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Mapping the evolution of seawater desalination research (2000–2024): Bibliometric and co-word analysis of 11,000+ publications

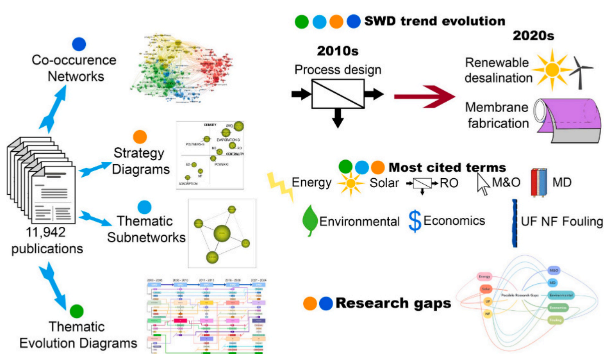
Gustavo Leite Dias Pereira *, Veeriah Jegatheesan

School of Engineering and Water, Effective Technologies and Tools (WETT) Research Centre, RMIT University, Melbourne, VIC 3000, Australia

HIGHLIGHTS

- Analyzed 11,942 unique items from WOS and Scopus databases for SWD research trends
- Geographic analysis revealed significant contributions from Chinese and North American institutions.
- High citation keywords: "reverse osmosis", "membrane", "solar", "energy"
- Early 2020s research focus: renewable energy sources, especially solar energy and evaporation

GRAPHICAL ABSTRACT



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ABSTRACT

Seawater desalination (SWD) can partially mitigate the increasing freshwater needs globally. Although, SWD is multifaceted and involves processes with environmental and economic challenges, research is often analyzed through Literature Reviews (LRs) in specific contexts that may miss general trends. Bibliometric Analyzes (BAs), however, provide researchers with an overview through Co-occurrence Networks (CNs), Strategic Diagrams (SDs), Thematic Subnetworks (TSs), and Thematic Evolution Diagrams (TEDs). Nevertheless, their use in SWD research has been limited, with minimal attention given to them. Thus, we created a bibliometric dataset, compared it with other BAs, and developed CNs, SDs, TSs, and a TED for SWD. Furthermore, key term searches (Energy, Solar, Reverse Osmosis, Modeling and Optimization, Membrane Distillation, Environmental, Economics, Fouling, Nanofiltration, and Ultrafiltration) and their literature are discussed. Geographical analysis shows China and the US lead SWD research, shifting from process design to membrane fabrication and solar energy. Furthermore, RO remains the leading technique despite high energy demands. Solar desalination shows promise but faces cost and scalability challenges. Environmental and economic concerns are discussed, as well as emerging solutions regarding, solar desalination, blue energy, "blue carbon", and zero liquid discharge. Research gaps include fouling effects and pretreatment incorporation in optimizations are also highlighted.

* Corresponding author.
E-mail address: s4027614@student.rmit.edu.au (G.L.D. Pereira).

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Nomenclature

BA	Bibliometric Analysis
BWRO	Brackish Water Reverse Osmosis
CDI	Capacitive Deionization
CN	Co-occurrence Network
DCMD	Direct Contact Membrane Distillation
ED	Electrodialysis
GHG	Greenhouse Gasses
HDH	Humidification-Dehumidification
HF	Hollow Fiber
LCA	Life-Cycle Analysis
LR	Literature Review
MCr	Membrane Crystallizer
MDC	Microbial Desalination Cell
MDCr	Membrane Distillation Coupled with Crystallization
MD	Membrane Distillation
MED	Multi-Effect Distillation
MF	Microfiltration
M&O	Modeling and Optimization
MSF	Multi-Stage Flash
MVC	Mechanical Vapor Compression
NF	Nanofiltration
ORC	Organic Rankine Cycle
PRO	Pressure Retarded Osmosis
PVDF	Polyvinylidene Fluoride
PVMD	Photovoltaic Membrane Distillation
PV-RO	Photovoltaic Reverse Osmosis
RA	Research Article
RED	Reverse Electrodialysis
RO	Reverse Osmosis
SCMD	Solar Collector Membrane Distillation
SC-RO	Solar Collector Reverse Osmosis
SD	Strategy Diagram
SDMD	Solar Dish Membrane Distillation
SD-RO	Solar Dish Reverse Osmosis
SE	Solar Evaporator
SGMD	Sweeping Gas Membrane Distillation
SORC	Solar Organic Rankine Cycle
SORCMD	Solar Organic Rankine Cycle Membrane Distillation
SOCR-RO	Solar Organic Rankine Cycle Reverse Osmosis
SP-RO	Solar Pond Reverse Osmosis
SWD	Seawater Desalination
SWRO	Seawater Reverse Osmosis
TED	Thematic Evolution Diagram
TS	Thematic Subnetwork
TVC	Thermal Vapor Compression
UF	Ultrafiltration
VMD	Vacuum Membrane Distillation
WOS	Web of Science
ZLD	Zero Liquid Discharge

1. Introduction

From the early 2020s up to recently, studies have shed light on the ever-increasing need for potable water, especially regarding sanitation and agricultural usage. As an example, India, with an estimated population of 1.404 billion in 2024 [1], will drastically increase water demand, posing threats to humans and the environment up to the year 2050. This change is driven by the crop cultivation, drinking water, animal husbandry, and industrial segments [2]. Furthermore, similar predictions also point to the same trend in countries such as Canada and the US. Climate change, in addition to population growth, improper management, and overuse of freshwater reserves are the leading causes of clean water scarcity, especially because of warmer winters, earlier runoffs, and declining snowmelt [3].

The lack of clean water sources has a domino effect in North America or the south of Asia, impacting several basic human needs such as food prices, crop production, and health. Water-scarce countries such as Egypt and Jordan have limited options to respond to the growing food demand [4]. Moreover, changes in irrigation in arid regions can lead to a loss of up to 69 % in crop production [5]. In some instances, there is water present but not suitable for human consumption. In a 2023 study, researchers from the University of Lagos assessed pollution levels in surface and groundwater in Nigeria, finding that only 11 % of the samples were suitable for consumption, while 53 % did not meet basic health standards [6]. As demonstrated by such works, water scarcity and economic insecurity are deeply connected, as it is also a fragility amplifier, which exacerbates existing vulnerabilities [7]. Therefore, there is an urgent need to implement cheaper and more accessible solutions for clean water production.

As of 2022, 97 % of earth's water in found in the form of salty water, with glaciers and ice caps accounting for most of the global freshwater reserves [8]. Given the increase in freshwater demand due to population growth and industrial expansion, water desalination is one of the solutions that can partially alleviate this demand. When compared to other water treatment systems, desalination plants not only have access to abundant seawater reserves such as oceans, seas, and salty lakes, but are also resistant against droughts and general patterns [9]. Furthermore, desalination systems also display greater geographic flexibility, being situated along coastlines, meanwhile other water treatment systems may depend on ponds and other freshwater sources such as rivers [10]. Moreover, water quality metrics such as total dissolved solids are crucial when it comes to potable water, with reverse osmosis (RO) being the primary source of desalinated water worldwide [11], often widely reviewed in terms of process design and large-scale systems [12,13].

Although seawater reverse osmosis (SWRO) and similar desalination technologies can provide significant potable water production, the industry still faces challenges such as the energy demand when compared to other water sources, as well as indirect green-house gas (GHG) emissions and brine discharge. Reports regarding the specific energy consumption of seawater desalination (SWD) demonstrate that 2.58–8.5 kWh/m^3 is needed. Meanwhile, the treatment of other sources such as wastewater reuse, wastewater treatment, groundwater, and surface water require 1.0–2.5, 0.62–0.87, 0.48, and 0.37 kWh/m^3, respectively [14]. Further reports also demonstrate the same trend, with Pacific Ocean SWD requiring 2.5–4.0 kWh/m^3, which is a much higher demand when compared to brackish water desalination (1.0–1.5 kWh/m^3), indirect potable reuse (1.5–2.0 kWh/m^3), water reclamation (0.5–1.0 kWh/m^3), and conventional surface water treatment (0.2–0.4 kWh/m^3) [15]. This higher energy demand, when powered by non-renewable energy sources, is responsible for indirect GHG emissions, especially if linked to thermal desalination technologies [16]. Moreover, desalination plants also discharge brine back into the ocean, which, if not treated thoroughly, can release chemicals such as antiscalants, coagulants, antifoaming agents, and cleaning compounds into the marine ecosystem [17].

Consequently, building such process plants requires attention on multiple non-technological fronts, such as environmental, financial, social, institutional, legal, and political [18]. In other words, a broader overview is necessary. Even so, the most common approach to evaluating published scientific articles remains Literature Reviews (LRs), which concentrate on a specific topic within the broader context.

Reviews in the field of desalination are situation-specific, focusing on clear-cut locations, such as China [19,20], Chile [21], or Egypt [22], on an explicit application, as in agriculture [23], crop irrigation [24], and magnesium recovery [25], and its use in tandem with renewable energy sources [26,27]. Although LRs are captivating sources for specific information, identifying the general scope of a field through them can be challenging. Additionally, review articles can only analyze a small fraction of all published literature, with LRs displaying a limited number of references. In contrast, bibliometric analyzes (BAs) can provide this general scope at the expense of specificity. Such studies employ co-word analysis, a method of obtaining and examining complex relationships and depicting the structure of knowledge in a specific field [34]. It does so by analyzing the reoccurrence of certain keywords, authors, and subjects, which results in useful data such as Co-occurrence Networks (CNs), Strategic Diagrams (SDs), Thematic Subnetworks (TSs), and Thematic Evolution Diagrams (TEDs). Table 1 displays notable BAs performed in the field of desalination, as well as outside.

