journal with 40,314 total citations was published by Elsevier. Researchers from the United States contributed the most global publications. The most productive academic institution was the National University of Singapore among 25 leading countries. The reverse osmosis topic is mostly used in Engineering and Water Resources area. The researchers from South Korea were the most productive authors in this area. The findings of this study will enable interested researchers to understand the performance of reverse osmosis research worldwide and provide recommendations for further research.

**Keywords:** reverse osmosis, bibliometric, VOSviewer.

## 1. Introduction

Over the past 40 years, reverse osmosis membrane technology has grown to 44% of the world's desalination capacity and 80% of the world's total number of desalination plants. Reverse osmosis membranes are now the leading technology for modern desalination plants. They are applied with specialized pre-treatment and membrane device design to several saltwater resources (Greenlee et al., 2009). It is well known that dissolved compounds can be isolated from their solvents by the process known as reverse osmosis (Petersen, 1993). Besides, according to Gambier and Badreddin (2009), the plant-based reverse osmosis membrane has become standard technology in many fields, such as eliminating alcohol and taint in the winery and medical applications, in semiconductor processing, in drinking and cooking for domestic purposes.

Although reverse osmosis technology has become increasingly involved, very few studies have concentrated on evaluating and analyzing scientific publications worldwide. In the previous work of Tanaka and Ho (2011) about global trends of desalination for the period 1991 to 2008, reverse osmosis was part of the discussion. They claimed that more research was recorded in earlier years and recently on marine desalination, incredibly on reverse osmosis. Many research focused on scale control on seawater distillery, acetic acid distillation, water distillation, solar distillation, and others during the 1950s. However, most of the research focused only on desalination instead of focusing on the method of desalination, such as reverse osmosis.

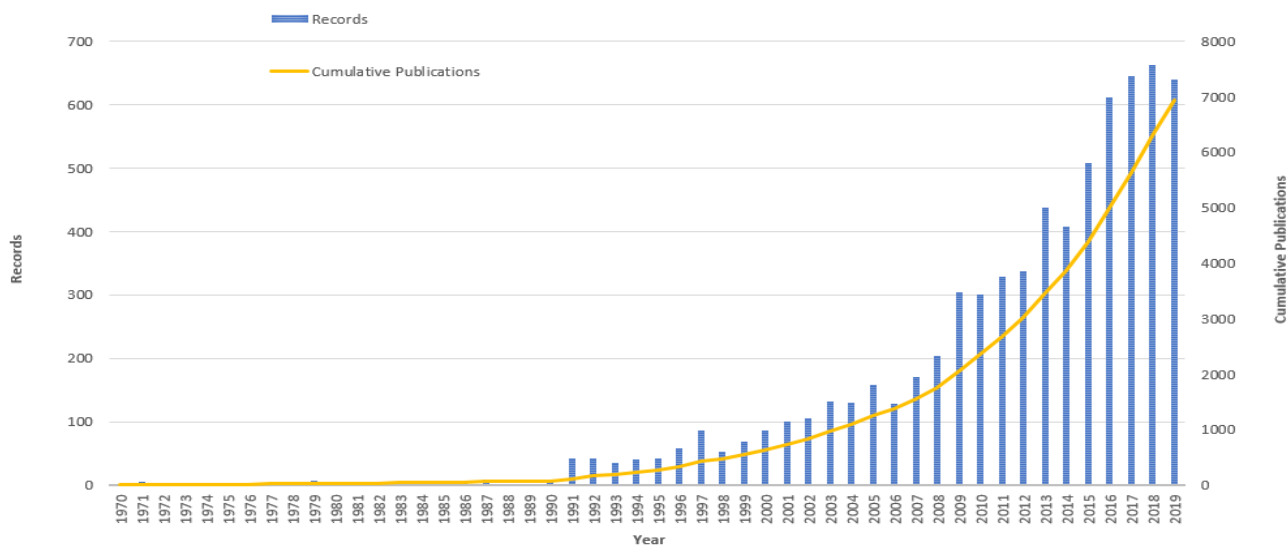
Despite the rapidly growing role of reverse osmosis in the 21<sup>st</sup> century, few attempts have been made to collect systematic data on the reverse osmosis process research. The use of the Science Citation Index (SCI) as a recovery mechanism has rarely

been questioned. Braun et al. (2000) stated that the most recognized and used database for the study of scientific publications is the Science Citation Index (SCI) from the Web of Science (WoS) databases.

