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Forward Osmosis Research Trends in Desalination and Wastewater Treatment: A Review of Research Trends Over the Past Decade

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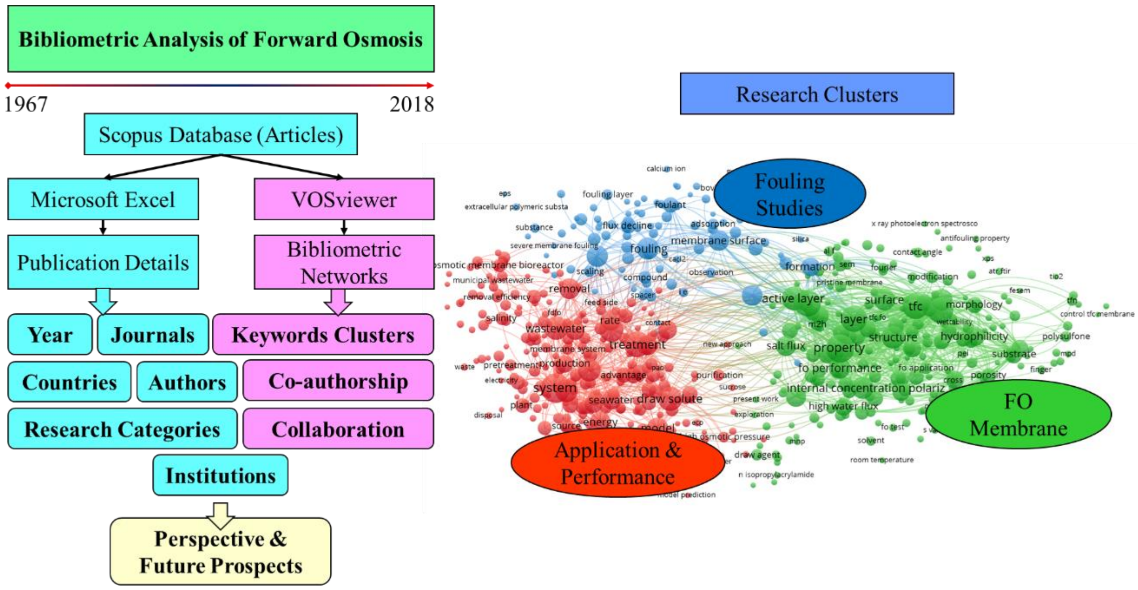
Graphical Abstract



Abstract

Issues of water scarcity and water security have driven the rapid development of various technologies to ensure water sustainability. The forward osmosis (FO) membrane process has been widely recognized as one of the more promising technologies to play an important role in alleviating the issues of water sustainability. Extensive research has been carried out worldwide to explore the potential of FO in desalination, water and wastewater treatment and reclamation. It is of the utmost importance to understand the topics of interest and research trends to further advance the development of FO process technology. In this study, a bibliometric analysis based on the Scopus database was carried out to identify and understand the global research trends of FO process based on 6 main analyses: basic growth trends, journals, countries, institutions, authors, and keywords. A total of 1462 article records published between 1967-2018 were extracted from Scopus and used as the raw data for bibliometric analysis using VOSviewer software. The total number of FO articles has sharply increased since 2009 and stabilized at around 250 publications in the past three years. The increase could be associated with the breakthrough in FO membrane science, where the contributions were from the 5 most productive countries: USA, China, Singapore, Australia, and South Korea. FO research started to diversify after the appearance of commercial FO membranes with improved characteristics, enabling the researchers to employ them for various application studies. Keywords analysis showed that the main directions of FO research could be categorized into three clusters: application of FO, membrane fouling study, and FO membrane synthesis. These bibliometric results provide a valuable reference and information on current research directions of FO for researchers and industry practitioners who are interested in FO technology.

Keywords: Bibliometric Analysis; Forward Osmosis; VOSviewer; Water Treatment; Desalination

Introduction

Water is one of the most precious natural resources, essential for sustaining life on earth. Without a sufficient and consistent supply of clean water, anthropogenic activities will be disrupted and socio-economic development will come to a standstill. However, increased demand for clean water from the rapid growth of human population, accelerated industrialization and urbanization and intensive agriculture activities, coupled with increased risk from climate change have significantly shrunk the limited freshwater resources [1,2]. In addition, the situation has been exacerbated by the disposal and released of hazardous pollutants, leading to contamination of water resources. All these incidents have led to water scarcity crises in various regions of the world. The consequences of water pollution and overexploitation of water resources are increasingly critical and putting lives and livelihoods at risk and reducing socio-economic growth in many countries [3].

The United Nations has encouraged many countries to set the production of clean water as a primary national agenda that needs to be addressed urgently [4]. Concurrently, many researchers have been involved in various areas of water research with the aim to identify the most technically- and economically-feasible processes to produce clean water for consumption. Over the past few decades, technological advancement has revolutionized the water industry with the emergence of several technologies capable of producing clean water from various water resources (including unconventional water sources such as contaminated water, wastewater and seawater). Among these technologies are adsorption, membrane separation, advanced oxidation processes and biological processes [5–7]. The development of water and wastewater treatment processes have even extended into the hybridization and integration of several technologies into more compact systems, as can be found in past publications [8–11].

Membrane technology has become one of the major technologies used in various water and wastewater treatment processes due to its efficient removal of contaminants from water bodies. For instance, reverse osmosis (RO) has been widely used to extract clean water from seawater [2,12]. Whilst RO is efficient at removing almost all impurities and contaminants in the water, its use in producing clean water poses several challenges. The operation of RO requires high hydraulic pressure, which increases the energy consumption and fouling of the membrane [13]. Although the advance of technology has significantly reduced the energy consumption and cost of the RO-based process, it is still energy- and cost-intensive [14]. This can become an economic burden for developing and under-developed countries to adopt membrane technology to address water scarcity issues. Hence, an alternative technology with lower energy consumption and costs for clean water production should be explored.

<u>Forward Osmosis Membrane Process</u>

Forward osmosis (FO) is an emerging membrane separation technology that has gained much attention for many applications in the past few years. Unlike the RO process that needs external pressure to function, FO is driven by the osmotic pressure difference between a concentrated draw solution (DS) and a diluted feed solution (FS) across a semipermeable membrane [2,15]. It has been reported that FO has very high water recovery, lower membrane fouling propensity and greater energy efficiency than the RO membrane process [16–19]. Due to these reasons, FO has attracted attention from both academic researchers and industrial practitioners [20]. FO has been applied to various areas including food processing, wastewater treatment, desalination and power generation [2,11,21,22].

Despite the high potential shown by the FO process, there remains several challenges that need to be overcome for successful commercial implementation of this technology. Some of the problems frequently encountered in FO processes include high reverse solute flux, concentration polarization (internal and external), weak membrane mechanical strength, low membrane flux, and intensive energy consumption for the regeneration of DS and recovery of water from DS [23]. These challenges must be resolved in order for the FO process to be truly competitive compared to other technologies and to be attractive to industry. The key aspects towards successful FO process are the improvement of energy efficiency of the whole process (FO and DS), membrane properties (water flux, antifouling, concentration polarization and reverse solute flux), draw solutes (osmotic pressure, regeneration and recoverability) and the integration or hybridization of FO with other technologies [20,24]. All these key aspects are interrelated and improvement in one aspect might not be an accurate indication on whether the FO process is more competitive or not. Hence, it is difficult to draw a comprehensive conclusion on the feasibility of the FO process for a particular application without looking at the larger picture that encompasses all the key aspects.

Extensive research has been conducted to resolve the challenges encountered by FO process. At the same time, advances in technology have resulted in improved performance of the FO process in the areas of FO membranes, draw solution, application and modeling. This can be seen from the publication of several review papers that have summarized the state of the art of FO technology. Table 1 shows the Top 20 review papers, in terms of numbers of citations, on FO of the past few years. To allow for the time required to build up the citation number, Table 2 tabulates the FO review papers that have been published from 2017 onwards. As can be seen from Table 1, most of the highly cited review papers discussed the application of the FO process in various industries, indicating that FO technology has drawn tremendous attention from researchers working in various applications. The applications of the FO process range from wastewater treatment to food manufacturing industries and desalination. On top of this, the highly cited FO review papers also focused on the topics related to the synthesis and fabrication of better performing FO membrane and the exploratory studies of draw solutes with better recoverability and easier regeneration. This trend aligns well with the interest of researchers to resolve the two major challenges that are currently impeding the performance of FO process.

Table 1

Top 20 highly cited FO review papers

No.	Title	Year	Journal*	Focus Area	Cited	Ref.
1	Forward osmosis: Principles,	2006	JMS	FO membrane and application	1248	[25]

	applications, and recent developments					
2	Recent developments in forward osmosis: Opportunities and challenges	2012	JMS	FO application and challenges of FO process	633	[26]
3	Forward osmosis: Where are we now?	2015	DES	FO membrane, draw solutes, fouling and application	261	[20]
4	Forward osmosis for application in wastewater treatment: A review	2014	WR	FO for wastewater treatment	252	[23]
5	Emerging forward osmosis (FO) technologies and challenges ahead for clean water and clean energy applications	2012	COCE	FO membrane and draw solutes for water and energy applications	192	[17]
6	Membrane fouling in osmotically driven	2016	JMS	FO membrane fouling	178	[27]

	membrane processes: A review					
7	A review of draw solutes in forward osmosis process and their use in modern applications	2012	DWT	Draw solutes	134	[28]
8	Forward osmosis niches in seawater desalination and wastewater reuse	2014	WR	FO for desalination and wastewater reuse	122	[22]
9	A critical review of transport through osmotic membranes	2014	JMS	Mechanisms and models of solute transport	88	[29]
10	Rejection of trace organic compounds by forward osmosis membranes: A literature review	2014	EST	FO application in rejecting trace organic compounds	83	[30]
11	A comprehensive review of hybrid forward osmosis systems:	2016	JMS	Hybrid FO process in various applications	82	[31]