Bibliometric analysis mapping Web of Science (WOS) and Google Scholar results regarding biodesalination has been conducted. With the help of co-occurrence networks, the authors collected data based on the keywords “Biodesalination” OR “Bio-desalination” OR “Biological Desalination” OR “Microbial Desalination.” Further analysis revealed that the field of biodesalination is growing, with publications from over twenty-one countries. The leading force in biodesalination research was determined to be China, the highest-ranking country in terms of collaboration ties [28]. Biodesalination research focuses on taking advantage of certain microalgae to remove salt from seawater. In specific cases, the organisms have also been used to desalinize and fixate carbon simultaneously [43], which, in some cases, can contribute to environmentally friendly processes. Recent research in the field has also focused on developing microalgae fuel cells, which not only can treat wastewater and fix carbon, but also generate electricity [44]. Likewise, technological advances in the field were concluded to be microbial desalination cells and microbial desalination and chemical recovery techniques [28].

Broader searches, such as the mapping of the entire 54-year history of the *Desalination* Journal, are also available. The four main categories of most published papers were reverse osmosis, brine and its recovery, modeling and optimization, and thermal desalination. Nevertheless, fields such as forward osmosis, renewable energy, and hybrid systems have been emerging as potential research foci. Moreover, the geographical analysis demonstrated that the leading countries publishing in the *Desalination* Journal are the US, followed by China, Germany, and India [29].

More specifically, solar desalination research was analyzed in the context of Morocco. The authors demonstrate how this subfield has increased by 133 % between 2010 and 2021, with the most productive countries being India, China, and Egypt. Additionally, their methodology showed that thermal processes have received more research attention than membrane processes in recent years. One interesting finding about solar desalination is that, according to the authors, 75 % of all documents related to solar desalination were published between 2010 and 2021, with the remaining 25 % expanding from 1952 to 2009 [31].

Similar conclusions were drawn regarding research prioritization in desalination. By limiting the WOS data to the nine most influential countries and only analyzing papers from 2013 to 2022, the authors concluded that this subsection represents 73 % of the global corpus and receives ~80 % of the total number of citations worldwide. The top five most productive countries were China, the US, India, Saudi Arabia, and Iran. Additionally, the three most researched topics involved nanofiltration, solar technologies, and graphene [32]. Further supporting evidence for these conclusions is presented in a study concerning the number of publications and citations linked to hybrid renewable energy-powered desalination. The authors found that Iran, the US, China, Egypt, and Saudi Arabia had the most publications, while the US, Greece, Singapore, Iran, and Saudi Arabia had the highest citation counts [33].

As demonstrated, geographical analyses are common in desalination. In addition, CNs have also been elaborated in this field [28–31,33]. More specifically, BAs such as [29,30] use CNs to demonstrate how desalination research has evolved. RO has remained relevant from 1966 until 2020, making up from 18.7 % to 29.3 % of all publications, still a rise in popularity of modeling and optimization has been occurring, increasing from 8.2 % in 1986–1995 to 17.8 % in 2006–2015. Furthermore, interest in thermal desalination technologies have decreased slightly, from 7.7 % to 4.9 % in the same periods [29]. BA has also been employed in the literature to produce water that is energy-efficient and cost-effective. By analyzing the frequency of desalination techniques and categorizing them into three major groups—thermal technologies, membrane technologies, and other technologies—it was shown that the most studied technologies, in descending order, are: RO, forward osmosis, MD, capacitive deionization, nanofiltration, ED, ultrafiltration, adsorption, direct contact MD, and vacuum MD [30].

Although CNs have been widely employed, studies with SDs in SWD are few [30,32]. In the case of energy-efficient low-cost water production, SD were used to classify the top contributing journals in terms of yearly publications and citations, with *Desalination* being one of the most cited and most published journals in the field [30]. Further geographical analysis has also been conducted through SDs, and, similarly, countries such as the US, China, Australia, the UK, and South Korea were classified

Table 1
Key bibliometric studies in desalination and unrelated fields.

Field of study / goal	Geographical analysis	CNs*	SDs	TSs	TEDs	Ref.
Biodesalination	No	Yes	No	No	No	[28]
Mapping the *Desalination* journal	Yes	Yes	No	No	No	[29]
Energy-efficient low-cost water production desalination	Yes	Yes	Yes	No	No	[30]
Solar desalination trends during 2010–2021	Yes	Yes	No	No	No	[31]
Desalination research prioritization	Yes	No	Yes	No	No	[32]
Renewable energy-driven desalination	Yes	Yes	No	No	No	[33]
Mapping the intellectual Structure of Knowledge in iMetrics	No	Yes	Yes	No	No	[34]
Mapping the knowledge areas and research on open data	No	No	Yes	Yes	No	[35]
Mapping high-performance computing research applications	No	Yes	Yes	No	No	[36]
Mapping the uses of STEAM in education	Yes	No	Yes	Yes	Yes	[37]
Mapping the structure of the coronavirus research field	No	Yes	Yes	No	No	[38]
Evaluation of the academic performance of TPACK in WoS	No	No	Yes	Yes	Yes	[39]
Mapping trends in STEM and STEM education	Yes	Yes	No	No	No	[40]
Electrochemical corrosion of biomaterials	No	No	Yes	No	Yes	[41]
Mapping the evolution of medical waste management research	Yes	No	No	No	Yes	[42]

* Co-occurrence Networks (CNs), Strategic Diagrams (SDs), Thematic Subnetworks (TSs), and Thematic Evolution Diagrams (TEDs).

as having high citation impact and high citations from patents from 2013 to 2022 [32]. Nevertheless, to our knowledge, SDs have not yet been applied to the article keywords, as well as abstracts and titles in SWD research. As demonstrated in Table 1, BAs from outside SWD employ SDs in article keywords in such a manner [34–39,41].

When applied to research terms, SDs can uncover motor-themes, which are research trends that are often cited (or have high centrality) and often published (or have high density). In open data research, SDs revealed that accessibility, open linked data, and graphic information systems are among the driving forces in this field [35]. Moreover, in applications of high-performance computing, uses of deep learning in object recognition, development of quantum computer error correction, and new drug development by machine learning display technological, economic, social, and public interests [36]. In addition, when applied to disciplines related to science, technology, engineering, art, and math (STEAM), motor themes such as broadening participation, science, and computational thinking were highlighted from 2019 to 2020 [37].

TSs are also used alongside SDs and serve as an interesting tool to highlight terms that are highly connected to the motor themes. For example, when used in STEAM education, broadening participation was mostly connected to fidelity and pedagogical approaches. As for science, themes regarding inclusion of women and equality are present. In the case of computational thinking, programming and robotics are also related [37]. Despite their usefulness, to our knowledge, TSs have not yet been applied to SWD research.

TEDs add a chronological element to these terms in such a way that emerging trends can be highlighted. Outside SWD, TEDs have been employed in the electrochemical corrosion of biomaterials [41] and medical waste management [42]. In these cases, research trends on biodegradable magnesium alloys, as well as titanium compounds from 2013 to 2021 [41]. As for medical waste management, themes regarding sustainability, circular economy, and the COVID-19 pandemic were trending research topics from 2018 to 2020 [42]. Although TEDs can capture trending research fronts in different periods, to our knowledge they also have not yet been applied to SWD.

Consequently, as demonstrated, the tools of bibliometric analysis have been partially employed to analyze the field of SWD, with geographical analyses and co-occurrence networks being used frequently. To our knowledge, strategic diagrams, thematic sub-networks, and thematic evolution diagrams have been rarely, if ever, used in SWD research. Therefore, in this work we aim to compile a dataset containing article keywords, titles, and abstracts, benchmarks our dataset results against the results from other BAs in desalination in terms of author ranking, papers published over time, and geographical analysis, and map the most cited terms in articles keywords and “abstracts and titles” in co-occurrence networks.

Furthermore, we also plan to plot strategy diagrams for the periods of 2000–2005, 2006–2010, 2011–2015, 2016–2020, and 2021–2024, as well as use TSs and to create a thematic evolution diagram of the seawater desalination research field, as novelty in the field. In addition, we also intend to target the ten most prominent terms, encounter the most cited research articles and literature reviews, and discuss these works in a review style with supporting literature.

2. Methodology

This paper addresses the use of the keywords “desalination” and “seawater” in documents indexed on the Web of Science (WOS) and Scopus databases. Many studies have used WOS [29–33] and Scopus [33,38,42]. However, items may exist in both databases, leading to bias in the overall database. The items searched were exclusively Research Articles from January 2000 to March 2024. As of 2024, WOS search prompts can be refined by document type, with the most common categories being: Articles, Proceeding Papers, Review Articles, Book Chapters, Editorial Materials, and Preprints. Similarly, Scopus also has analogous options: Articles, Conference Papers, Reviews, Book Chapters, Conference Reviews, and Preprints. For the general search protocol used in this study, only Articles were selected. Nevertheless, after the discussion of the results regarding the general search, refined search protocols were created to trace the most cited LRs and RAs for highly cited terms. The refined search protocols for literature reviews were conducted with the option “Review Articles” selected in WOS. As for the refined search protocols regarding research articles, the option “Articles” was selected. Table 2 shows the general search protocol adopted in this study. The refined search protocols are better discussed in Section 3.2.

The items were searched in two main ways, each corresponding to the different spellings of the word “seawater”, resulting in the ‘desalination AND seawater’ and “desalination AND ‘sea water’” search queries. The results were exported as RIS files and merged with the help of the Zotero reference manager (2023 version). Duplicated items were merged through the “Duplicate Items” option available in Zotero. The final database consists of 11,942 unique items. All RIS files and the final database are available in the Data Availability section. Fig. 1 shows the stages of database treatment.