The Institute for Scientific Information (ISI) began gathering referencing and other literary effect data in 1945 onwards. This information was made available electronically in 1979. The Science Citation Index Expanded is the new journal citation and database accessible on the internet (Schubert et al., 1989). Moreover, the Institute for Scientific Information (ISI), Science Citation Index (SCI), and Web of Science databases are the most frequently used source databases for a comprehensive analysis of scientific achievement in all fields of research (Bayer & Folger, 1966).

In a previous work by Li and Wang (2010), reverse osmosis desalination is one of the most effective methods of extracting fresh water from marine and other water sources. The membrane properties significantly affect water quality and energy costs during reverse osmosis desalination processes. Significant research efforts to develop a high-performance reverse osmosis (RO) membrane were carried out recently. Other than that, Tanaka and Ho (2011) conducted a study on global trends and performances of desalination research. This study aims to evaluate the global scientific performance of desalination research to assess the properties of research trends and performances.

In this paper, this study aims to analyze the reputation and trends of reverse osmosis research from 1970 until 2019 to help other researchers understand the overview of reverse osmosis research worldwide and predict the dynamic directions of the research. The objectives are as follows:



**Fig. 1.** The records and cumulative publications of research articles on reverse osmosis in Web of Science from 1970 until 2019.

- i. To analyze the distribution patterns of reverse osmosis journal articles.
- ii. To investigate the contribution of productive authors, the leading countries, the most productive academic institutions, and the research areas.
- iii. To focus on the terminology and the research topics.

## 2. Methodology

A bibliometric analysis paper is distinct from a review paper, aiming mainly to examine the recent trends, challenges, and future directions for a particular subject (Khudzari et al., 2018). This bibliometric analysis was carried out using the built-in tool of Web of Science and VOSviewer software.

### 2.1 Data source and search strategy

The primary sources for the bibliometric data were by Thomson Reuter databases, which are the Science Citation Index, the Social Citation Index, and the Arts and Humanities Citation Index, now regrouped under the Web of Science (WoS) (Archambault et al., 2009). "Reverse osmosis process" was used as the search phrase to search the topic in Web of Science. The results were further refined to include only articles or proceeding papers. The results showed that 7,035 accurate records were obtained from the Web of Science. This research has a limitation for the year of publication, and it is from the oldest publication, 1970, to the more recent, 2019. The search parameter used for the search was: TOPIC: (reverse osmosis process) AND YEAR PUBLISHED: (1970-2019) Refined by DOCUMENT TYPES: (ARTICLE OR PROCEEDINGS PAPER) AND DOCUMENT TYPES: (ARTICLE OR PROCEEDINGS PAPER) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI. As a result, there were 6,939 documents shown. Also, most document types were articles.

Based on the year, source, author, affiliation, country, research area, document types, languages, and the central topic's search, the results were evaluated. For ranking, bibliometric

measures such as total publications, top institutions, leading authors, and h-index were used.

### 2.2 Bibliometric maps

VOSviewer allocates research papers in related subjects, themes, or fields in clusters (Ding et al., 2001). The 6,939 articles' data that contained all the records and cited references were exported to text files, and after that, the text files were exported to VOSviewer. The VOSviewer (Visualization of Similarities) is a software tool to create and display bibliometric maps. Also, the VOSviewer was applied to analyze and visualize the relationship among some objects. There are some virtual objects in this study, including country, author keyword, and leading author. There may be a link or relationship between two objects or any pair of objects. Every relationship has a value, which is a positive numerical value. The higher the value, the stronger the relationship between them (Khudzari et al., 2018).