	Performance, applications and future prospects					
12	Membrane concentration of liquid foods by forward osmosis: Process and quality view	2012	JFE	FO application in food industry	75	[32]
13	Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction	2016	WR	FO application for wastewater nutrient recovery	70	[33]
14	Recent advances in polymer and polymer composite membranes for reverse and forward osmosis processes	2016	PPS	FO membrane synthesis and fabrication	66	[34]
15	Osmotic membrane bioreactor (OMBR) technology for	2016	JMS	FO for wastewater	64	[35]

	wastewater treatment and reclamation: Advances, challenges, and prospects for the future			treatment and reclamation		
16	Fertilizer drawn forward osmosis desalination: The concept, performance and limitations for fertigation	2012	RESB	FO application for fertigation	63	[36]
17	A review on the recovery methods of draw solutes in forward osmosis	2014	JWPE	Draw solute regeneration	53	[37]
18	What is next for forward osmosis (FO) and pressure retarded osmosis (PRO)	2015	SPT	Short review on FO membrane and application	46	[38]
19	The osmotic membrane bioreactor: A critical review	2015	ESWRT	FO application and draw solutes	45	[39]

20	Forward osmosis: Understanding the hype	2015	RCE	FO application	34	[40]

*JMS – Journal of Membrane Science; DES – Desalination; WR – Water Research; COCE – Current Opinion in Chemical Engineering; DWT – Desalination and Water Treatment; EST – Environmental Science and Technology; JFE – Journal of Food Engineering; PPS – Progress in Polymer Science; RESB – Reviews in Environmental Science and Biotechnology; JWPE – Journal of Water Process Engineering; SPT – Separation and Purification Technology; ESWRT – Environmental Science: Water Research and Technology; RCE – Reviews in Chemical Engineering

The interest in FO technology does not stop with the highly cited review papers. Within the 2-year period 2017-2018, another 18 new review papers have been published. As expected, the three major focus areas of the review papers remain the same, which are the FO membrane, draw solutes and application of FO process. Overall, the published review papers reflect the trends of FO research and the areas that are of most concern to the research community. Unsurprisingly, the areas of interest resonate with the key aspects and challenges of the FO process. However, as the research on FO technology is growing at an accelerated rate, it is hard for the stakeholders (especially researchers and industry practitioners) in the field to read all the publications thoroughly. Therefore, on top of the review and scientific papers that have been focusing on technical findings, it is necessary to properly summarize the existing research using an appropriate method to capture the trends of FO research related to water.

Table 2

Review papers on FO from 2017 onwards

No.	Title	Year	Journal*	Focus Area	Ref.
1	Forward osmosis application in manufacturing industries: A short review	2018	MEM	FO application in manufacturing industries	[41]
2	Recent advance on draw solutes development in Forward Osmosis	2018	PRO	Draw solutes	[42]
3	Advances in forward osmosis membranes: Altering the sub-layer structure via recent fabrication and chemical modification approaches	2018	DES	FO membrane synthesis and fabrication	[43]
4	Salinity build-up in osmotic membrane bioreactors: Causes,	2018	BT	FO application	[44]

	impacts, and potential cures				
5	Membranes and processes for forward osmosis-based desalination: Recent advances and future prospects	2018	DES	FO membrane synthesis and hybrid process application	[45]
6	Osmotic's potential: An overview of draw solutes for forward osmosis	2018	DES	Draw solutes	[46]
7	Osmotic membrane bioreactor and its hybrid systems for wastewater reuse and resource recovery: Advances, challenges, and future directions	2018	CPR	FO application	[47]
8	Prospect of ionic liquids and deep eutectic solvents as new generation draw	2018	JWPE	Draw solutes	[48]

	solution in forward osmosis process				
9	An odyssey of process and engineering trends in forward osmosis	2018	ESWRT	FO membrane, application and draw solutes	[49]
10	Understanding mass transfer through asymmetric membranes during forward osmosis: A historical perspective and critical review on measuring structural parameter with semi-empirical models and characterization approaches	2017	DES	Modeling and characterization of forward osmosis membrane	[50]
11	A short review of membrane fouling in forward osmosis processes	2017	MEM	FO membrane fouling	[51]
12	Studies on performances of	2017	DWT	FO for desalination process	[52]

	membrane, draw solute and modeling of forward osmosis process in desalination – a review				
13	Employing forward osmosis technology through hybrid system configurations for the production of potable/pure water: A review	2017	JT	Hybrid FO process for potable water production	[53]
14	Advances in draw solutes for forward osmosis: Hybrid organic-inorganic nanoparticles and conventional solutes	2017	CEJ	Draw solutes	[54]
15	Recent advances in forward osmosis (FO) membrane: Chemical modifications on	2017	DES	FO membrane synthesis and fabrication	[55]

	membranes for FO processes				
16	Forward osmosis as a platform for resource recovery from municipal wastewater - A critical assessment of the literature	2017	JMS	FO for resource recovery	[21]
17	Review on methodology for determining forward osmosis (FO) membrane characteristics: Water permeability (A), solute permeability (B), and structural parameter (S)	2017	DES	FO membrane characteristics	[56]
18	A review of forward osmosis membrane fouling: types, research methods and future prospects	2017	ETR	FO membrane fouling	[57]

*MEM – Membranes; PRO – Processes; DES – Desalination; BT – Bioresource Technology; CPR – Current Pollution Reports; JWPE – Journal of Water Process Engineering; ESWRT – Environmental Science: Water Research and Technology; DWT – Desalination and Water Treatment; JT – Jurnal Teknologi; CEJ – Chemical Engineering Journal; JMS – Journal of Membrane Science; ETR – Environmental Technology Reviews

Bibliometric Analysis

To better understand the past, ongoing and future research landscape of FO technology, a quantitative analysis that provides usable and relevant statistical information is required for scientific guidance. Bibliometric analysis is an effective method that applies quantitative and statistical analysis to describe the historical progress and quantitative trends of research publications of a subject of interest [58,59]. Generally, it is a powerful tool that helps academics to explore, organize and analyse large amounts of information (such as publications, countries, institutions, authors, journals, categories and keywords) in a quantitative manner [60]. The outcomes from bibliometric analysis can help to evaluate the present situation and growth trend of a specific research field and to identify the research contributions from various countries, institutions and scholars [61,62]. The use of bibliometric analysis to analyse the trends in research has gained popularity, encompassing different disciplines such as medicine [63], biomass energy [64], environmental sciences [65], sustainable city [66], arts and humanities [67], economics [68], lean and cleaner production in manufacturing [69] and engineering [70–72]. However, to our best knowledge, even with the publication of several review papers on FO process, there is a lack of relevant statistical research-trend information on FO technology based on bibliometric analysis. Considering the growing research interest on FO and its huge potential in various applications, a quantitative bibliometric study on FO technology will help in terms of advancing and providing a potential guide for current and future studies.

The aim of this study is to evaluate the extent and trend of research in FO technology based on the outputs of the academic literature database using bibliometric analysis. A comprehensive and multi-perspective summary of the research on FO was carried out by analyzing the FO-related literature published in Scopus from 1967 to 2018. These documents were evaluated based on 6 main aspects: basic growth trends analysis, journals analysis, countries analysis, institutions analysis, authors analysis, and keywords analysis. This article does not attempt to dissect the technical findings of the FO process or to distill new knowledge regarding the FO technology. Rather, we intended to investigate whether new insights might emerge when examining the academic literature database from some new perspectives.

Data Collection and Methodology

The academic literature database from 1967 to 2018 was extracted from Scopus. For this bibliometric analysis, the keyword topics searched in Scopus was “Forward Osmosis” and “Direct Osmosis” where 1830 publication records were found. The term “Direct Osmosis” was included in the searching as some authors used this term in their publications, especially during the first few years when FO was being introduced and precise terminology was not yet agreed upon. Only documents published in the English language were considered. The document types of the publications can be split into 5 major categories; article (1462; 80%), conference paper (155; 8%), review (105; 6%), book chapter (56; 3%), and others (52; 3%). Only the articles were used as the raw data source, as the intention of this paper was to investigate the trend of FO research and for that purpose, the citation data for journal articles were much more reliable [73]. The 1462 article records and the associated citation and bibliographical information were downloaded as the raw data source for further analysis. Each of the data (title and abstract) was read through and screened to remove redundant or irrelevant information. After the screening process, only 1384 article records were found to be sufficiently relevant. Simple statistical data, such as the number and growth of publications (according to year, journal, and country), research category of publication, and subject areas of publications were analyzed using Microsoft Excel. The bibliometric networks (i.e., keyword co-occurrence, collaboration and co-authorship networks) were interpreted and visualized by VOSviewer [74]. In addition to the bibliometric network analysis, the VOSviewer was also used to find the keywords clusters. All the compiled publications were analyzed in 6 main aspects: growth of publication number, journal and research category of publication, contribution of publication according to countries, institutions, and authors, and clustering and connection between the research keywords.

Bibliometric analysis

Basic Growth Trend

The number of FO publications per year is shown in Fig. 1. As the number of publications before the year of 2005 were insignificant in number (in the range of 0 to 2), it was omitted from the graph. It is evident that most of the FO publications (accounting for 97.5% of total publications) occurred in the most recent 10 years (2009-2018). This phenomenon revealed that the research on FO technology has only recently attracted significant attention from researchers. The publication growth trend shows four interesting phases; stagnant, startup, booming and stable. The stagnant period was before the year 2005, as very low to no FO publications were reported in each of these years, though FO was first reported decades ago. From reading through the abstracts prior to 2005, it was found that the majority of the studies were on fabrication and use of cellulose acetate membrane for FO performance evaluation. The low number of publication prior to 2005 could be due to the technical challenges in fabricating high performing FO membranes, as well as in realizing the potential of FO in various applications.

After 2005, the publication numbers increased steadily until the year 2010, where the number doubled as compared to the previous year. The increasing amount of publications can be attributed to the availability of commercial FO membrane that helped to accelerate the study of the FO process (spearheaded by Hydration Technology Innovations [75]). This marked the first breakthrough for FO membrane synthesis where the cellulose triacetate FO membrane was thinner compared to the older generation (cellulose acetate) membrane [76,77]. Associated with this improvement, FO process could attain higher flux and reduced internal concentration polarization. The emergence of commercial FO membrane with improved properties has encouraged academics and industry practitioners to start exploring applications of FO that was infeasible with the older generation membranes.