Initially, 11,326 items were obtained through the WOS search, and 4403 items were obtained through the Scopus search. After combining both databases, a total of 15,729 items were available, of which 7003 were duplicates. A duplicate merger resulted in the final database with 11,942 items used in this study. Co-word analysis was conducted to determine the most widely used terms in two groups: “Article keywords” and “Abstracts and Titles”. CNs were plotted through the VOSviewer software (version 1.6.20) [28–30,34], while SDs, TSs, and TEDs were plotted through the sciMAT software (version 1.1.06) [37,39,41,45]. Additionally, co-authorship analysis, with settings outlined in Table 3, was conducted using VOSviewer. Furthermore, data on the distribution of papers across countries was directly extracted from WOS.

The database was separated into five time periods: 2000–2005, 2006–2010, 2011–2015, 2016–2020, and 2021-Present. Similar keywords were grouped under the same label through a Thesaurus, i.e., the terms “reverse-osmosis”, “reverse osmosis”, “RO”, and “SWRO” (seawater reverse osmosis), are all considered as part of the “ro” label. The Thesauri used in this study are available in the Data Availability section. A co-occurrence network of keywords was constructed by selecting those with a minimum of 20 citations, encompassing the 500 most frequently cited terms. Exclusions were made for countries and locations. Additionally, a thesaurus was compiled to enhance the comprehensiveness of the analysis. Similarly, another co-occurrence network was created for abstracts and titles, with a minimum of 50 citations, encompassing the 500 most cited terms (Table 3). Countries, locations, verbs, and adjectives were also excluded. Furthermore, a thesaurus has also been used. In addition, the settings used in sciMAT are available in Table 4.

As depicted in Fig. 2, strategy diagrams have four quadrants, each one with a different interpretation of how developed and central keywords can be. The X-axis displays centrality, meanwhile, the Y-axis portrays density. In the context of SDs, centrality is a measure of connection strength between two distinct research themes, thus, a theme with high centrality also has a significant impact on different research fronts. As for density, within this framework, it stands for the coherence of a given theme and how it develops over time. Moreover, high-density themes harbor clusters with enduring longevity, evolving progressively

Table 2
Overview of search protocols used for dataset compilation in this study.

Search engine	Period	Type of documents	Keywords searched
Web of Science (WOS) Scopus	January 2000 to March 2024	Research articles*	desalination AND seawater desalination AND “sea water”

* Does not include preprints or proceedings.

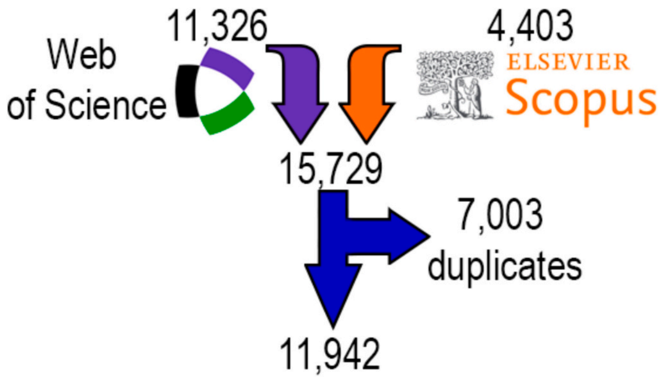


Fig. 1. Schematic illustration of the stages of database treatment, with 11,326 publications from Web of Science and 4403 publications from Scopus. After the removal of 7003 duplicates, the final dataset was composed of 11,942 distinct publications.

Table 3
VOSviewer settings for the co-authorship and co-occurrence analyses performed in this study.

Setting type	Setting
Counting method (co-authorship analysis)	Fractional counting*
Maximum number of authors per document (co-authorship analysis)	25
Minimum number of documents of an author (co-authorship analysis)	5
Number of authors to be selected (co-authorship analysis)	200
Counting method (co-occurrence analyses)	Binary counting
Minimum number of citations (co-occurrence analyses)	20
Number of terms to be selected (co-occurrence analyses)	500

* Fractional counting assigns co-authorship link strength based on the number of co-authors, reducing influence from documents with many authors.

Table 4
sciMAT settings for the co-occurrence networks constructed in this study [41].

Setting type	Setting
Matrix type	Co-occurrence
Normalization measure	Inclusion index*
Quality metric	G-index**
Cluster algorithm	Simple centers***
Maximum cluster size	4
Minimum cluster size	5
Evolution measure	Inclusion index
Overlapping measure	Inclusion index

* A similarity measure used in SciMAT for normalizing networks, reflecting commonality between items based on shared attributes.
** A measure of scientific productivity, emphasizing highly cited publications, calculated as the highest number of papers with g^2 citations.
*** A clustering method in SciMAT that identifies central items in networks, providing straightforward clustering solutions.

over time [46].

The upper right corner (Quadrant 1, or Q1) defines the "Motor themes", also known as the mainstream. They possess high centrality and density, in other words, these terms are not only commonly cited but also linked to numerous clusters. Moving to the upper left corner (Q2), we find peripheral and developed clusters. Thus, these themes are not as strongly connected to other clusters as the motor themes. As a result, these nodes may belong to subfields or exist as external fields that overlap with the motor themes.

Transitioning to the bottom left corner (Q3), we encounter

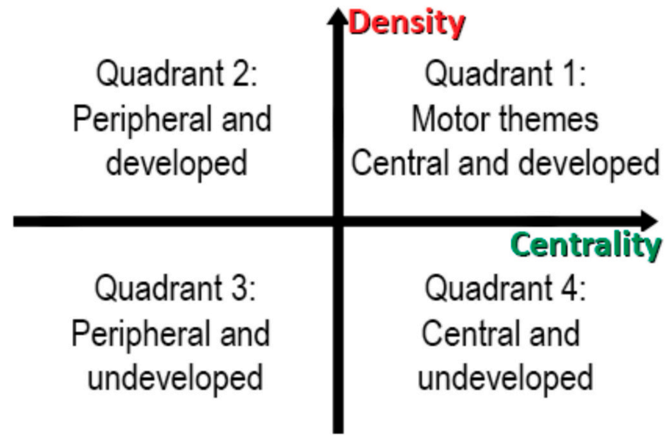


Fig. 2. Strategy diagram or density-centrality plots with Quadrant 1 displaying the motor themes, Quadrant 2 displaying peripheral and developed themes, Quadrant 3 displaying peripheral and underdeveloped themes, and Quadrant 4 displaying central and underdeveloped themes.

peripheral and underdeveloped themes. Therefore, these clusters are not strongly connected to other clusters and lack the emphasis in clusters Q1 and Q2. Hence, Q3 is home to emerging and declining trends, which can become motor themes or disappear over time. As for Q4 (bottom right corner), this section encloses clusters with high centrality and low density, representing themes with strong connections to other clusters but lacking extensive research like the motor themes. Important past trends and promising research fronts can be found here.

Strategy diagrams have been plotted for all periods studied. Further analysis was performed over the period 2021-Present. Although sciMAT requires a quality metric to be chosen (such as the h-index [47]), this was not discussed in the strategy diagrams [41], but it is analyzed regarding the period of 2021–2024. This has been done through thematic subnetworks for the most highly cited terms. Connections between these terms were also evaluated. Other search protocols were also built based on these terms to determine which LRs and RAs have had the largest impact in the field of SWD.

3. Results & discussion

To evaluate the reliability of our dataset, we have conducted three primary tests: Co-author (or co-citation) analysis, geographic examination, and analysis of publication trends. Furthermore, we also compared our findings with similar bibliometric studies already published.

Co-citation analyses have been performed in previous bibliometric studies, ranking authors in terms of number of publications and total number of citations. For example, in mapping the *Desalination* journal, the following rank was obtained: Hilal, N., Ismail, A.F., Matsuura, T., Drioli, E., and Mohammadi, T. (number of citations); Hilal, Drioli, E., N., Ismail, A.F., Fane, A.G., Semiat, R., and Vigneswaran, S. (number of publications) [29]. In biodesalination: Aly Hassan A., Gude, V.G., Jafary, T., Titah, H.S., Kokabian, B. (number of publications) [28]. As for hybrid renewable energy-driven desalination: Belhadj, J., Ng, K·C, Turki, M., Smaoui, M., Shazad, M.W., Roboam, X., Maleki, A., Krichen, L., Hilal, N. (number of publications); Ahmed, F.E., Gude, V.G., Wang, P., Amy, G., Ghaffour, N. (most cited articles through normalized total citations) [33]. Given these previous results in desalination and adjacent fields, it is also expected that these authors have a significant impact on SWD.

Fig. 3, which ranks the total link strength of SWD research authors, shows that Drioli, E., Ghaffour, N., Vigneswaran, S., Ng, K·C, are among the 30 most influential authors. Moreover, Fig. 4 displays the co-citation network for SWD, which highlights four main clusters formed by the authors Lee, S. (Cluster 1), Chung, T.S. (Cluster 2), Ghaffour, N. (Cluster 3), and Drioli, E. (Cluster 4), with eight other smaller clusters, making up

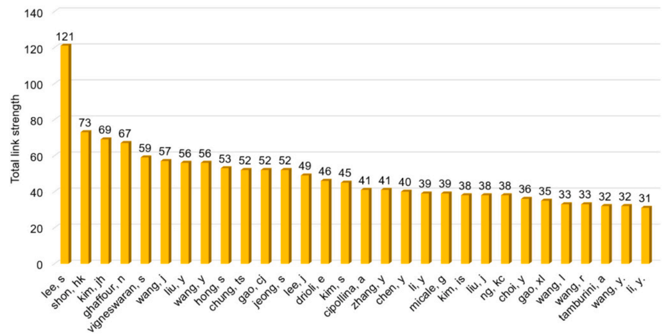


Fig. 3. SWD research authors ranked by total link strength calculated by VOSviewer based on the compiled dataset.