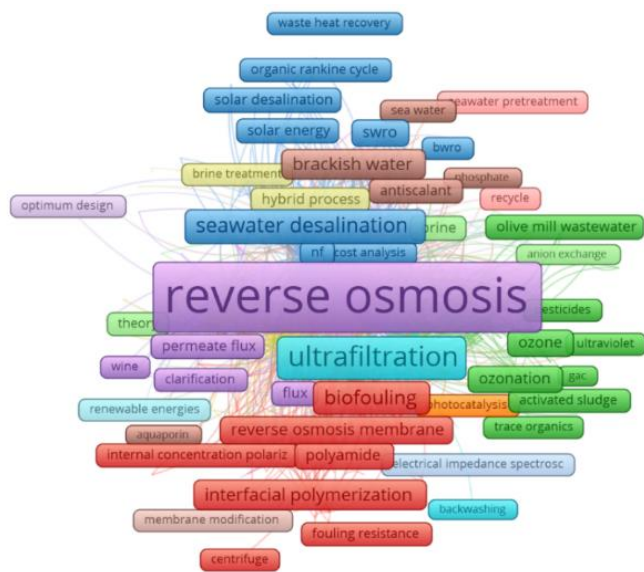
## 3. Results and Discussion

### 3.1 Annual publications

The total of research articles on reverse osmosis that had been published is 6,939 for 49 years. The records of articles and cumulative publications for the years 1970 until 2019 are shown in Fig.1. The figure shows that the number of articles increased rapidly from 1 to 6,939 and the increase started in the year 1991. The significant interest in reverse osmosis research has been proposed since 1990. Since then, annual publications have gradually risen, leading to a rapid rise in overall accumulated publications. The number of publications reached a peak (663 articles) in 2018, showing a gradual increase from 1991 until 2002 to reach 100 records. Despite that, after 2003 onwards, the increase in the number of publications was 200 every six years. In that case, the annual publication will continue to increase.

### 3.2 Author keyword

The author's keywords are an overview of the theme of an article that specifies a detailed information (Dai et al., 2015).



**Fig. 2.** A screenshot of the bibliometric map created based on co-occurrence of author keywords with network visualization mode. The minimum number of documents of a country is set to five.

As the author's keyword analysis provides researchers with sufficient information on research patterns, it has proved extremely valuable in tracking the growth of research topics (Wen et al., 2012). In the present study, the author keywords related to reverse osmosis are 10,464 in total. The minimum number of occurrences of keywords was set to five, meeting the threshold of 711 keywords for the mapping in VOSviewer.

The most frequently searched keywords with 1,645 co-occurrences and 4,020 links to other keywords are shown in Fig. 2. We also found the use of general terms, namely 'desalination' (5,671 occurrences, 1,769 links), 'nanofiltration' (604 occurrences, 1,490 links), 'forward osmosis' (412 occurrences, 1,060 links), and 'ultrafiltration' (234 occurrences, 922 links). There were also other conceptual keywords that co-occurred, such as 'fouling', 'membrane', 'water treatment', 'water reuse' and many more. Moreover, we observed that a few of attributes-substrate or combination keywords were used for the term of reverse osmosis. These included 'reverse osmosis membrane' (56 occurrences), 'reverse osmosis concentrate' (48 occurrences), 'seawater reverse osmosis' (36 occurrences), 'reverse osmosis desalination' (19 occurrences), 'reverse osmosis electrodialysis' (17 occurrences), and reverse osmosis brine' (5 occurrences).

'Desalination' and 'nanofiltration' were the most frequently used keywords. Desalination is a process of removal of salts and minerals from a substance to produce fresh water. Reverse osmosis is also best known for its use in desalination. Furthermore, nanofiltration is a membrane filtration process used most often with low total dissolved solids water and removal of disinfection. In the previous work of Ahmad et al. (2006), in areas where potable water demand has overwhelmed natural supply, reverse osmosis is most significant because it can reject all the solutes that ultrafiltration does not. In that case, from the observation, reverse osmosis and nanofiltration seemed to complement each other; hence many keywords co-occurred. Besides, according to Yang et al. (2018), reverse osmosis, electrodialysis, and nanofiltration are all representative

membrane technology, and observation in desalination research from 1997 to 2012 has proven the dominant position for membrane technology.

### 3.3 Preferred Journal

Table 1 shows the top 10 most productive journals in reverse osmosis topic. The top two journals were published by Elsevier. Elsevier published five journals in total as shown in the table. Moreover, there were also two journals published by the American Chemical Society. The remaining three journals have been published by Desalination Publication, IWA Publishing (International Water Associations), and Taylor & Francis, Inc.