Subsequently, the FO publications entered a booming phase, where the number increased from 37 (2010) to 238 (2016) publications per year, recording an average increase in publication rate of 29 publications per year. Such a large jump in publication number could be associated with the diversification of FO research. Prior to this, studies were mostly focusing on application evaluation. After the year 2010, the nature of FO research became more diverse, where active studies were conducted on membrane synthesis, fouling, modelling and draw solutes. In addition, the number of FO research groups has also grown larger and more researchers have contributed to FO publication. During this period, a newer generation of FO membrane (thin-film composite) was introduced and brought to the market. Thin-film composite FO membrane was reported to be superior to previous FO membranes in terms of permeability and stability at broader pH ranges [78]. In 2010, Oasys Water launched the world's first polyamide-based thin-film composite FO membrane [79]. Afterwards, FO has increasingly been tested for pilot and commercial scale application. For instance, Oasys Water has shown that the incorporation of FO technology into their industrial wastewater treatment systems could treat and reclaim water from shale gas produced waters (USA), harsh coal-to-chemicals wastewaters (China), and flue gas desulfurization purge water at the power plants in China's coal belt [80]. It was reported that such integrated processes could benefit the industries in term of reduced electricity and steam consumption, maximized recovery of product water, and lowered overall cost.

As well as the conventional polymer-based membranes, a biomimetic FO membrane with promising characteristics has also emerged as a potential membrane for various FO applications [81]. The incorporation of aquaporin into the biomimetic FO membrane granted it high water permeability and selectivity, which is of importance to FO applications. The key player of biomimetic FO membrane in the market is Aquaporin A/S (Denmark), who was reported to be collaborating with Darco Water Technologies Ltd (Singapore) by supplying Aquaporin Inside® FO membranes for a low-energy zero liquid discharge pilot system for industrial wastewater treatment [82,83].

Since 2016, the FO publication figures stabilized at around 240 publications per year. The stabilization of the number of FO publications implies the technological bottleneck and saturation of FO studies faced by the research community. Overall, as can be seen in the growth trend, the evolution of publication number was closely linked with the breakthrough in the research of FO technology: advancement of membrane science, appearance of commercial FO membrane and the diversification of FO studies.

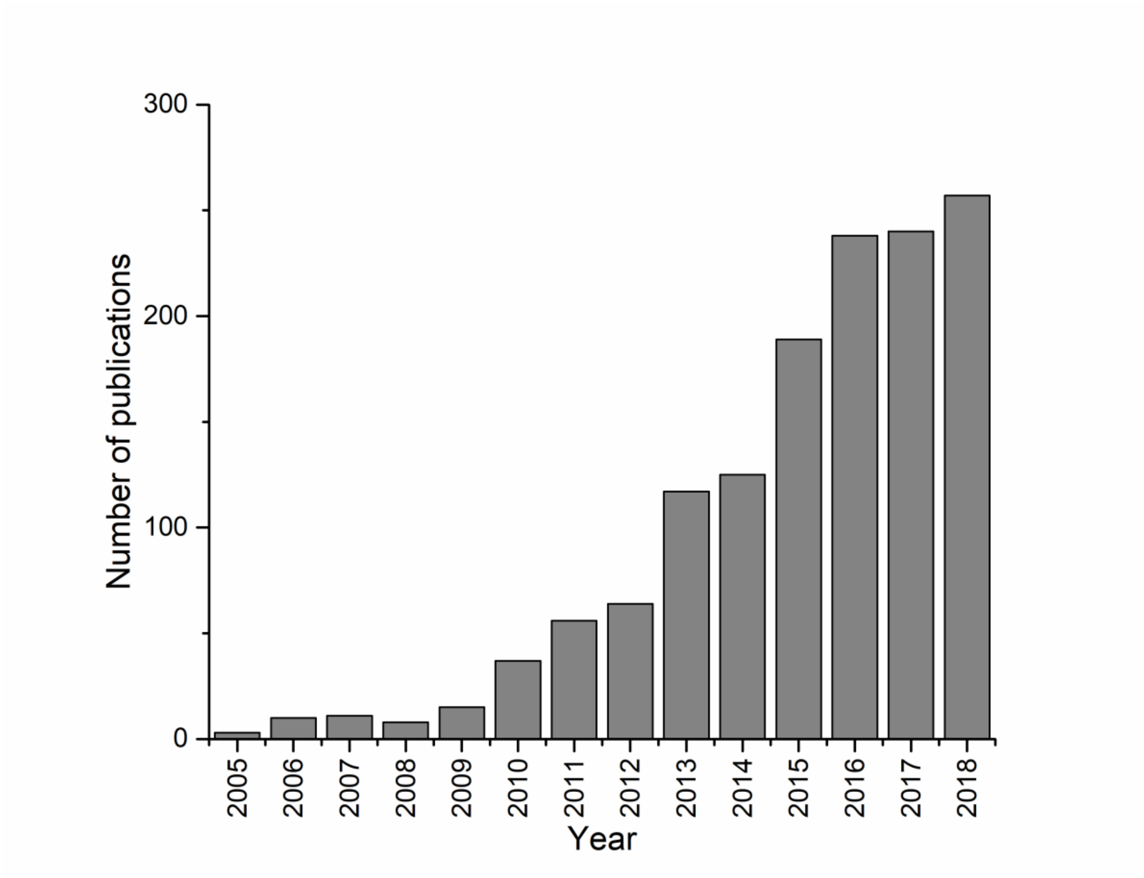


Fig. 1. Growth trend of FO publication (2005 – 2018).

<u>Journals Analysis</u>

Table 3 displays the top 10 most productive journals that account for 70.5% of total FO publications. The corresponding Impact Factors (IF) of the journals are also shown. The top 3 journals with the highest number of publications (more than 100 papers each) on FO technology were Journal of Membrane Science, Desalination, and Desalination and Water Treatment. This finding was not surprising, as the FO research was aligned with the aims and scopes of the aforementioned journals emphasizing on the research related to membrane, desalination and environmental considerations.

Table 3

The top 10 most productive journals for FO publications

Ranking	Journal	IF*	Publication Number	Percentage (%)
1	Journal of Membrane Science	6.578	305	22.2
2	Desalination	6.603	222	16.2
3	Desalination and Water Treatment	1.383	145	10.6
4	Environmental Science and Technology	6.653	59	4.3
5	Water Research	7.051	57	4.2
6	Chemical Engineering Journal	6.735	50	3.6
7	Bioresource Technology	5.807	40	2.9

8	Separation and Purification Technology	3.927	34	2.5
9	Industrial and Engineering Chemistry Research	3.141	31	2.3
10	RSC Advances	2.936	24	1.7

*IF were obtained from InCites Journal Citation Reports

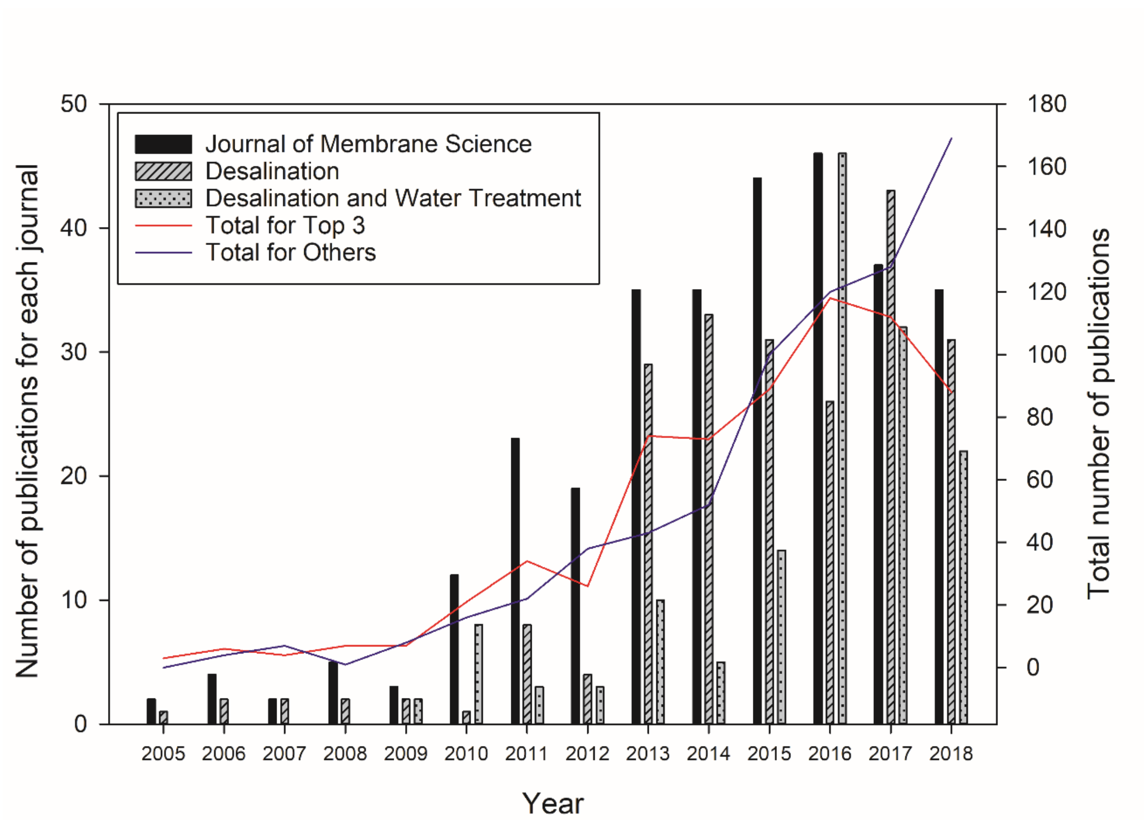


Fig. 2. Publication according to journals.