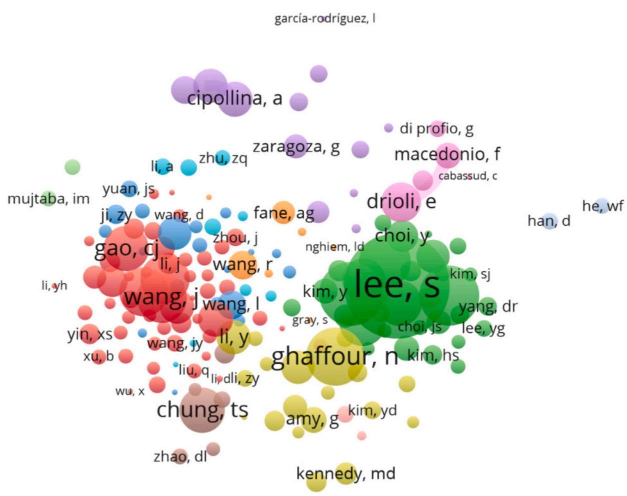


Fig. 4. Co-citation network for SWD for the 200 most influential authors, which formed Clusters 1, 2, 3, and 4.

a total of 12.

As for Cluster 1, Lee, S., Shon, H.K., and Kim, J.H. are the most influential. A common subject in their work is physicochemical and other types of pretreatments for membrane technologies such as SWRO [48–51], FO [52–54], PRO [55–57], and RED [58], Cluster 1 seems to revolve around authors who worked on pretreatments for membrane systems. Regarding Cluster 2, Chung, T.S., Li, X., and Wang, P. are distinguished authors. A common thread among their research is the use of FO as an alternative to RO [59–61], hybrid systems such as FO-MD [62] and FD-PRO [63], and membrane fabrication for FO [64,65]. Therefore, Cluster 2 incorporates works concerning FO.

Meanwhile, Cluster 3 formed around influential authors, primarily Ghaffour, N. and Ng, K.C. A common theme between these authors is the various research fronts they are involved. Although the main subject of this cluster revolves around MD [66,67], membrane filtration [68,69], multieffect systems [70–73], FO [74], PRO [75], and HDH [73,76] are also present. Given the remarkable plethora of subjects, it is important to point out that Ghaffour, N., Li, Y., and Ng, K.C. have obtained such status for being co-authors in various works on desalination. Lastly, Cluster 4 formed around authors like Drioli, E., Macedonio, F., and Curcio, E. These authors frequently collaborate, in desalination process design (simulations and experimental fronts). Their works often encompass the use of exergy, energy, economic, and environmental analyses in hybrid membrane desalination systems (NF-RO, NF-RO-MD, NF-RO-MCr-MD, etc.) [77–80]. ZLD [81,82] and membrane fabrication [83] are also common.

Apart from co-citations, another similar trend regarding the number of publications has been observed in our dataset. Naseer and collaborators have concluded that, from papers published between 1981 and 2020, 94.5 % of all literature regarding energy-efficient low-cost water production was issued between 2000 and 2020 [30]. An analogous increase in desalination research has been found in the general mapping of the *Desalination* journal, in which the total number of citations expanded from 860 in 1997 to 5555 in 2007 [29], with subfields such as biodesalination (an increase of 86.63 % between 2016 and 2019 [28]) and solar desalination (75 % of all publications issued between 2010 and 2021 [31]) having comparable trends. In the present framework, as demonstrated in Fig. 5, there is continuous growth in seawater desalination research. In the present case, 89.02 % of papers have been published between 2010 and 2024. Given the scope of our analysis, which includes papers up to March 2024, it is anticipated that the final data point will exhibit continued expansion over the remainder of the year. This trend mirrors the trajectory observed in the *Desalination* journal, where publication figures escalated from 52 in 2000 to 243 in 2010, culminating in a notable 986 publications by 2020. This points to an increase of approximately 20 times in yearly publications over 20 years of SWD research.

Regarding geographical contributions, previous bibliometric studies in desalination and related fields have identified the most influential countries based on various metrics, including the number of publications, citations, industry collaborations, and citations from patents. These studies encompass: Desalination for energy-efficient and low-cost water: China, the US, South Korea, Australia, and Saudi Arabia (number of publications) [30]. Mapping the *Desalination* journal: the US, China, Germany, India, and France (number of publications); China, the US, India, Iran, and Malaysia (number of citations) [29]. Biodesalination: China, the US, and India (number of publications) [28]. Solar desalination: India, China, Egypt, the US, and Saudi Arabia (number of publications); China, India, the US, Egypt, and Saudi Arabia (number of citations) [31]. Hybrid renewable energy-driven desalination: Iran, the US, China, Egypt, and Saudi Arabia (number of publications); the US, Greece, Singapore, Iran, and Saudi Arabia (number of publications) [33]. Desalination research prioritization: China, the US, India, Saudi Arabia, and Iran (number of publications); China, the US, South Korea, Japan, and Germany (industry collaborations); the US, China, Saudi Arabia, Australia, and South Korea (citations from patents) [32].

Given these results, both China, the US, and South Korea are incredibly competitive in fields adjacent to SWD, especially in the metrics of number of publications and number of citations. Nevertheless, arid countries have been an important hub for desalination research, notably Saudi Arabia, Iran, Egypt, and the United Arab Emirates (UAE). Other reoccurring countries are, in no order, Australia, Spain, India, England, and Germany. Given that SWD is a subfield of desalination and is very similar to the studies shown in Table 1, similar results are expected from its geographical analysis. As expected, Fig. 6 demonstrates that most publications regarding SWD are issued for Chinese (3260), American (1486), South Korean (892), Saudi Arabian (816), and Australian (596) institutions. This trend aligns with the previously mentioned published literature, which, in turn, partially verifies the

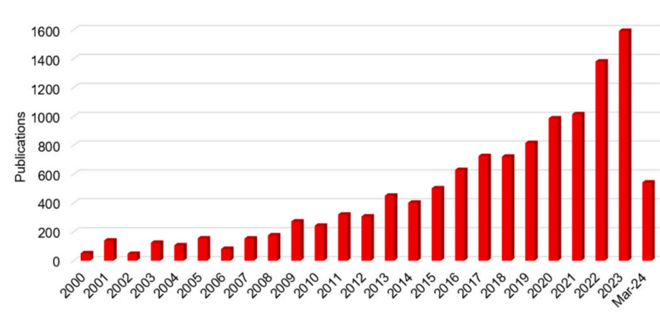


Fig. 5. Growth of SWD publications over time (January 2000 – March 2024).

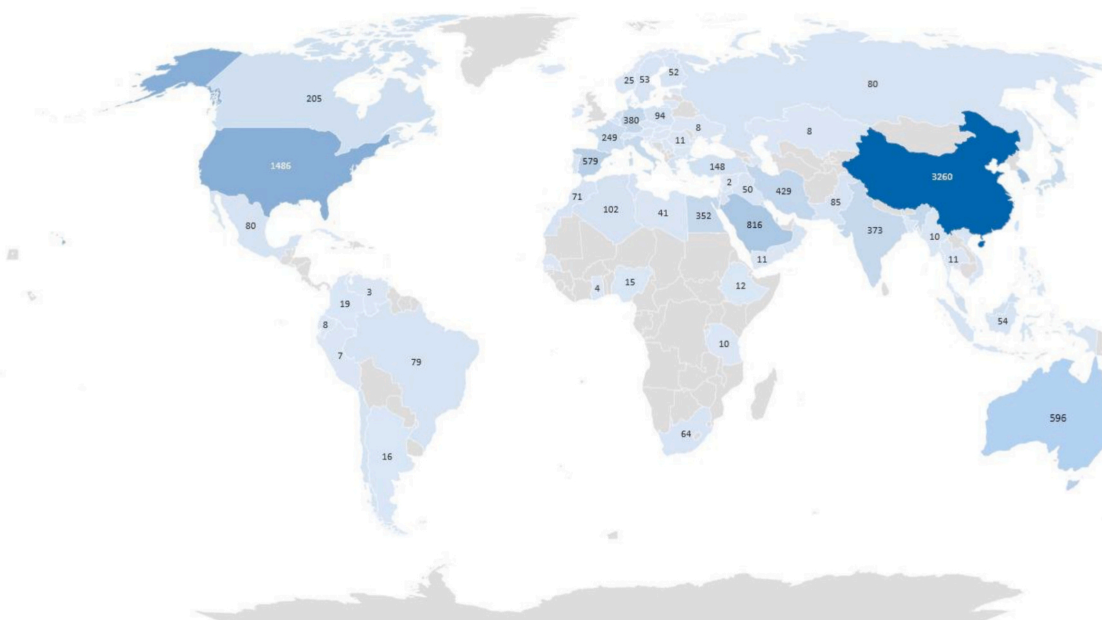


Fig. 6. Geographical distribution of SWD publications based on Web of Science data obtained during the general search.

trustworthiness of our dataset.