The top journals by Elsevier were *Desalination* and *Journal of Membrane Science*, where the recorded total publication was 1,249 and 714, respectively, also covering 18.002% and 10.291% of the total of publication. The total citations for *Desalination* were 40,314, and *Journal of Membrane Science* recorded 36,696 citations. These journals were also two of the top five most productive journals, followed by *Desalination and Water Treatment* (695, 10.017%), *Separation and Purification Technology* (200, 2.883%), which was also published by Elsevier and *Water Research* journal (189, 2.724%).

According to the journal impact factor trend 2018, the journal with the highest journal impact trend 2018 of 8.355 had belonged to the *Chemical Engineering Journal* by Elsevier Science SA. Although the journal recorded only 89 total publications and 2,429 total citations, and ranked 9th, nevertheless, the journal impact factor trend 2018 was the highest. There were six journals with a journal impact factor of 5 and above. Moreover, although ranked 3rd with 695 records of complete publication, *Desalination, and Water Treatment* journal had the lowest journal impact factor trend 2018, which was 1.234.

Journal impact factor indicates for each journal, the yearly average number of citations received by articles published in the last two years. It is also recurrently used as a representative for the relatable to each journal within its field. According to Penava and Dorotea (2015), the impact factor approximately provides the prestige of a journal that has been published individually. Hence, the journal impact factor should not be regarded as the only factor. Besides, the authors should acknowledge whether the journals will offer the research to the right audience or not and contribute to the research field.

### 3.4 Leading countries, top institutions, and collaborations.

Table 2 shows the top 25 most productive countries in reverse osmosis research. The USA was recorded as the top productive country with 1,252 total publications (18.046%). The most productive academic institution in the USA was Yale University, and it recorded 74 total publications of a given academic institution. The second most productive country was the People's Republic of China which recorded 963 total publications (13.88%) and the most productive academic institution with 112 total publications was the Chinese Academy of Science. South Korea was ranked third. Its total publications were 543 (7.826%), which was significantly lower than the people's Republic of China's, and the top academic institution in South Korea was

**Table 1** The top 10 most productive journal on reverse osmosis research with total citations and journal impact factor trend in 2018.

No	Journal	Publisher	Records	Percentage	Total Citations	Journal Impact Factor Trend 2018
1	Desalination (Q1)	Elsevier	1,249	18.002%	40,314	6.035
2	Journal of Membrane Science (Q1)	Elsevier	714	10.291%	36,696	7.015
3	Desalination and Water Treatment (Q3)	Desalination Publications	695	10.017%	4,604	1.234
4	Separation and Purification Technology (Q1)	Elsevier	200	2.883%	4,939	5.107
5	Water Research (Q1)	Pergamon-Elsevier Science Ltd	189	2.724%	9,653	7.913
6	Environmental Science Technology (Q1)	American Chemical Society	130	1.874%	7,967	7.149
7	Water Science and Technology (Q3)	IWA Publishing	130	1.874%	1,740	1.624
8	Industrial Engineering Chemistry Research (Q1)	American Chemical Society	90	1.297%	1,918	3.375
9	Chemical Engineering Journal (Q1)	Elsevier Science SA	89	1.283%	2,429	8.355
10	Separation Science and Technology (Q3)	Taylor & Francis INC	72	1.038%	796	1.354

Korea University with 109 total publications of a given academic institution.

Two universities that were among the top 100 best universities based on the World Universities Ranking 2020 were Yale University and Korea University, which were ranked 17th and 83rd, respectively. These two universities were in the top 3 of the most productive countries and academic institutions. This indicates that the reverse osmosis research area gained attention in the world's leading universities. Malaysia was ranked 21st with 115 total publications and the most productive academic institution in this field was University Teknologi Malaysia with 40 total publication.

Fig. 3 shows the frequency of countries per region. The thicker the line, the stronger the link between countries. Bibliographic coupling is like co-citation; it is a measure of similarity using citation analysis to determine the similarity between documents. The higher the number of references between the two publications, the greater the bibliographic coupling between them (Van et al., 2014).