Fig. 2 depicts the growth of publications in the 3 most productive journals from the year of 2005. Publication before the year of 2005 was not considered as some of the journals had not been established and the publication number was not significant in number. It can be observed that there were three interesting growth spikes for the top 3 journals (JMS, DES and DWT). The publication output for JMS rose significantly from 3 papers in 2009 to 46 papers in 2016, with an increment rate of 5 papers per year. JMS recorded the earliest growth spike as compared to the other journals. As can be seen in Fig. 3, the increment of FO publication in JMS was mainly contributed by FO membrane synthesis and application research. In this context, synthesis refers to studies involving the fabrication of new FO membranes using novel materials or the modification of existing FO membrane for improved performance. For the application category, the main target of the studies was to explore the performance of FO technology and the potential of FO process to be used in various applications, such as wastewater treatment, desalination and concentration processes. This phenomenon indicated that the articles accepted by JMS were more to pioneer study (synthesis and application), aligned with the scope of this journal. Interestingly, publications in other aspects (fouling, modeling and draw solution) also recorded a constant number of publications from the year 2014. Fouling represents FO studies which mostly emphasize fouling phenomena and associated approaches to counter fouling issues (such as cleaning and manipulation of operating conditions). On the other hand, modeling includes mathematical modeling and simulation that aims to better understand the fundamental factors affecting the FO process, so as to be able to more accurately predict the FO performance. For draw solutes, the studies involved the exploration of different types of draw solutes to improve ease of regeneration.

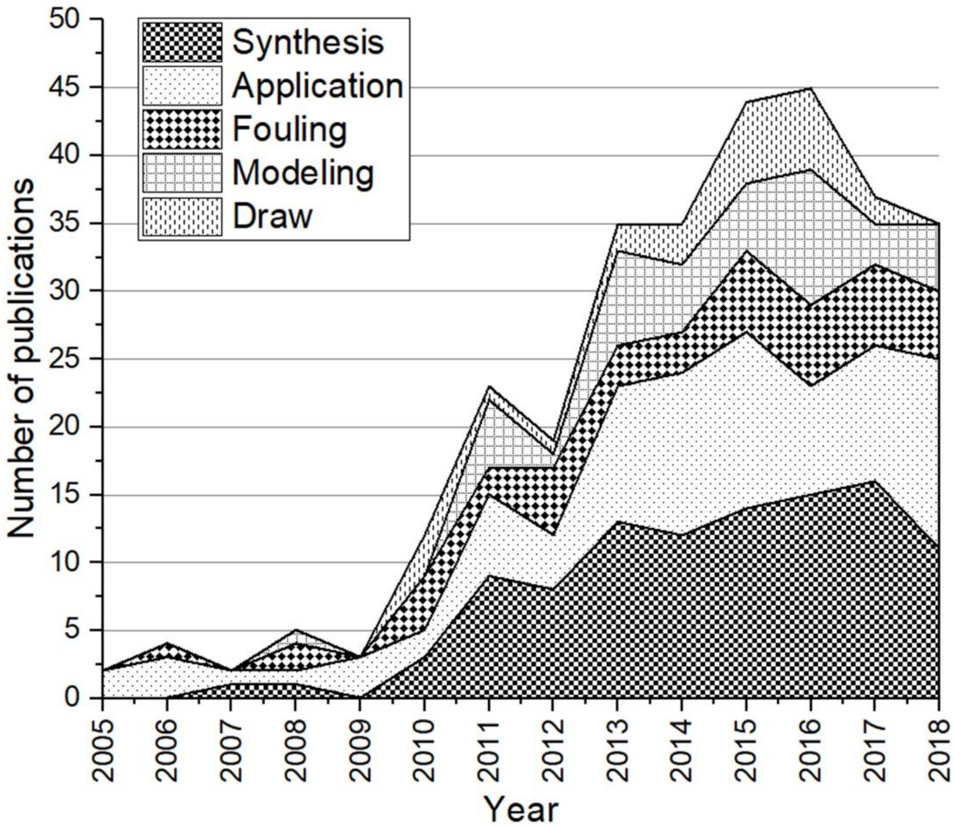


Fig. 3. Nature of research publication in JMS.

The second significant publication growth was presented by DES where the number of publications increased from 4 in 2012 to 43 in 2017, observing a ten-fold of increase within 5 years. The growth spike appeared 3 years later for DES compared to JMS. This could be due to the FO application to desalination processes gained popularity after the initial studies in synthesis and application categories were reported in JMS and other journals prior to 2013. The research scope for articles published in DES was heavily dominated by application of FO process, as shown in Fig. 4 where it contributed a huge percentage of publication number. This trend reflected that most of the articles accepted by DES were focusing on the utilization of FO technology in processes dedicated to the field of desalination. A significant number of articles from fouling and synthesis categories have also been observed, especially after the sharp drop after 2016 on publications related to application. Even though FO has been generally known as a low-fouling process (due to its non-pressurized operating condition), the fouling issue still prevails in most of the applications. For instance, FO dewatering of activated sludge recorded 80% decline in flux after operation for 8 hours and fouling control must be taken to improve the feasibility of long-term FO operation [84], accounting for the high level of attention to this research category.

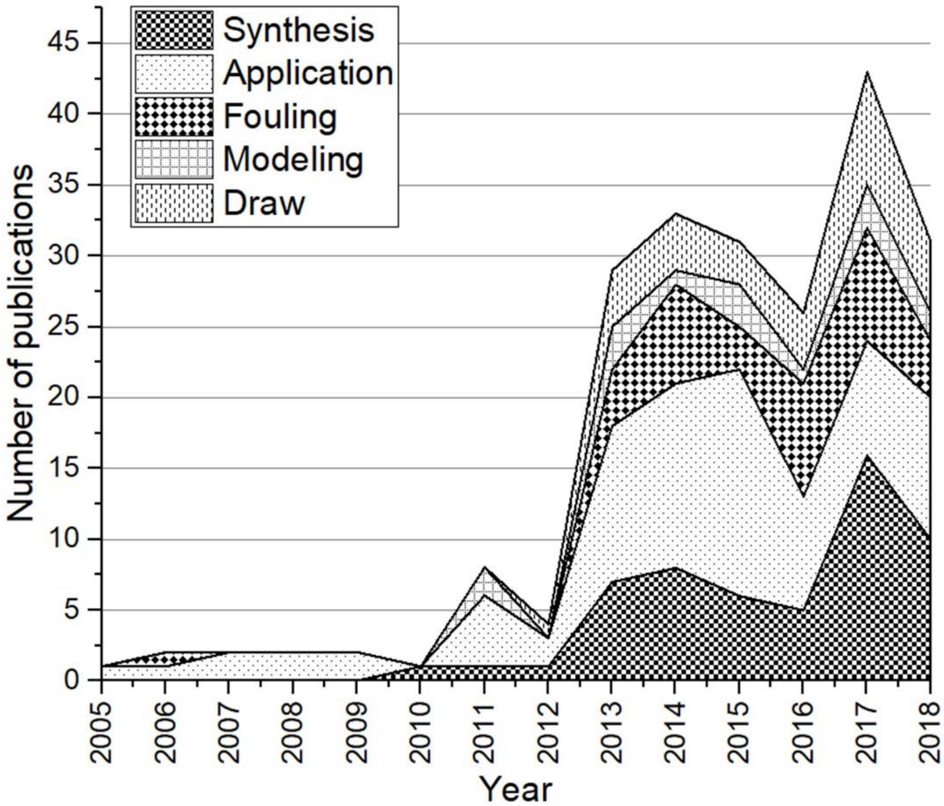


Fig. 4. Nature of research publication in DES.

Finally, the last spike in publication number was recorded by DWT, where there was a sharp increase from 5 publications in 2014 to 46 publications in 2016. The growth for DWT lagged 6 years behind the spike seen in JMS. This could be attributed to the maturity of FO research, where more researchers can conduct FO experiments due to the ready availability of commercial FO membrane and the experience (research findings) shared by other researchers in JMS and DES. The majority of the papers for FO in DWT fell into the category of FO application studies (Fig. 5). This sharp rise in application category publication revealed that active research has been done to explore the potential of FO technology in a wide variety of fields, such as nutrient recovery and wastewater reclamation, on top of the common desalination and water treatment studies.

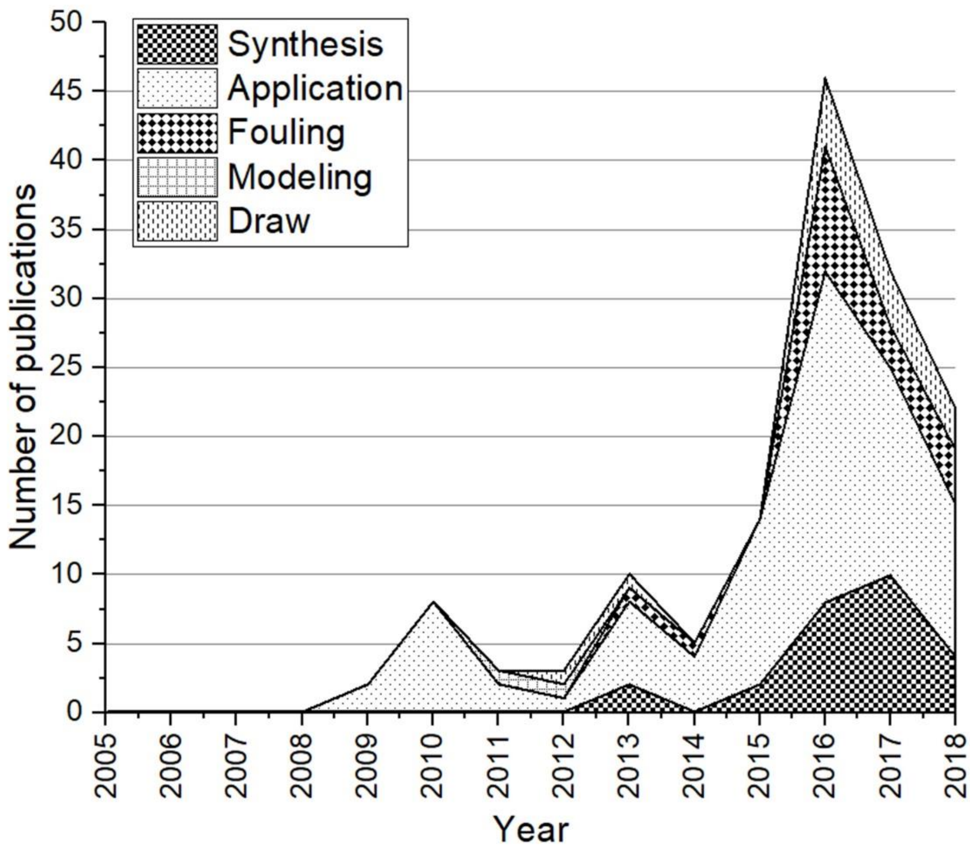


Fig. 5. Nature of research publication in DWT.