Consequently, given that our dataset produced analogous results to the published literature regarding co-citations, geographical impact, and increasing research articles published over time, this dataset can be classified as dependable and representative of the SWD field. Therefore, co-occurrence networks have been plotted to evaluate the most highly

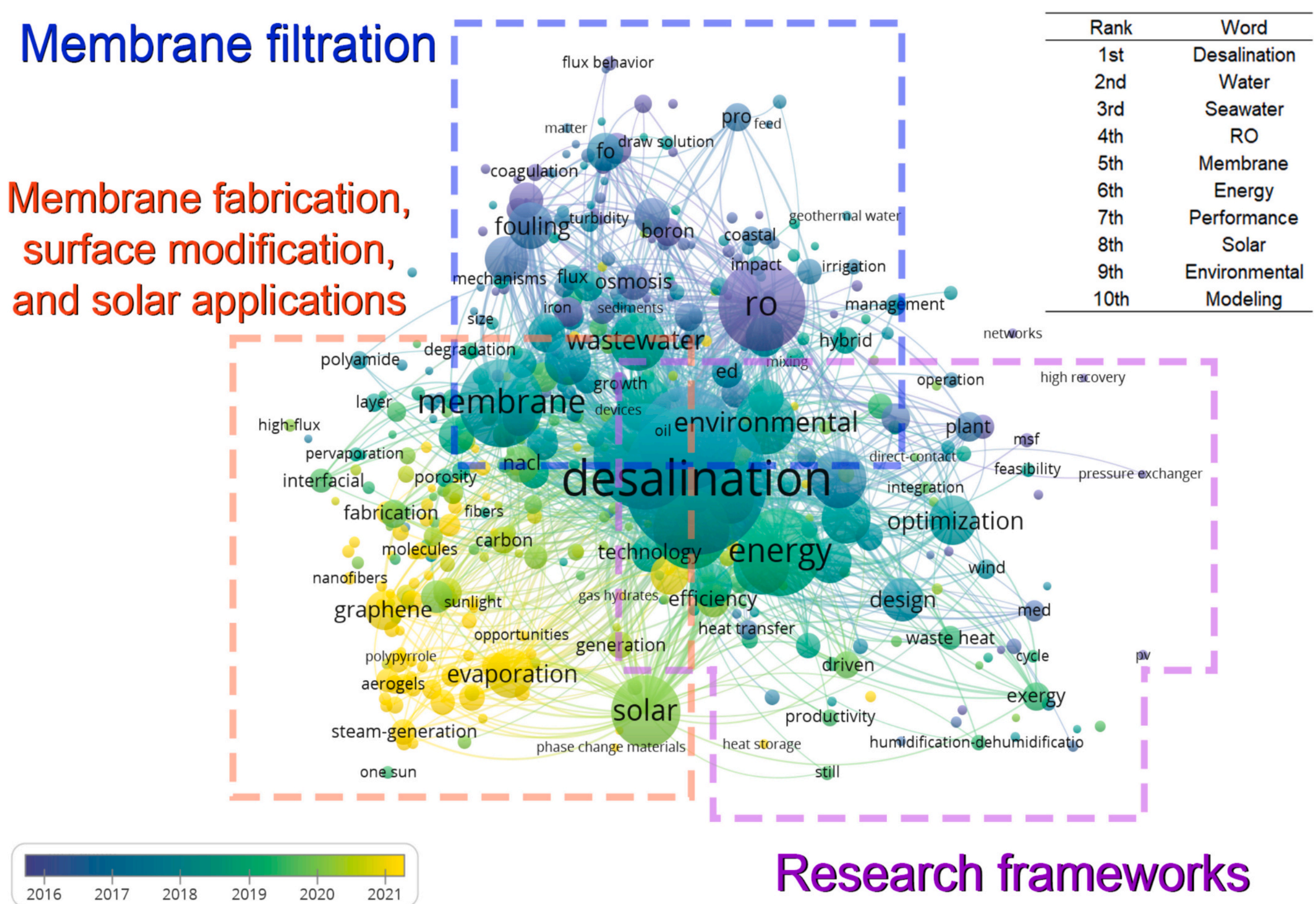


Fig. 7. Chronological and co-occurrence network analysis of article keywords in the compiled dataset. Clusters: Membrane filtration; Membrane fabrication, surface modification, and solar applications; Research frameworks.

cited article keywords and terms in abstracts and titles.

3.1. Co-occurrence networks of high-frequent terms

Co-occurrence networks have been plotted for "article keywords" and "titles and abstracts." Regarding article keywords, Fig. 7 shows their occurrence, connections, and chronological evolution. The original CNs regarding clusters, density, and chronology are available in the Supplementary Material published along with this paper.

The co-occurrence network for article keywords has six clusters (three main clusters and three smaller sub-clusters). Cluster 1 (blue) encompasses membrane filtration (i.e., UF, fouling, and pretreatments, NF, PRO, FO, and concentration polarization). Cluster 2 (orange) shows membrane fabrication and surface modification terms (i.e., surface, morphology, electrospinning, and graphene) as well as solar-related applications (evaporation, light absorption, and steam generation). Lastly, Cluster 3 (purple) has a range of research frameworks related to energy, economics, modeling, and optimization.

As expected, Fig. 7 reveals that the top three most occurring keywords are "desalination", "water", and "seawater". Nevertheless, the following keywords are noteworthy: "RO," "membrane", "energy", "performance", and "solar". In the present analysis, the keyword "performance" is subjective because it is presented out of context. Still, the presence of the "RO," "membrane", "energy", and "solar" point to more concrete technologies. In addition, Fig. 7 also demonstrates that these keywords are highly connected, however, as depicted, there is a shifting interest in research topics regarding SWD, with "RO" dating to the mid-2010s, "membrane" and "energy" to the late 2010s, and "solar" to the beginning of the 2020s. Based on the keywords "RO", "membrane", and "solar".

The keyword "RO", which is one of the research hotspots, is connected to most of the SWD network. Still, from 2015 to 2017, "RO" is connected to common desalination terms and processes ("UF", "NF", "operation", "plant", "pressure exchanger", "coagulation", and "fouling"). From 2017 to 2019, computational terms ("optimization" and "modeling"), other membrane technologies ("FO" and "PRO"), and membrane fabrication and modification ("surface", "interfacial", "membrane", and "polyamide") terms are present. Moreover, in this period, a keyword connected to "RO", "membrane", and "energy" is "recovery". This, coupled with other keywords such as "pressure exchanger" and "waste heat", indicate that energy recovery systems (ERSs) in desalination processes were widely studied.

More recently (2021–2024), terms regarding "graphene" and "solar" have been prominent. The keyword "membrane" shows the same behavior up to 2019, with the most recent literature citing "graphene", "evaporation", and "steam-generation".

The keyword "energy" exhibits a similar trend, associating with terms from the late 2010s and early 2020s. From 2015 to 2017, it is connected to common desalination terms and processes ("fouling", "NF", "concentration polarization", "systems", and "plant"). From 2017 to 2019, branching terms regarding computation ("modeling" and "optimization"), "economics", and "environmental" were researched. As for 2019 to 2021, terms concerning membrane fabrication and surface modification ("fabrication" and "graphene"). Other terms, such as "light absorption", "steam generation", "evaporation", and "evaporators" were present from 2021 to 2024. As for "solar", its connections date to the late 2010s and beginning of the 2020s, with the most recent literature (2021–2024) mentioning "graphene", "light absorption", "steam generation", "evaporation", and "evaporators".

Consequently, given these observations, there is a clear shift in SWD research regarding article keywords. Chronologically, from 2015 to 2016, research topics were more process-focused, evaluating metrics and phenomena that have a wider impact on process design, such as fouling and membrane filtration, especially in RO. From 2017 to 2019, research in seawater desalination started focusing on different sides of process design, on economics and environmental impacts. The use of modeling and optimization also seems to grow in this period. As for 2019 to 2021, membrane fabrication and surface modification terms are widely used. More recently (2021–2024), various terms regarding solar energy are prominent. In a general sense, given the present analysis, there seems to be a shift from process design and technologies that employ utilities (i.e., RO and membrane filtration) to membrane fabrication and renewable energy sources, especially solar energy.

Similar trends are also expected in the "titles and abstracts" co-occurrence network, which is presented in Fig. 8. The original CNs regarding clusters, density, and chronology are available in the Supplementary Material published along with this paper. The "titles and abstracts" co-occurrence network has four clusters. In Fig. 8, Cluster 1 (purple) encompasses process design and research frameworks, which involve terms such as "plant", "environmental", "energy", and "case study", desalination processes like "MED" and "HDH", and blue energy terms akin to "PRO" and "RED". Cluster 2 (cyan) describes membrane-related processes, with most terms connected to membrane fabrication and surface modification (i.e., "contact angle", "spectroscopy", "thin film", and "diffusion"). Other terms related to membrane usage are also present ("FO", "MD", and "nanofiltration"). Cluster 3 (blue) includes terms that are correlated with membrane filtration and fouling ("fouling", "pretreatment", "flux decline", "chemical cleaning", "ultrafiltration", and "turbidity"). Lastly, Cluster 4 (orange) aggregates terms linked to solar energy, especially solar evaporation, with keywords like "solar energy", "light absorption", "light", and "evaporation".

Furthermore, based on Fig. 8, the most occurring keywords in abstracts and titles are "membrane", "solar", "plant", "evaporation", and "surface". Moreover, an analogous pattern to the article keywords emerges, with "plant" being used mostly in the mid-2010s, "membrane" and "surface" in the late 2010s, and "solar" and "evaporation" at the beginning of the 2020s.

In addition, the keyword "plant" is connected to terms like "seawater desalination plant", and "case study" within Cluster 1 (mostly regarding process design), as well as some connections to Cluster 3 in the mid-2010s (i.e., "fouling" and "pretreatment"). In the late 2010s, different research frameworks in Cluster 1 started to appear (such as "environmental", "exergy", "management", and "electricity"). In terms of the keyword "membrane", most of the late 2010s connections contain membrane fabrication terms ("polyamide", "modification", and "polymeric") and separation processes ("FO", "MD", and "NF"). Moreover, the keywords "membrane" and "surface" are highly connected through common terms ("morphology", "spectroscopy", "thin film", "hydrophobicity", and "group" to name a few), in Cluster 2. Finally, the keywords 'solar' and 'evaporation' exhibit most of their connections in the late 2010s and early 2020s. These two keywords are highly connected, particularly because of solar evaporation systems, thus, keywords such as "light", "absorption", "solar energy", and "low thermal conductivity".