In this analysis, the total countries that were recorded were 110 in total. Out of the 110, 40 countries produced at least 30 articles. The USA led the list with the highest number of total link strength of 807,767, the highest number of documents, with 1,096 documents in total, and the highest number of total citations of 44,421. It was followed by the People's Republic of China (839 documents, 14,949 citations), South Korea (503 documents, 11,031 citations), Australia (404 documents, 12,033 citations) and others. Malaysia recorded 104 documents and 2,478 citations.

### 3.5 Research area

Table 3 shows the overview of research areas in this study. Reverse osmosis topic mostly occurred in the engineering area

with 5,127 total number of articles (73.887%). The water resources area was ranked 2nd with 2,728 total number of articles about reverse osmosis (39.314%). In the 3rd rank was Environmental Sciences Ecology, which recorded 1,279 total number of articles (18.432%). These top three research areas recorded more than a thousand articles about reverse osmosis. Also, these three research areas are related to each other; engineering is the use of scientific principles to design and build machines and structures and the reverse osmosis process is done by using a machine. Reverse osmosis is a water purification process that uses a partially permeable membrane to remove ions, unwanted molecules, and larger particles from drinking water, and it is related to water resources. Environmental Sciences Ecology will solve problems related to water pollution and reverse osmosis can help to treat water quality.

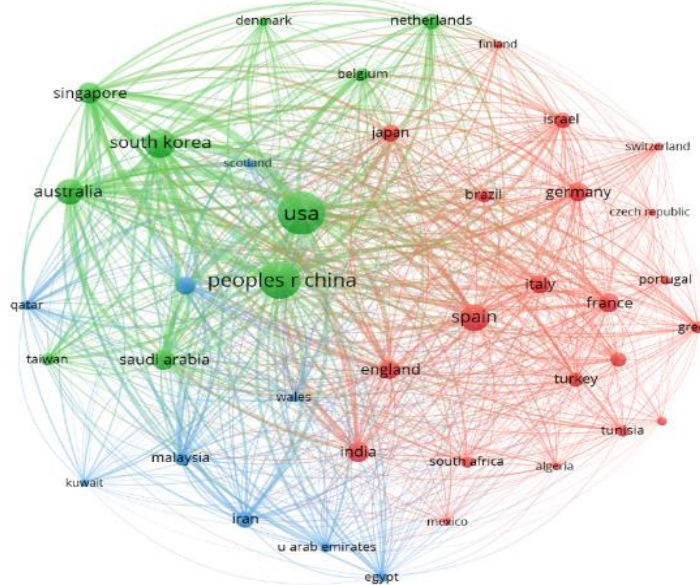
The other research areas are Polymer Science (863, 12.437%), Chemistry (649, 9.353%), Energy Fuels (316, 4.554%), Material Science (296, 4.266%), Science Technology other topics (294, 4.237%), Food Science Technology (249, 3.558%), Biotechnology Applied Microbiology (148, 2.133%), Physics (122, 1.758%), and Agriculture (106, 1.528%). In the mathematics area, there were only eight articles, (0.115%).

### 3.6 Leading authors

Table 4 shows the 15 most productive authors in reverse osmosis topic from eight different countries, which are South Korea (four authors), USA (one author), Singapore (two authors), Australia (two authors), Italy (one author), People's Republic China (three authors), England (one author) and Belgium (one author). The top author is Lee, Sangheon who is from South Korea with a total publication of 90 (1.297%) and 24 h-index. The second author is from the USA, Elimelech, Menachem, with 72 total publications (1.038%) and an h-index of 49, which is the highest h-index among all authors. Next, Chung, Tai-Shung from