The variation of research scope and publication trends of the three major journals in this area indicates that the initial FO studies were more inclined towards the exploration and synthesis of FO membranes, as shown by the first growth spike in JMS. This also shows that the publication in JMS was more to pioneering studies, as without the experience of FO membrane synthesis, other types of research works would have been difficult to proceed. The development of FO membranes has encouraged other researchers to venture into other areas of research and led to the subsequent growth spikes in DES and DWT, where the researchers were more willing to explore other areas of FO studies. This resulted in the diversification of FO research, as the publications in other FO research areas increased considerably. However, the trend showed that the number of publications in these journals declined after the year of 2016-2017. This could be due to the fact that the maturity of FO technology (in terms of research and development at the lab scale) had reached a plateau stage. Even though the total number of FO publications in the top 3 journals has been a declining trend since 2016, the overall number of publications still recorded a slight increase to 257 in 2018. From Fig. 2, it can be seen that the drop of publication in the top 3 journals was offset by the sharp increase of publication in other journals.

The research categories of the FO publications are shown in Fig. 6. Out of 18 research categories identified from Scopus, only 5 were included (with percentage of share more than 10%). It has to be noted that some publications fell in more than one category, resulting a percentage summation of more than 100%. Five of the most common research areas were Chemical Engineering, Chemistry, Environmental Science, Materials Science, and Engineering, where the number of publications that fell in these categories was more than 500. The results are in agreement with the bibliometric analysis done on the similar fields (membrane technology and water treatment), where the top research areas were related to Chemical Engineering, Chemistry and Environmental Science [71,72]. The major research categories identified in Fig. 6 can be linked with the publication nature in the journals aforementioned. All the FO studies required the knowledge and skills that fall under the top 5 research categories.

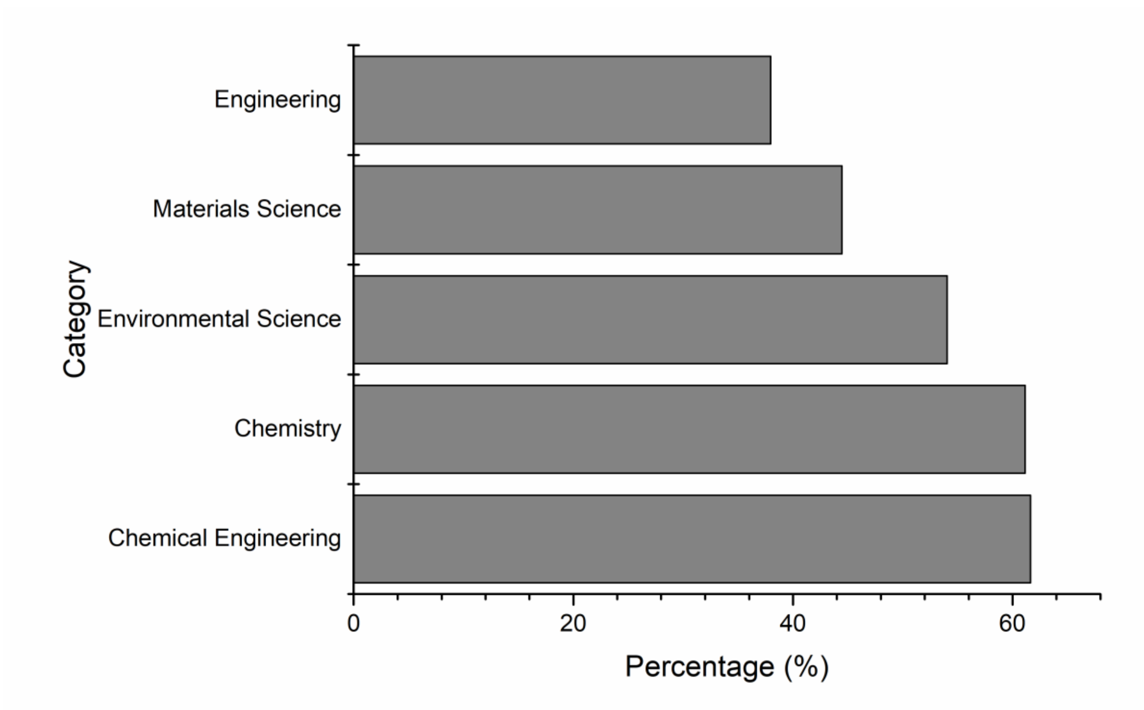


Fig. 6. Most popular research categories for all publications.

Table 4 shows the top 15 highly cited FO publications from the year 2005 to 2018. All the highly cited articles were published prior to 2010, since publications require a certain period of time to build up the citation number. As shown in the table, the nature of the highly cited articles concentrated on the fouling issue. This is an interesting observation as generally the FO process is known to have a low fouling propensity. Yet, the highly cited articles mainly came from this fouling category, which is an indication that fouling is still a major challenge to the application of FO, similar to other membrane processes.

Table 4

The top 15 cited publications

No.	Title	Year	Journal	Cited	Nature of study	Ref.
1	Influence of concentrative and dilutive internal concentration polarization on flux behavior in forward osmosis	2006	JMS	683	Fouling	[85]
2	A novel ammonia-carbon dioxide forward (direct) osmosis desalination process	2005	DES	632	Application	[76]
3	Desalination by ammonia-carbon dioxide forward osmosis: Influence of draw and feed solution	2006	JMS	552	Draw Solution	[86]

	concentrations on process performance					
4	High performance thin-film composite forward osmosis membrane	2010	EST	536	Synthesis	[87]
5	The forward osmosis membrane bioreactor: A low fouling alternative to MBR processes	2009	DES	491	Application	[88]
6	Organic fouling of forward osmosis membranes: Fouling reversibility and cleaning without chemical reagents	2010	JMS	490	Fouling	[89]
7	Coupled effects of internal concentration polarization and fouling on flux behavior of forward osmosis membranes during humic acid filtration	2010	JMS	435	Fouling	[90]

8	Chemical and physical aspects of organic fouling of forward osmosis membranes	2008	JMS	387	Fouling	[77]
9	Comparison of fouling behavior in forward osmosis (FO) and reverse osmosis (RO)	2010	JMS	376	Fouling	[91]
10	Internal concentration polarization in forward osmosis: role of membrane orientation	2006	DES	369	Application	[92]
11	Reverse draw solute permeation in forward osmosis: Modeling and experiments	2010	EST	358	Fouling; Modeling	[93]
11	Membrane fouling and process performance of forward osmosis membranes on activated sludge	2008	JMS	358	Fouling	[94]

13	Characterization of novel forward osmosis hollow fiber membranes	2010	JMS	356	Synthesis	[95]
14	Selection of inorganic-based draw solutions for forward osmosis applications	2010	JMS	348	Draw Solution	[96]
14	Forward osmosis for concentration of anaerobic digester centrate	2007	WR	348	Application	[97]
14	Energy requirements of ammonia-carbon dioxide forward osmosis desalination	2007	DES	348	Application	[98]

Countries Analysis

The Scopus records indicate that there were 59 different countries that contributed to the FO publication records. Table 5 presents the top 20 most productive countries in FO research. The top 5 countries which contributed more than 200 publications were China (326), United States (325), Singapore (247), Australia (228) and South Korea (215). These data should not be misunderstood as single publications since a publication can be related to more than one country due to the collaboration between the researchers and institutions from different regions.

Table 5

The top 20 most productive countries in FO research

Ranking	Country	Number of publications
1	China	326
2	United States	325
3	Singapore	247
4	Australia	228
5	South Korea	215
6	Saudi Arabia	80
7	United Kingdom	53
8	Iran	52
9	India	48
10	Japan	41
11	Qatar	35
12	Malaysia	33
13	Spain	32
14	Canada	29
15	Netherlands	29

16	Belgium	28
17	Taiwan	25
18	Denmark	23
19	Hong Kong	23
20	Egypt	21

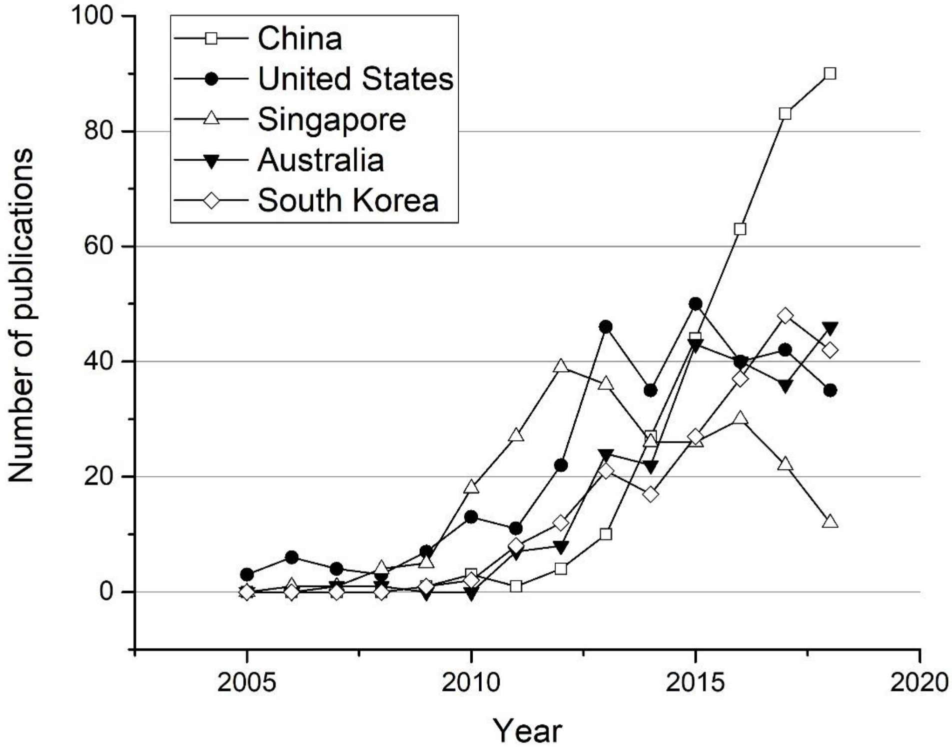


Fig. 7. Growth trends of the publication number from the top 10 most productive countries.