Consequently, the same shift in SWD research observed in Fig. 7 is also present in Fig. 8. Therefore, there is also a change from process design in the mid-2010s to different research frameworks, such as environmental studies and exergy analyses, in the late 2010s. Research fronts regarding membrane fabrication and surface modification are also popular in this period. The early 2020s have solar energy and solar evaporation as widely studied topics. To further back this change in SWD research, strategy diagrams have been plotted for the periods of 2000–2005, 2006–2010, 2011–2015, 2016–2020, and 2021-Present.

3.2. Strategy diagrams

The overlapping map for the network is presented in Fig. 9, meanwhile, the strategy diagrams for the periods 2000–2005, 2006–2010, 2011–2015, 2016–2020, and 2021-Present were plotted in Fig. 10, respectively. All thematic subnetworks referenced in the strategy diagrams can be found in the Supplementary Material. As shown in Fig. 9, of most of the keywords were retained. For the sake of brevity, only the motor themes will be discussed in terms of TSs in the following manner:

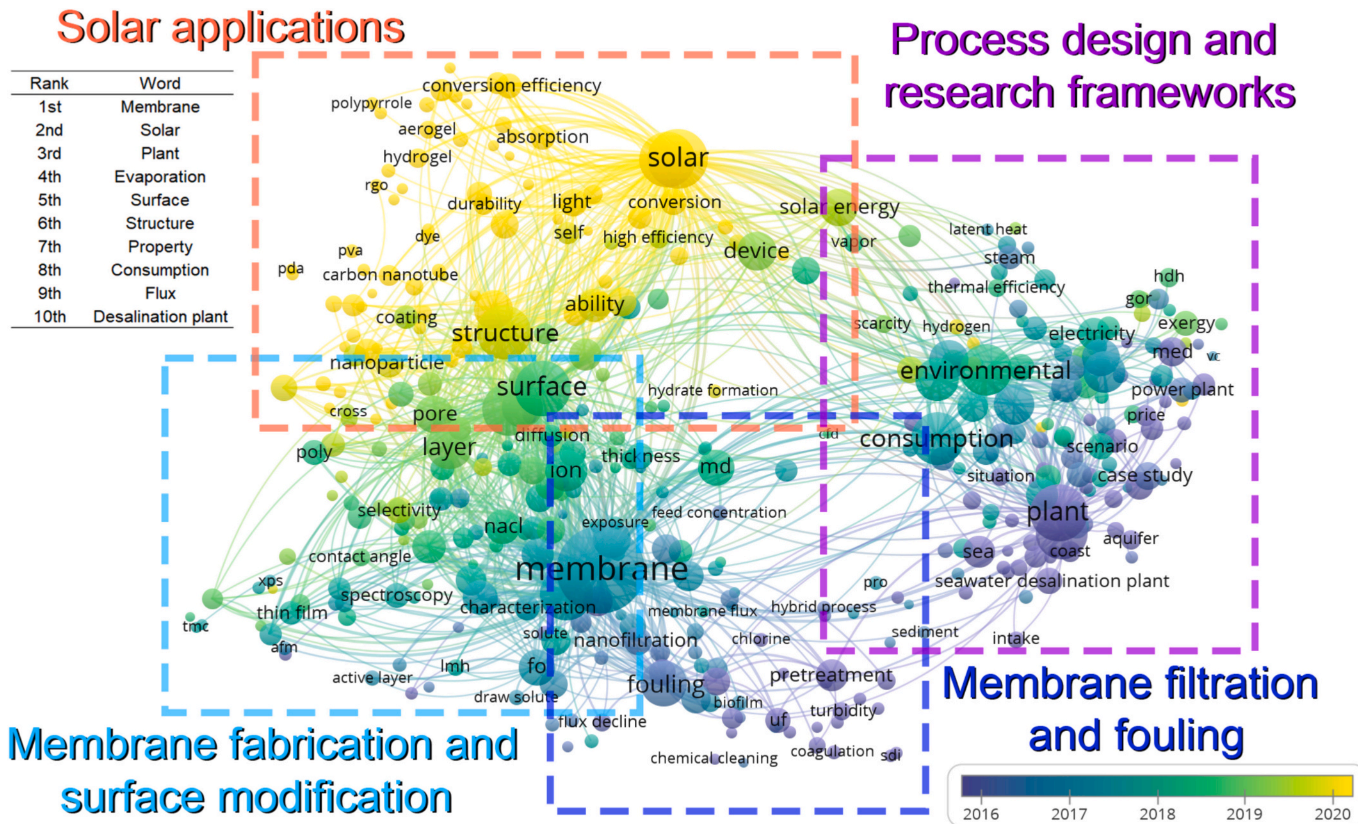


Fig. 8. Chronological and co-occurrence network analysis of titles and abstract in the compiled dataset. Clusters: Solar applications; Process design and research frameworks; Membrane fabrication and surface modification; Membrane filtration and fouling.

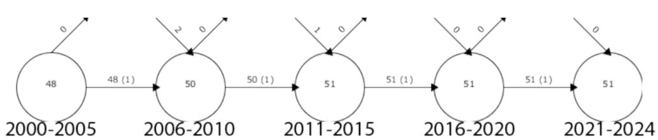


Fig. 9. Overlapping map (2000–2024) demonstrating how keywords moved between periods.

Term (subnetwork connection one, subnetwork connection two, and so on). If terms are followed by a "-g", the term is used in a general sense. In the case of specific uses, additional context is provided.

For the period of 2000–2005, the motor themes were SWD (RO, water-g, membrane-g, energy-g), environmental (economics, power-g, solar, clean/potable/freshwater), pretreatments (fouling, MF, UF, and hollow fiber membranes), and thermal energy (modeling and optimization, MED, MSF, and evaporation-g). As for low-density and low-centrality terms, wastewater, and ion exchange works have been scarcely cited and researched in SWD. However, in the case of wastewater, it is important to point out that the present dataset is biased towards seawater research, therefore these trends in desalination and does not reflect the state of wastewater research at the time.

From 2006 to 2010, the motor themes were SWD (RO, water-g, membrane-g, modeling, and optimization), energy-g (economics, environmental, solar, and power-g), and UF (pretreatments, fouling, NF, and MF). As for peripheral and developed themes, the term polymers-g appears, especially due to the use of polymeric membranes. Since this term has applications in other areas outside SWD, it has been thoroughly researched, nevertheless, it has low centrality for not being highly connected to other terms in the field. Another new term is MD, which has both low density and centrality. Additionally, both terms for wastewater and ion exchange increased in density and centrality, which indicates that more papers in these fields are being published and cited, respectively.

Between 2011 and 2015, the motor themes were SWD (RO, water-g, energy-g, and membrane-g), fouling (NF, UF, polymers-g, and pretreatments), FO (power-g, wastewater, PRO, and hollow fiber membranes), and solar (economics, wind, HDH, modeling, and optimization). Absorption, a highly researched technology, has had a few applications in SWD, nonetheless, it was not connected to many terms (low centrality). In addition, environmental aspects were highly connected to the network, still, little work was performed on this front. Furthermore, works in hydrophobic membranes, MED, and ED started surfacing.

The period of 2016–2020 had SWD (RO, energy-g, water-g, and membrane-g), power-g (economics, environmental, PRO, modeling, and optimization), fouling (NF, UF, polymers-g, and pretreatments), and MD (crystallization, hollow fiber membranes, PVDF membranes, and hydrophobic membranes) as motor themes. Additionally, there was an increase in works involving the term "solar", however, this term was less cited. Furthermore, the term "exergy" appears along with capacitive deionization. Even though the term "absorption" displayed higher values of density and centrality in previous periods, from 2016 to 2020 a decrease in both has been seen.

As for the most recent period (2021–2024), the motor themes are SWD (water-g, energy-g, membrane-g, solar), RO (fouling, NF, environmental, modeling, and optimization), evaporation-g (thermal energy, absorption, graphene, and clean/potable/freshwater), and MD (wastewater, HDO membrane, PVDF membrane, and hollow fiber membrane). Low-density and low-centrality terms are ED, MF, and adsorption, meanwhile, power-g highlights low density but high centrality. In a general sense, from 2000 to 2024, similar terms tend to be the motor themes. Naturally, terms such as SWD, water-g, and clean/potable/freshwater are common in all strategy diagrams given the

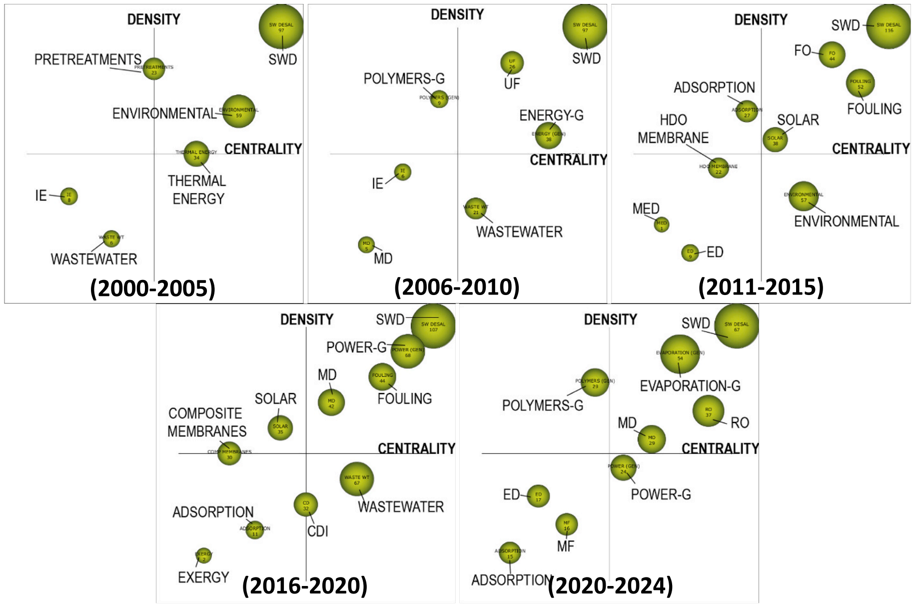


Fig. 10. Strategic diagrams for the periods of 2000–2005, 2006–2010, 2011–2015, 2016–2020, and 2021-Present.

innate bias of the dataset, nevertheless, the remaining motor themes and thematic subnetworks detail how seawater desalination research has evolved.