**Table 2** The top 25 most productive countries and academic institutions in reverse osmosis publications.

No	Countries	Records	Percentage	The Most Productive Academic Institutions	Total Publication of a Given Academic Institution
1	USA	1,252	18.046%	Yale University	74
2	People's Republic of China	963	13.88%	Chinese Academy of Science	112
3	South Korea	543	7.826%	Korea University	109
4	Australia	450	6.486%	University of Technology Sydney	85
5	Spain	442	6.371%	University Politecnica De Valencia	41
6	Singapore	285	4.108%	National University of Singapore	136
7	India	263	3.791%	Indian Institute of Technology	41
8	Germany	261	3.762%	RWTH Aachen University	35
9	Saudi Arabia	261	3.762%	King Abdullah University of Science Technology	70
10	England	240	3.459%	University of Bradford	47
11	France	237	3.416%	Universite De Toulouse	24
12	Italy	234	3.373%	University of Calabria	61
13	Canada	220	3.171%	University of Alberta	34
14	Japan	202	2.912%	Hiroshima University	25
15	Iran	199	2.868%	Islamic Azad University	28
16	Netherlands	177	2.551%	Delft University of Technology	64
17	Israel	153	2.205%	Ben Gurion University	59
18	Poland	151	2.176%	Silesian University of Technology	58
19	Turkey	146	2.104%	Istanbul Technical University	31
20	Brazil	135	1.946%	Universidade Federal De Rio De Janeiro	28
21	Malaysia	115	1.658%	University Teknologi Malaysia	40
22	Belgium	98	1.424%	Katholieke Universiteit Leuven	49
23	Greece	95	1.380%	Aristotle University of Thessaloniki	24
24	Taiwan	95	1.380%	Chung Yuan Christian University	22
25	South Africa	89	1.293%	Tshwane University of Technology	13



**Fig. 3.** A screenshot of the bibliometric map created based on the bibliographic coupling of countries with network visualization mode. The minimum number of documents of a country is set to 30.

Singapore is ranked third with 62 total publications (0.894%) and 24 h-index. Following this, the top author is related to the leading countries which recorded the USA and South Korea as the most productive countries and author.

Fig. 4 shows the network of authors in reverse osmosis. The thicker the link between authors, the stronger the relation between them. There are four different clusters represented by

colours (red, blue, green, and yellow). The colour of an item is determined by the cluster to which the item belongs. The green cluster seem to cover research in reverse osmosis membrane and engineering. The red cluster seem relate to agriculture, and food science and technology. The blue and yellow cluster seem relate in water treatment and polymer science technology. Thus, the highest number of documents, citations and total link strength is under the green cluster, which is Elimelech, Menachem with the 91,867, the highest total link strength.

### 3.7 Document types

Table 5 shows the document types, including retracted publication, related to reverse osmosis. The highest document type is article, with 6,451 records (92.967%). It is followed distantly by proceeding papers (1,378, 19.859%), book chapters (121, 1.744%), early access (11, 0.159%), data paper (3, 0.043%), and retracted publication (1, 0.014%).

### 3.8 Languages

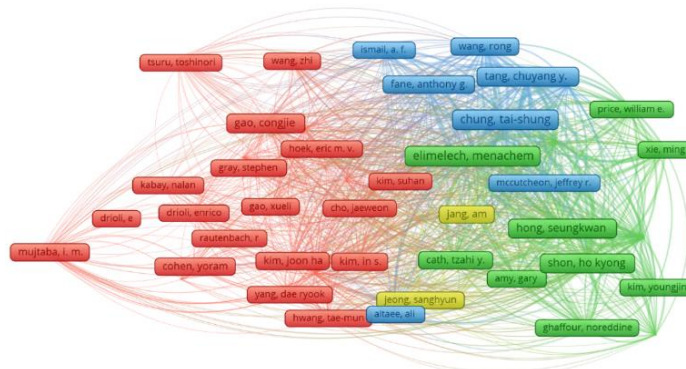
In the field of reverse osmosis, there are 16 languages used for all the document types in Web of Science, and there is one unspecified language. The languages of the documents published were dominated by English, which is 98.155% (6,811 records) in total. The other languages that had been used are German, Polish, Chinese, Spanish, and Portuguese. Since the leading country for this research is the USA (Table 2), English is the most used language. Besides, most of the journals listed in Table 1 were published in English, so English was expected to have a higher percentage.