The growth trends of the publication number from the top 5 most productive countries are shown in Fig. 7. It can be seen that the researchers in USA were the pioneers in FO research as the FO publication in the early period was dominated by USA. Two years after that, Singapore researchers started publishing in the FO filed. Their publication numbers increased rapidly, overtaking USA after 2009. This could be attributed to the strong support from the Singapore government in water research and development. With limited surface water resources, Singapore has sought to obtain clean water from other sources, such as wastewater and seawater using advanced membrane technology. This strategy was implemented with intensive water-related research and development led by Singapore's National Water Agency – PUB, through the Environment and Water Industry Programme Office (EWI). EWI coordinates the research collaboration between the government agencies, industries and academic institutes. Through this coordination and research link, a collective value of S$453 million (funding from National Research Foundation, PUB and in-kind contribution from collaborators) has been pumped in for water-related research and development, involving 613 projects and collaborations with 27 countries [99]. Among the key areas of research were membrane technologies for wastewater reclamation and desalination. The intense funding and support ever since 2004 has helped to boost the FO research and increase the number of FO publications. However, the momentum did not last long where the number of publication gradually decreased after 2012.

The FO publications of China, South Korea and Australia started to increase after the year of 2010. China is especially of note as the number of their FO publications increased abruptly from 10 (2013) to 90 (2018) in a short period of time and maintained position as the most productive countries after 2015. This phenomenon was also observed in ceramic membrane research, where China recorded a sharp increase in publication after 2014 [71]. The reason behind this increasing trend in publications was that the Chinese government has introduced a series of policies to support water and membrane research. Water scarcity and pollution have been a major threat to China’s continuous and sustainable development. The Chinese central government has intensified efforts to control and remedy water pollution by the introduction of the Water Pollution Prevention and Control Action Plan in 2015 [100]. With such an action plan, the local stakeholders have to ensure that the handling of wastewater complies with stringent regulations. Since FO is one of the membrane technologies that could be used to resolve issues associated with wastewater management, it has received tremendous research attention from Chinese researchers, leading to a sharp increase in the number of FO publications originating in China.

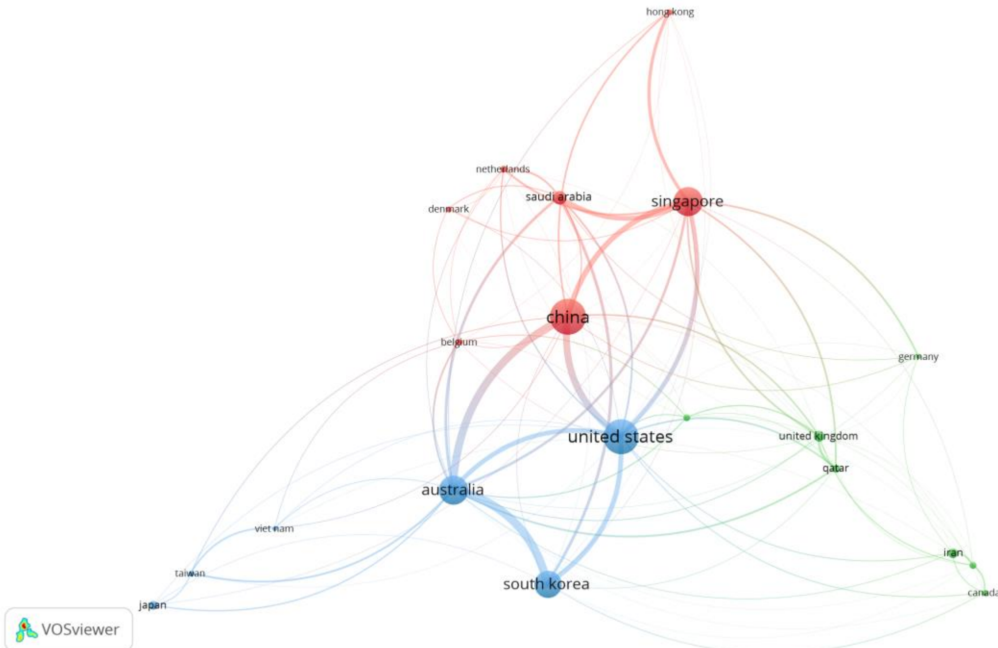


Fig. 8. Collaboration network between the top 20 productive countries in FO publication.

Fig. 8 shows the collaboration network between the top 20 most productive countries in FO research. Each country is represented by a circle and the curves connecting the circles are the publication in collaboration between the two linked countries. The size of the circle was determined by the number of FO publications produced by that particular country, whereas the thickness of the curves connecting the circles was proportional to the strength of collaborations between the two countries in co-author publication. The color of the circles indicates the research cluster to which the countries belong. As can be seen in Fig. 8, the size of the few larger circles was resonant with the top 5 productive countries (China, United States, Singapore, Australia, and South Korea). The collaboration strength between the countries was both represented by the thickness of link in Fig. 8 and scores in Table 6. The link referred to the number of countries a particular country was connected in term of co-author publication. All the countries displayed extensive collaboration network, with United States and Australia recording the highest number (18 links) of collaboration partners (country). In terms of collaboration strength (represented by the thickness of the curve connecting the countries and data in Table 6), Australia has the highest link strength at 160. This indicated that the research collaboration between the Australia and its collaborators was strong and more extensive.

Table 6

Collaboration link and strength in the top 5 productive countries

No.	Country	Link	Total Link Strength	Number of Citation	Norm. Citation Score
1	United States	18	124	18939	413.4
2	China	16	122	5108	348.23
3	Singapore	14	118	13594	285.05
4	Australia	18	160	6057	267.89
5	South Korea	11	84	3597	156.30

The number of citations and normalized citation scores were used to examine the quality of the FO research conducted according to country. As can be seen in Table 6, the United States received the highest number of citations at 18939, followed by

Singapore at 13594 citations. Such a high number of citations could be attributed to the large number of FO publications at a very early stage (Fig. 7) that eventually became the guidance and reference source for other researchers. Furthermore, the normalized number of citations received by the United States (413.4) was also far ahead of the other countries. This signified the fundamental nature of the FO research in the United States which subsequently was cited highly. Though the number of FO publications from China was on a par with the United States, the number of citations lagged far behind the United States. One of the reasons could be due to the fact that most of China's FO publications were quite recent (304 articles were published in the past 5 years) and therefore received less attention among the researchers.

Institutions Analysis

The FO publication records are from 160 different institutions. The top 10 most productive institutions, in terms of publication numbers, are displayed in Table 7. The three institutes that published more than 100 papers are the National University of Singapore (153; Singapore), Nanyang Technological University (126; Singapore) and University of Technology Sydney (122; Australia), indicating their strength in producing FO research publications. It should be cautioned that the data are non-exclusive, as a publication can be related to more than one institution due to the collaboration between the researchers and institutions.

The presence of research centres in the particular institute was explored. The establishment of a water- and membrane-related research centre would likely become the hub where the research funding will be channeled and the pool for talented researchers. With a critical mass of quality researchers and sufficient funding, FO studies of various natures (fundamental to application) can be conducted. This will help the institution to perform well in research, be it findings or publications. For instance, NUS Environmental Research Institute was focusing on research related to environmental issues and offering measures to tackle water-related problems via interdisciplinary approaches [101]. FO process has also benefited from the presence of this research institute as it falls under membrane technology, which is one of the key research field in the centre. NUS Faculty of Engineering also listed water as the core engineering research, with membranes as the key research technology [102].

To further strengthen and promote the membrane-related research, Membrane Science and Technology Consortium (MSTC) has been established as an umbrella organization under NUS [103]. Similarly, NTU also has established a membrane-based research centre, known as Singapore Membrane Technology Centre (SMTC) under the Nanyang Environment and Water Research Institute [104]. The presence of these two membrane-based research centres has resulted in the two universities becoming world leaders in membrane technology. Subsequently, it is not surprising that NUS and NTU featured as the top two productive institutions in terms of FO research publications. The rest of the high-performing institution also shared a similar strategy, such as the establishment of the Centre for Technology in Water and Wastewater (UTS), Advanced Membranes and Porous Materials Center (KAUST), and Water Desalination and Reuse Center (KAUST) [105–107].

Table 7

The top 15 most productive institutions in FO research

Ranking	Institution	Country	Number
1	National University of Singapore (NUS)	Singapore	124
2	Nanyang Technological University (NTU)	Singapore	112
3	University of Technology Sydney (UTS)	Australia	100
4	Yale University	USA	69
5	King Abdullah University of Science and Technology	Kingdom of Saudi Arabia	67
6	Korea University	South Korea	65

7	Chinese Academy of Sciences	China	64
8	University of Wollongong	Australia	39
9	University of Connecticut	USA	37
10	Gwangju Institute of Science and Technology	South Korea	33

Authors Analysis

The top 10 most productive authors, in terms of numbers of publications in peer reviewed journals, in FO research are tabulated in Table 8. It can be seen that Australia and Singapore featured the greatest number of most prolific authors, with 3 top prolific authors currently affiliated to each country. Interestingly, currently the Australian authors are working in the same university (University of Technology, Sydney). Nanyang Technological University also has 2 prolific authors working on FO research. Overall, the current affiliation of this group of researchers tallied well with the most productive institutions.