Based on the SDs (Fig. 10) and on the TSs (Supplementary Material), Fig. 11 has been charted and color-coded for better understanding of motor-theme continuity. As expected, among the most cited keywords in the dataset are SWD and water-g. However, RO, membrane-g, and energy-g have also been present from the first period, often associated with SWD. Furthermore, given that keywords associated with membrane filtration have had a prominent role (RO in five periods, membrane-g in five periods, fouling in five periods, UF in four periods, NF in four periods, pretreatments in four periods, and hollow fiber membranes in all periods). This is expected, as in Fig. 7 and Fig. 8.

In terms of research frameworks, studies focused on environmental and economic aspects have been prominent in four out of the five periods analyzed. Although "power-g" and "energy-g" are broad terms, they, along with "modeling" and "optimization," have been widely utilized. Notably, the keyword "solar" has emerged as a central term in SWD from 2021 to 2024. Additionally, other desalination technologies such as MD, crystallization, and evaporation-g have surfaced in recent publications and may become key themes. Derived from the terms presented, ten refined search prompts were elaborated (Table 5 and Table 6).

Even though the articles presented were the results of the refined search prompts, in some cases, their contents do not correspond to the keyword. Furthermore, as demonstrated, some articles result from multiple prompts. Thus, to discuss them coherently, they have been separated into eight groups: General desalination; MF, UF, and NF pretreatments; Reverse osmosis; Forward osmosis; Membrane distillation; Solar desalination; Environmental, economic, and social impacts;

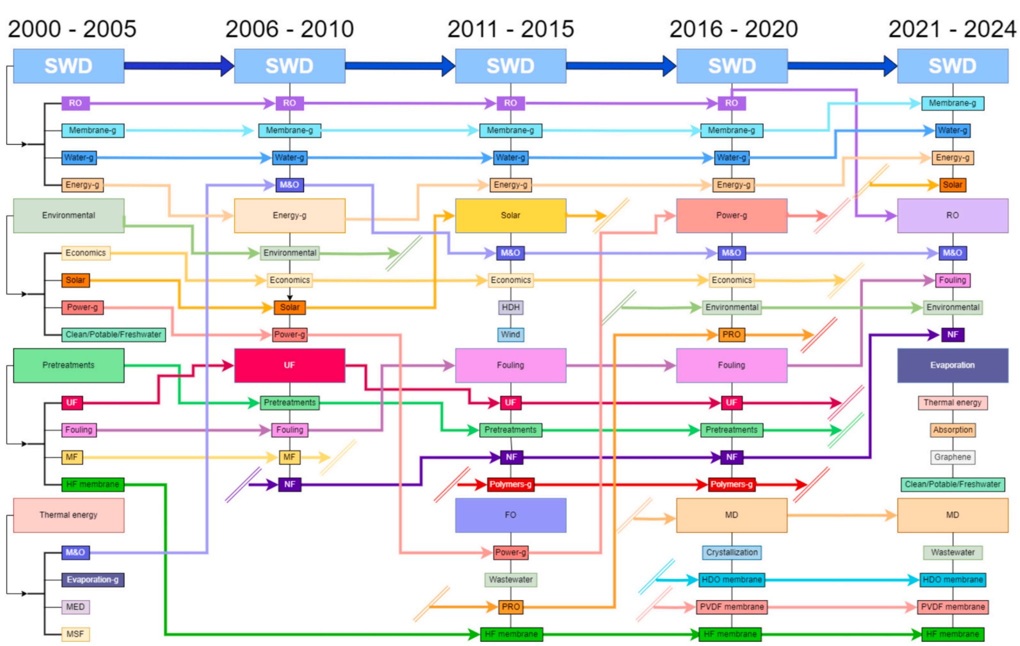


Fig. 11. Thematic evolution diagram of motor themes from January 2000 to March 2024. Keywords with lasting impact: Energy; Solar; RO; Modeling and optimization; Membrane distillation; Environmental; Economics; Fouling; NF; UF.

Table 5
Refined search protocols utilized for Literature Reviews in this study.

		Search prompt*	Top 5 LRs
Keyword	Energy	desalination AND seawater AND energy AND review	[84–88]
	Solar	desalination AND seawater AND solar AND review	[26,89–92]
	RO	desalination AND seawater AND "reverse osmosis" AND review	[12,90,93–95]
	M&O	desalination AND seawater AND modeling AND review	[13,93,96–98]
		desalination AND seawater AND optimization AND review	[99–103]
	MD	desalination AND seawater AND "membrane distillation" AND review	[77,104–107]
	Environmental	desalination AND seawater AND environmental AND review	[16,108–111]
	Economics	desalination AND seawater AND economic AND review	[86,112–115]
	Fouling	desalination AND seawater AND fouling AND review	[84,87,104,105,116]
	NF	desalination AND seawater AND nanofiltration AND review	[84,87,117–119]
	UF	desalination AND seawater AND ultrafiltration AND review	[120–122]

* Search engine: WOS; Period: January 2000 to March 2024; Types of documents: Literature Reviews; Sorted by citations.

Table 6
Refined search protocols utilized for Research Articles in this study.

		Search prompt*	Top 5 RAs
Keyword	Energy	desalination AND seawater AND energy NOT review	[80,123–126]
	Solar	desalination AND seawater AND solar NOT review	[124,125,127–129]
	RO	desalination AND seawater AND "reverse osmosis" NOT review	[80,130–132]
	M&O	desalination AND seawater AND modeling NOT review	[59,133–136]
		desalination AND seawater AND optimization NOT review	[135,137–140]
	MD	desalination AND seawater AND "membrane distillation" NOT review	[80,141–144]
	Environmental	desalination AND seawater AND environmental NOT review	[17,145–148]
	Economics	desalination AND seawater AND economic NOT review	[79,149–152]
	Fouling	desalination AND seawater AND fouling NOT review	[59,131,153–155]
	NF	desalination AND seawater AND nanofiltration NOT review	[130,153,156–158]
	UF	desalination AND seawater AND ultrafiltration NOT review	[159–163]

* Search engine: WOS; Period: January 2000 to March 2024; Types of documents: Research Articles; Sorted by citations.

Blue energy, "blue carbon", ZLD, and membrane-less processes.

3.3. General desalination

Research on seawater desalination often emphasizes membrane filtration processes and thermal desalination, which is reflected in the findings from the refined search prompts. Membrane filtration is categorized into four main types: Microfiltration (MF, 100 nm to 2 μm of pore diameter in low-pressure-driven filtration), Ultrafiltration (UF, 2–100 nm), Nanofiltration (NF, 0.5–2 nm), and RO (<1 nm) [164–166]. Through the years, RO has been a predominant desalination technology [90,96,111], though alternative membrane methods such as Forward Osmosis (FO) are also being explored [94]. Occasionally, MF, UF, and NF have been employed as pretreatments [153,160].

Membrane processes can be integrated with thermal technologies, forming the basis for Membrane Distillation (MD) [104]. Each desalination technology has distinct environmental, economic, and social advantages and disadvantages. RO is heavily reliant on external energy sources [147]. Consequently, there has been considerable research into combining RO with environmentally friendly energy, solar technologies, and hybrid systems [79,91,112]. Furthermore, some desalination setups do not use membrane filtration, just solar absorption [155].

Given the nature of membrane filtration, one of the biggest challenges regards fouling and pore blocking in general [105,118,119]. Fouling is the deposition of matter on the membrane's surface or its pores, which causes flux reduction over time in full-scale SWD plants [167]. Matter deposition inside pores is mostly prevalent in MF, UF, and NF, nonetheless, RO membranes are considered fundamentally non-porous, thus, surface deposition is only considered [84]. Counter-fouling techniques have been employed in diverse ways, with the most common approaches being through surface modification, active antifouling, and passive antifouling [87]. Other fouling-managing techniques come from optimizing process conditions such as transmembrane pressure [168], stream temperatures, feed and permeate flow rates, and concentration feed [169]. Further optimization can also be done through mathematical modeling [102], still, dependable thermophysical data and regressions are needed for accurate simulations, such as the correlations reviewed in [93].

3.3.1. MF, UF, and NF as pretreatments

In the context of SWD, MF and UF membranes can be used as a pretreatment before desalination, filtering algae and microalgae. Lab-scale experiments in submerged MF and UF membranes (10 kDa, 300 kDa, and 0.2 μm) demonstrated that the MF membrane with a 0.2 μm pore diameter reached a permeate flux of 29 L/(h.m^2) under 0.3 bar of transmembrane pressure after 180 min of filtration. This treatment reduced the microalgae, total suspended solids, and turbidity by 99 %, 87 %, and 98 %, respectively. Furthermore, fouling occurred due to cake formation, with a flux reduction from roughly 120 to 29 L/(h.m^2) at 20 °C [160]. In this context, a challenge to MF and UF is biofouling, moreover, additional tests also reveal that shear increases biofouling drastically through pore blocking and tighter-porosity cake deposits for MF and UF fluxes at room temperature (21 ± 1 °C) and pressures of 69 kPa (10 psi) for MF and 210 kPa (30 psi) for UF, respectively [161].

Attempts to address this issue include membrane fabrication by blending silver-containing surface-modifying macromolecules. Silver cations in the form of silver lactate and silver citrate can be blended into a PVDF solution, which enriches the surface silver content and provides antibacterial ability to the membrane. UF tests performed showed that such an addition not only improved its effects against *E. coli* but also displayed less flux reduction when compared to the non-modified PVDF [163].