**Table 3** The list of research areas in reverse osmosis publications.

Research Areas	Records	Percentage
Engineering	5,127	73.887%
Water Resources	2,728	39.314%
Environmental Sciences Ecology	1,279	18.432%
Polymer Science	863	12.437%
Chemistry	649	9.353%
Energy Fuels	316	4.554%
Material Science	296	4.266%
Science Technology Other Topics	294	4.237%
Food Science Technology	249	3.558%
Biotechnology Applied Microbiology	148	2.133%
Physics	122	1.758%
Agriculture	106	1.528%
Thermodynamics	88	1.268%
Marine Freshwater Biology	72	1.038%
Computer Science	70	1.009%
Biochemistry Molecular Biology	58	0.836%
Nuclear Science Technology	45	0.649%
Mechanics	44	0.634%
Public Environmental Occupational Health	40	0.576%
Geology	37	0.533%
Mining Mineral Processing	34	0.490%
Automation Control Systems	25	0.360%
Metallurgy Metallurgical Engineering	23	0.331%
Operations Research Management Science	23	0.331%
Meteorology Atmospheric Sciences	22	0.317%
Toxicology	22	0.317%
Electrochemistry	21	0.303%
Nutrition Dietetics	17	0.245%
Microbiology	15	0.216%
Pharmacology Pharmacy	14	0.202%
Urology Nephrology	12	0.173%
Geochemistry Geophysics	11	0.159%
Instruments Instrumentation	11	0.159%
Plant Sciences	11	0.159%
Oceanography	10	0.144%
Crystallography	9	0.130%
Construction Building Technology	8	0.115%
Mathematics	8	0.115%
Mineralogy	8	0.115%
Acoustics	6	0.086%
Biophysics	6	0.086%

**Table 4** The list of the most productive authors in reverse osmosis research area.

No	Authors	Total publications	Percentage	h-index	Country
1	Lee, Sangheon	90	1.297%	24	South Korea
2	Elimelech, Menachem	72	1.038%	49	USA
3	Chung, Tai-Shung	62	0.894%	32	Singapore
4	Kim, Joon Ha	61	0.879%	18	South Korea
5	Shon, Ho Kyong	60	0.865%	20	Australia
6	Hong, Seungkwan	58	0.836%	25	South Korea
7	Drioli, Enrico	55	0.793%	25	Italy
8	Gao, Congjie	53	0.764%	19	People's Republic of China
9	Nghiem, Long Duc	48	0.692%	29	Australia
10	Fane, Anthony Gordon	45	0.649%	25	Singapore
11	Mujtaba, Iqbal Mohammed	45	0.649%	11	England
12	Wang, Jie	42	0.605%	12	People's Republic of China
13	Wang, Yan	41	0.591%	15	People's Republic of China
14	Kim, Seungju	37	0.533%	13	South Korea
15	Van Der Bruggen, Bart	37	0.533%	17	Belgium



**Fig. 4.** A screenshot of the bibliometric map created based on the bibliographic coupling of authors with network visualization mode. The minimum number of documents of a country is set to 30.

**Table 5** The list of document types that have been used in reverse osmosis research area.

Document types	Records	Percentage
Article	6,451	92.967%
Proceedings paper	1,378	19.859%
Book chapter	121	1.744%
Early access	11	0.159%
Data paper	3	0.043%
Retracted publication	1	0.014%

**Table 6** The list of languages that have been used in reverse osmosis research area.

No	Languages	Records	Percentage
1	English	6,811	98.155%
2	German	26	0.375%
3	Polish	20	0.288%
4	Chinese	16	0.231%
5	Spanish	15	0.216%
6	Portuguese	11	0.159%
7	Japanese	9	0.130%
8	French	6	0.086%
9	Korean	5	0.072%
10	Italian	4	0.058%
11	Russian	4	0.058%
12	Croatian	3	0.043%
13	Czech	3	0.043%
14	Turkish	3	0.043%
15	Romanian	1	0.014%
16	Ukrainian	1	0.014%
17	Unspecified	1	0.014%

## Conclusion

This paper evaluated a summary of the developments in reverse osmosis process research based on 6,938 publications from the Web of Science (WOS) database. Based on the author keywords co-occurrence analysis, the general terms were usually found in “desalination”, “nanofiltration”, “forward osmosis” and “ultrafiltration”. We have discovered countries and academic institutions, for instance, USA, which have many publications and strong international collaborations. Furthermore, as shown in the VOSviewer mapping, the USA had the highest number of total link strength (807,767) and the highest number of documents (1,096). The research areas showed that Engineering was mostly found in reverse osmosis research. In future research, related contents could be more extensive and should be more specific to different research subjects. Hence, to choose an adequate research method, the research front still needs to work harder to explore more things about the reverse osmosis process and in-depth expansion.

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