Table 8

The top 10 most productive authors in FO research

Ranking	Author	Current Affiliation	Publications
1	Chung, Tai Shung Neal	National University of Singapore (Singapore)	79
2	Shon, Hokyong	University of Technology Sydney (Australia)	66
3	Tang, Chuyang Y.	The University of Hong Kong (Hong Kong)	62
4	Elimelech, Menachem	Yale University (USA)	55
5	Phuntsho, Sherub P.	University of Technology Sydney (Australia)	52
6	Wang, Rong	Nanyang Technological University (Singapore)	49
7	McCutcheon, Jeffrey R.	University of Connecticut (USA)	43
8	Fane, A.G. (Tony)	Nanyang Technological University (Singapore)	41
9	Nghiem, L.D.	University of Technology Sydney (Australia)	40
10	Hong, Seungkwan	Korea University (South Korea)	39

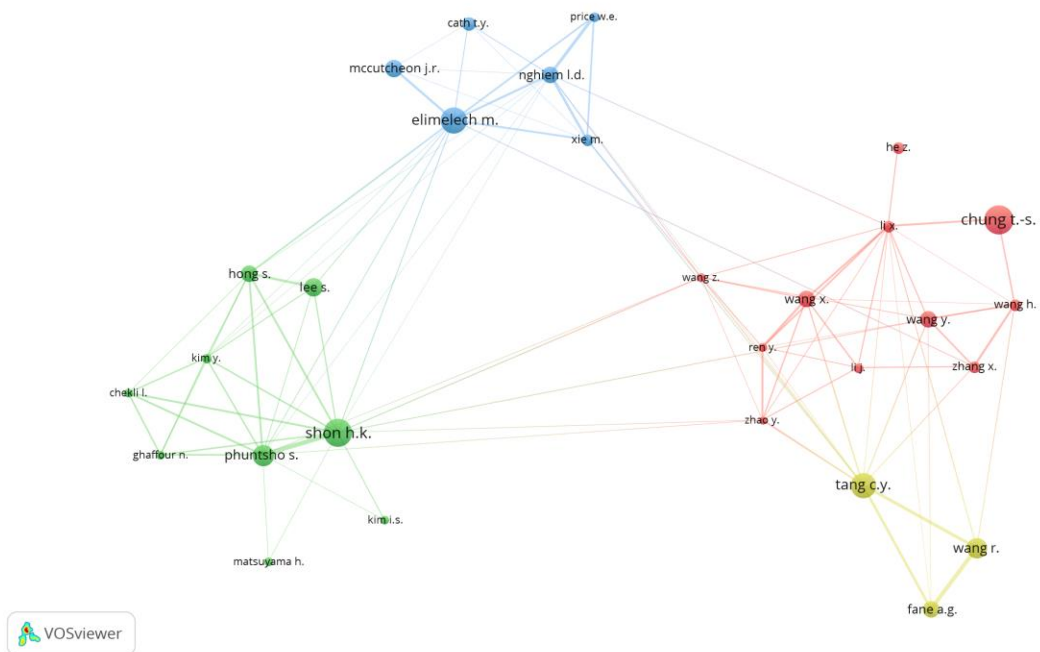


Fig. 9. Collaboration network between the top 30 productive authors in FO publication.

To better understand the collaboration network between the researchers, the connection between the top 30 researchers was considered (Fig. 9). It can be seen that the researchers can be separated into four clusters, sorted according to the intensity of co-authorship occurrence. Researchers within the same cluster have stronger research collaboration strength and share more similar publications with the researchers within that particular cluster. The details of collaboration strength and citation are shown in Table 9. The term 'link' refers to the number of authors a particular author is connected to. It has to be noted that this collaboration network is limited to the top 30 productive researchers to facilitate the analysis of clustering. In other words, the link strength shown for each author in Table 9 did not reflect the real connection the author has, since the rest of the researchers are not included. The citation information indicated the number of times the articles under an author was being cited. As expected, the pioneer of FO research, Menachem Elimelech, recorded the highest number of citations and normalized citations.

Table 9

Link strength and citation details of the top 10 productive authors in FO research

No.	Author	Link	Total link strength	Citation	Normalized citation
1	Chung, Tai Shung Neal	2	8	5154	95.14
2	Shon, Hokyong	13	54	1326	70.84
3	Tang, Chuyang Y.	11	35	4544	87.08
4	Elimelech, Menachem	11	34	9151	135.33
5	Phuntsho, Sherub P.	12	50	1119	63.08
6	Wang, Rong	4	39	3293	58.12
7	McCutcheon, Jeffrey R.	4	9	4447	60.14

8	Fane, A.G. (Tony)	4	34	3042	47.47
9	Nghiem, L.D.	12	34	1804	76.23
10	Hong, Seungkwan	8	26	1625	48.57

Keywords Analysis

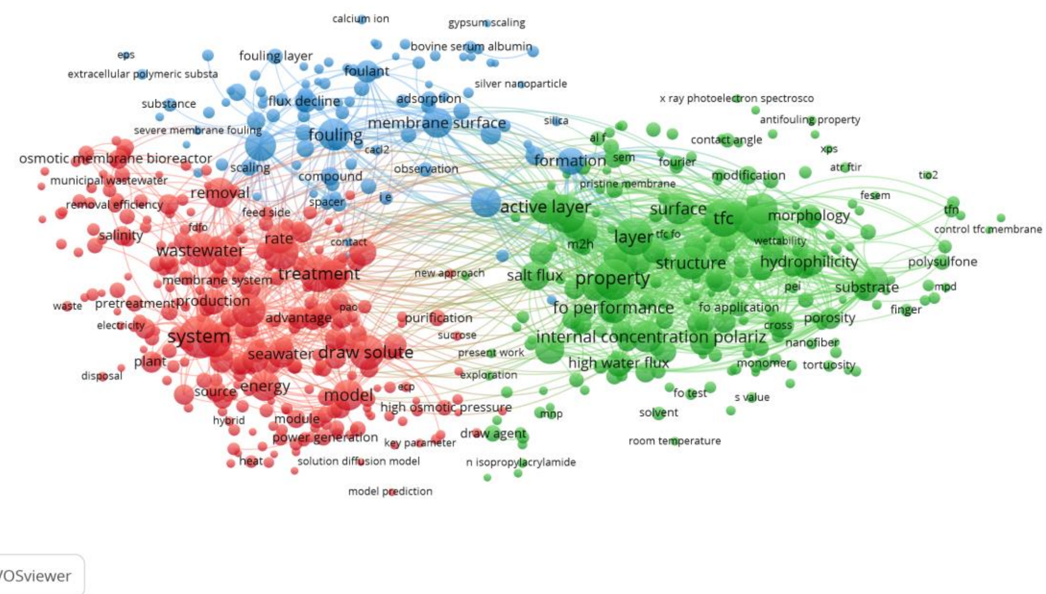


Fig. 10. Co-occurrence network of the author keywords.

A total of 22881 author keywords were recorded, among which 804 keywords have been used more than 10 times. Further analysis and simplification was done using VOSViewer to generate the keyword co-occurrence network that shows the connection and importance (weightage) of 600 most relevant keywords as displayed in Fig. 10. Each keyword is represented by a circle where the size indicates the number of occurrences of a particular keyword. The connection between the circles (keywords) is revealed by the curves connecting the circles. As can be seen in Fig. 10, the keywords can be classified into three Clusters; Cluster 1, 2, and 3 are shown in red, blue, and green color, respectively. The more relevant the keywords, the closer are the circles in the cluster.

Generally, Cluster 1 contains the keywords related to the application and performance study of FO process, as can be seen by the few representative words such as “system”, “treatment”, “wastewater”, “seawater”, “removal”, and “draw solute”. Keywords in Cluster 2 are more to membrane fouling study, clearly indicated by the “fouling”, “foulant”, “flux decline”, “membrane fouling”, and “membrane surface” keywords. Lastly, Cluster 3 focuses more on FO membrane, where the keywords such as “layer”, “property”, “hydrophilicity”, “thin film composite”, “surface”, and “modification” demonstrate the study related to FO membrane characterization and fabrication. The presence of these three clusters reveals the major FO research fields that are currently ongoing worldwide.

As illustrated in Fig. 3-5, a huge portion of FO publications in the top 3 journals were contributed by FO application-type articles. This categorization was supported by the high occurrence of keywords related to the study of FO performance and application, as in Cluster 1. For instance, extensive publications have shown the potential of the FO process for wastewater treatment [108], nutrient concentration [109,110], resource recovery [111–113], food concentration [114], produced water remediation [115], and desalination [116]. All these topics have appeared as keywords in Fig. 10. Apart from reporting on the FO system performance, modeling and simulation of FO process have also been employed to predict and understand the FO process [117,118]. The keyword "model" is closely connected to "draw solute", "simulation result", "system", and "treatment" in Cluster 1, as well as few main keywords in Cluster 2, such as "property", "water permeability", and "internal concentration polarization". Such linkage shows the existence of FO studies where researchers utilized modeling to understand the influence of FO membrane properties on the performance [119]. This category of study would close the gap between FO process and membrane synthesis groups and offer better understanding of how the FO membrane will behave in various applications.

One observation is that the keywords related to draw solution are located near the crowded center of Cluster 1 (indicating its significance in FO research). Draw solution has been generally recognized as a major obstacle for FO process to be economically feasible, as the regeneration of draw solution would require high consumption of energy, unless regeneration is not required, as in the case of fertigation [120,121]. The co-occurrence network shows that "draw solute" is connected to keywords on FO process performance in Cluster 1, "membrane fouling" in Cluster 2, and "salt flux" and "high water flux" in Cluster 3. This linkage reveals the influence the type of draw solute would have on the FO performance.

Certain types of draw solutes resulted in high reverse salt flux that deteriorated the FO performance, while it has also been observed that some draw solutes would accelerate the FO membrane fouling propensity [122]. This signifies the need to select the proper draw solute to avoid unnecessary drawbacks in FO performance.

Even though FO has been frequently reported as a low fouling membrane process, the keywords provided by the authors suggest that FO fouling is a popular study topic among the researchers. Since FO process has been mostly tested on solutions (especially wastewater) containing organic substances, organic fouling (where the organic foulants deposited on the membrane surface) was the most frequently encountered issue in FO operation [123]. Fouling problems would degrade the FO performance and incur extra costs due to frequent cleaning and membrane replacement [124]. Though many articles reported that FO membrane fouling was mostly reversible, the flux recovered after each cycle of cleaning normally did not reach the preceding flux level. Subsequent operation and cleaning cycles would eventually reduce the flux to an unacceptable and impractical level. Hence, as in the case for other membrane processes, the incorporation of a certain level of feed solution pretreatment might be necessary to reduce the FO fouling propensity.

The success of membrane technology lies in the characteristics and properties of the membrane. Without a suitable membrane, the technology would not be able to develop. Such is the case for reverse osmosis and it is equally as true for the FO process. As analyzed above, the booming of FO publications could be attributed to the breakthrough in FO membrane synthesis that led to the presence of the first commercial FO membrane in 2006. Moving forward, active research has been conducted on the synthesis and modification of FO membranes to obtain a better performing membrane with desirable characteristics. The characteristics and properties focused by the researchers were membrane morphology and structure, water flux, reverse salt flux, rejection capability, and antifouling and anti-biofouling, as shown by the keywords in Fig. 10 [125–129]. In recent years, thin film composite (TFC) FO membrane has emerged as a popular type of FO membrane for synthesis and fabrication studies. Various types of TFC FO have been synthesized and generally it has been reported that marked improvements in fouling resistance and water flux have been achieved [125,127,129]. Just like the emerging of reverse osmosis as the main membrane technology associated with the TFC reverse osmosis membrane, the presence of better performing FO membrane was expected to further increase the application potential of FO process in various industries.

Perspective & Future Prospects

The healthy growth in the number of publications on FO over the last ten years indicated that FO technology has come to be an important technology for membrane processes. While the number of publications has stabilized over the last few years, the trend of research on FO is expected to continue to mature especially in these five main aspects:

(i) fabrication of new FO membrane using novel materials or the modification on existing FO membrane for improved performance

Unlike other pressure-driven membranes, both sides of FO membrane (active layer and support layer) have significant influences on the FO performance. The active side has been commonly oriented towards the feed solution while the support side normally faces the draw solution. This signifies the challenges in the fabrication of FO membrane as one has to fine-tune proper formulation and modification to get the desired properties on the two sides. Future membrane science research should work on the modification of both sides (as majority of existing studies only focus on one side, the consequence of improvement on either side has on the other side remains unclear). Incorporation of nanomaterials in synthesizing FO membrane has shown encouraging outcomes where it leads to the improvement of membrane properties. Various types of nanomaterials ranging from organic to inorganic to biomimetic have been extensively incorporated during the synthesis of FO membrane. However, the compatibility, stability, and feasibility of these nanocomposite FO membranes still remain a challenge. Apart from thin film composite FO membrane, the only commercial membrane with nanomaterials is Aquaporin. Other nanoparticle-incorporated FO membranes are still at lab-scale, despite numerous articles reporting improved properties. One should not fall into the fallacy of incorporating different nanoparticles in FO membrane synthesis. Such study will not contribute significant advancement to FO membrane science. Also, multifunctional nanomaterials have shown an increasing research trend and it could be that some alternative materials could be incorporated in the FO membrane synthesis. The multifunctional properties may solve the issue of compatibility and stability while at the same time bring more improvement to the membrane.

(ii) development of novel FO process (integrated and hybrid FO process) to be used in various applications, such as wastewater treatment, desalination and concentration processes

The working principles of the FO process have made it challenging to be an individual unit operation employed in any processes. Hence, to harness the full potential of FO process, it can be integrated/hybridized with other advanced treatment processes. Past studies have shown that the overall performance of a particular process (such as anaerobic treatment and produced water remediation) has been improved with the incorporation of FO process. FO can also be employed as a pretreatment before thermal desalination processes to improve the overall water recovery rate. The working principle of the FO process enables it to utilize the desalination brine solution as a draw solution, where it will be diluted and subsequently reduce the scaling propensity of the thermal desalination process. This shows a promising research pathway for FO researchers. Having said that, the integration/hybridization expands the role of FO process from only focusing on water related processes to supporting other type of applications, such as energy (biogas), crystallization, and fertilizer. Such a change of paradigm will offer another perspective to other researchers and industries, where they will be more convincing on the role of FO process in non-water-based application. This will be a healthy development to encourage more people to explore the potential of FO in various application.

(iii) analysis of fouling phenomena and the associated approaches to counter the fouling issues (such as cleaning and manipulation of operating conditions)

Though the FO process is generally known as a low fouling process due to its low-pressure operation, fouling issues still inevitably present in the FO process. This is due to the fact that FO has been frequently processing low-quality feed water that contains a lot of suspended solids and impurities. The presence of these impurities could easily block the membrane surface and gradually reduce the flux. In other pressure-driven membrane processes, the feed water quality has to be refined to ensure the membrane processes can perform as desired. One of the commonly adopted approaches is to have proper pretreatment prior to the membrane process. Such lessons can be adopted for the FO process, where researchers should consider improving the feed water quality by integrating the FO process with a proper pretreatment. The influence of pretreatment prior to the FO on the overall performance has not yet been widely studied. This, together with the feasibility of having a pretreatment stage and the overall benefits (cost associated with cleaning frequency and cost of membrane replacement) should be evaluated. Concentration polarization (especially internal concentration polarization) has been a major limiting factor that results in a discrepancy in the observed and promised performance of FO process. Considering that internal concentration polarization is the crucial limiting factor in any FO process, mitigation approaches such as improving the intrinsic properties of the FO membrane and external measures preventing and disrupting concentration polarization and fouling should be explored.

(iv) modeling including mathematical modeling and simulation that aim to better understand the fundamental factors affecting the FO process and be able to more accurately predict the FO performance

Based on the publication data presented above, the work on modelling of FO membrane processes have been quite limited. Generally, modelling of membrane processes are focusing on (i) mass transport across the membranes, and (ii) process modelling for predictive purposes. The majority of the FO models for mass transport have been based solution-diffusion (SD) and convection-diffusion equations. Most of these models, however, have neglected fouling effects since the phenomena is quite complex. Some models have managed to incorporate the internal and external concentration polarization (ICP and ECP) into the equations. The main challenge for the future of FO modeling must be to gain further understanding of the fundamental phenomena occurring during the FO process in order to find answers to the questions posed above. Once the models are accurate enough, the process modelling can be developed through simplified models and design methodologies which can be helpful for non-specialist scientists and engineers. Advanced modelling method such as computational fluid dynamics (CFD) can also be used to help elucidate the fundamental behavior and hydrodynamics inside the FO membrane module.

(v) exploration of different types of draw solutes with ease of regeneration to be employed in FO process

As the driving force for the FO process is the difference in chemical potential between the draw and feed solutions, much recent and ongoing research has focused on finding novel draw solutes. The ideal draw solute should be capable of generating high osmotic pressures, show low membrane flux, and be capable of being regenerated easily. As potentially the major energy use in FO operations is in the regeneration of the draw solute, most research has focused on this step, either with novel solutes or novel low energy processes. State of the art draw solutes have included polyelectrolytes, responsive hydrogels, and nanoparticle-based systems. These are often large molecules or particles which can be re-concentrated using high flow filtration systems, such as ultrafiltration, or by changing their physical properties to allow recovery by other means. However, as re-concentration requires the osmotic potential of the draw solution to retain its original value, there is likely to be a minimum energy needed to re-concentrate any diluted draw solution. As this energy requirement may push the theoretical energy needed for the combined FO/draw solution regeneration system to greater than the energy consumption of a rival technology, such as reverse osmosis, this may render many of these alternative draw solution technologies as dead ends, outside of niche requirements. Alternatively, research has been carried out to find situations where the draw regeneration process itself may be low energy. This has included the use of fertilizers or soil treatments, where the diluted draw solution can be used for other applications, such as fertigation, without a regeneration step at all. Membrane distillation may be used where either waste heat is available or cheap renewable energy, such as solar heaters, are practicable, removing much of the energy costs for draw re-concentration. Such avenues may provide a route to industrial applicability for FO, but may be restricted to specific situations.

Apart from the above areas, there is also a strong need for larger scale studies of FO processes dealing with real in-field applications. Such studies should be carried out at the pilot scale or larger scale and long-term operational data should be obtained to ascertain the viability and profitability of the process. Only under such conditions, the fouling control and mitigation as well as membrane susceptibility to complex feed materials can be understood. Such studies will lead towards a more sustainable and successful FO membrane operation which can help to decide the commercial viability of the processes. In order for FO to be successfully applied at a commercial scale, the role of government is very important in providing the impetus through appropriate incentives and policy that can push the technology forward.

Conclusions

Based on the bibliometric analysis, the progress on FO research has been tremendous over the last 10 years with a growth ratio of 17 times from 2009 to 2018. The exponential growth is contributed by researchers from 59 different countries with China and United States emerging as the countries that have contributed most to research on FO. The initial impetus for the growth in FO research was started in 2009-2010 which can be attributed to the availability of commercial FO membrane that helped to accelerate the study on FO process. Since then, FO research has been expanded to cover various areas including various types of applications, fouling studies, novel draw solutes and modelling. Subsequently, more study on the following research areas can be conducted: synthesis of FO membrane using novel materials or the modification on existing FO membrane for improved performance; development of novel integrated/hybrid FO process to be used in various applications; analysis of fouling phenomena and associated approaches to counter the fouling issues; mathematical modelling and simulation to better understand the fundamental factors affecting the FO process and for performance prediction; and exploration of different types of draw solutes with ease of regeneration. Future works should continue in these areas as well as in demonstrating the commercial viability of the FO membrane processes.

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