NF treatments have many functions such as the removal of pesticides, viruses and bacteria, nitrates, and arsenic. In SWD, the removal of hardness and natural organic material is desired [153]. Hardness removal consists of the separation of Mg^{2+} and Ca^{2+}, which causes scaling in processes such as SWRO and MSF [117]. NF membranes can be improved in many ways to suit the seawater feed composition. One example is the use of graphene oxide for enhancing heavy metal removal. By modifying polycarbonate membranes, the authors not only improved the removal of Mg^{2+}, but also improved the removal of Pb^{2+},

Ni^{2+}, Cd^{2+}, and Zn^{2+}. Experimental tests revealed that a high pure water permeability of 5.01 L m^{-2} h^{-1} bar^{-1} was achieved [157]. Even though NF pretreatments can reduce hardness before desalination, NF membranes impose multiple capital and operating costs. Moreover, fouling by organic and inorganic materials can degrade their performance over time. Thus, its use in desalination needs to go in tandem with feasible, cost-effective cleaning and performance restoration procedures [118].

As presented, MF, UF, and NF technologies have potential as pretreatments in SWD due to algae, microalgae, and hardness removal, nonetheless, biofouling and fouling are difficulties to be overcome.

3.3.2. Reverse osmosis

Being the primary source of desalinated water worldwide [11], RO has been widely reviewed over the years in terms of process design and large-scale systems [12,13], fouling management [119,120], and membrane materials [116]. Reverse osmosis involves two driving forces: the transmembrane pressure and the concentration gradient. When two solutions of varying concentrations encounter a membrane, the concentration disparity generates an osmotic pressure, prompting solvent molecules from the lower-concentration solution to diffuse through the membrane into the higher-concentration solution. However, if the transmembrane pressure exceeds the osmotic pressure, the process reverses, leading to concentration shifts in the opposite direction for the two streams.

Large-scale RO desalination process design follows six main stages: water abstraction (or water intake), pretreatment, pumping system design, membrane separation unit design, energy recovery systems, post-treatment, and control system design. Water intake can be conducted through coastal and beach wells or open-water intakes, with wells providing water with less turbidity, biofouling, and total dissolved solids. As for pretreatments, as already discussed, MF, UF, and NF modules can be used. Other pretreatments also involve pH adjustment and the addition of antiscalants and antifoulants. The pumping system depends on the geographical location of the desalination plant and is necessary for water transport and pressurizing the feed. The membrane separation unit is at the heart of the process, with RO modules achieving salt rejections between 98 and 99 % depending on the process conditions. Energy recovery systems are necessary due to the high energy consumption required for RO. Given that the final product of RO is high-purity water, post-treatment is necessary to comply with drinking water standards, therefore, re-mineralization, re-hardening, and disinfection through chlorination are conducted. Process control strategies are then implemented to ensure the process runs accordingly despite disturbances in feed quality [12].

In the case of SWRO, particulates, hydrocarbons from oils, algal blooms, and other microorganisms function as contaminants. While microfauna and flora can be dealt with using MF, UF, NF pretreatments and additives, boron (in the form of boric acid) is still a challenging contaminant due to its effects on reproductive and developmental effects [84]. Attempts to optimize boron removal in SWRO systems have been prominent over the years [137], with current boron rejections achieving $>$90 % for water temperatures below 18 °C and $<$ 80 % for temperatures above 28 °C. Consequently, seasonal changes in water temperature influence boron rejection [170]. Hence, boron removal holds significance in the research and development of large-scale seawater desalination.

In terms of the process, the fouling of RO membranes is a common issue. Primarily caused by matter deposition, it leads to concentration polarization, forming a gel-like layer with varied effects depending on surface groups. The primary outcome is a gradual reduction in flux over time. RO systems can suffer biofouling, organic fouling, colloidal fouling, and inorganic scaling [119]. In this scenario, biofouling in the form of biological growth (accumulation of microbial cells) can create biofilms, organic fouling as in carbon-based molecules can directly interact with the membrane's surface by adherence. Moreover, colloids can lead to cake formation, and inorganic scaling, such as ionic and non-soluble compounds, can cause deposition and lower water recovery. Calcium carbonate is particularly challenging due to its low solubility [84]. Fouling management is often done case-by-case, with further study needed.

Even so, membrane fabrication and surface modifications typically target fouling management, with nanoparticles, carbon nanotubes, graphene, and zwitterion being the most widely studied materials for fouling control in RO membranes from 2007 to 2017 [119]. Other extensively studied membranes include polymeric membranes, zeolite thin-film nanocomposite membranes, and biomimetic membranes [116]. The fields of membrane fabrication and surface modifications in desalination are extensive and continually evolving areas of research. However, the scope of this article will not encompass these topics.

Given the broad scope of RO, hurdles like fouling (biofouling, organic fouling, colloidal fouling, and inorganic scaling), contaminants such as boron, and low-solubility compounds such as calcium carbonate can increase fixed-capital investments, operating costs, and shorten the lifespan of RO membranes. Broader challenges of SWRO and SWD are discussed in Section 3.3.6.

3.3.3. Forward osmosis

FO is often described as an alternative to RO. In this process, two solutions meet a semipermeable membrane, one of these solutions is the feed, meanwhile, the other is called a draw solution (DS). Given that the draw solution has a higher concentration than the feed, an osmotic pressure difference emerges across the membrane, which draws water from the feed solution to the DS. Consequently, there is no need for external energy in the form of work. This is the reason FO is mentioned in research works, in comparison to RO. Nevertheless, FO has its only set of shortcomings, for example, it has been shown that, regardless of the draw solution, FO cannot reduce the required minimum energy for desalination. Moreover, a hybrid system like FO-RO cannot consume less energy than a standalone RO system. Still, one of the advantages FO has is its lower fouling predisposition, along with its higher fouling reversibility when compared to RO [94].

Forward osmosis research has many fronts, such as changes in the draw solution [130], membrane fabrication [59], and draw solutes [162]. For instance, the effects of ammonia–carbon dioxide draw concentrations in FO have been studied. However, as detailed, the experimental water fluxes obtained were far lower than anticipated based on pure water permeability data. This phenomenon was attributed to concentration polarization, characterized by the buildup of material on the feed side, exerting electric forces influenced by the membrane surface. Even though this is the case, their FO system has shown reasonably high-water flux for this type of desalination, with NaCl rejections reaching 99.45 % [130].

As for membrane fabrication, cellulose acetate has been employed to minimize concentration polarization in constructed membranes with ultra-thin selective layers. As a result, the interactions between the bottom interface of the polymer and the casting substrate can manipulate the membrane's surface affinities, which allowed the authors to change its hydrophobicity. Furthermore, after devising their membrane construction methods, even lower internal concentration polarization was obtained [59].

Other interesting developments in FO regard the use of super hydrophilic nanoparticles in a FO-UF system. By synthesizing magnetic nanoparticles with super hydrophilic coatings, these particles can be dissolved in a draw solution, which was used it in a lab-scale FO module. Moreover, these nanoparticles can be separated from the draw solution through UF, which not only regenerates the DS, but also produces clean water. Even though FO-UF is a promising technique, the agglomeration of the magnetic nanoparticles can become a challenge in further cycles, however, this can be solved by magnetic separation followed by ultrasonication [162].

Even though FO is considered an alternative to RO, many challenges still need to be addressed, especially regarding DS regeneration and scalability, however, in some cases, FO is not only feasible but can also be preferable.

3.3.4. Membrane distillation

MD has been thoroughly reviewed and discussed [77,104,106,114], especially as an addition to RO systems to increase water recovery [141]. Four membrane configurations are discussed in MD: Direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD). DCMD is the simplest form of MD, and it consists of two counter-current streams coming into contact through a hydrophobic membrane. Given the pressure and temperature differences, water vapor is formed in the feed inlet side, which passes through the membrane and is condensed in the other side. One of the downsides of DCMD is the heat loss through conduction, still, it is also able to produce high flux [104,114]. As for AGMD, it comprises most of the same setup, however, an air gap is introduced between the membrane and the coolant. Although heat loss through conduction is reduced, this happens with the addition of mass transfer resistance, which reduces the water flux obtained [104,114].

In the case of SGMD, the air gap is now substituted by a moving gas stream, which sweeps through the membrane's surface. This modification not only partially retains the advantage of AGMD (reduced heat loss through conduction), but also increases the mass coefficient. This setup is typically used for the removal of volatile substances. Lastly, VMD uses a vacuum at the permeate side instead, which, in turn, makes the heat lost by conduction negligible. The vapor is then condensed and processed further [104,114]. VMD has been used in RO brines with little to no effect from temperature or concentration polarization, still, scaling due to calcium precipitation was observed, on the membrane's surface, and did not cover the pores [141].

Some challenges faced by MD systems are energy efficiency limitations, impact of membrane properties, and economic viability. Regarding energy efficiency, given that this process depends on water evaporation, it also requires more energy than RO, which also makes it less energetically efficient. As for the impact of membrane properties, its surface plays a key role in wettability and fouling. Conventionally, MD membranes are hydrophobic (typically made of PVDF or polytetrafluoroethylene—PTFE), nevertheless, surface charge and hydrophilicity determine fouling, scaling, and wetting behavior. Apart from hydrophobic behavior, superhydrophibic, omniphobic, and hydrophilic changes to the surface can increase MD performance [107]. Superhydrophobic membranes have been used in DCMD though the addition of carbon nanotubes to flat-sheet electrospun fluoride-co-hexafluoropropylene membranes. The incorporation of 5 wt% of carbon nanotubes not only increased the contact angle to 158.5°, but also increased flux (from 18 to 18.5 to 24–29.5 L m^{-2} h^{-1})) while keeping a high salt rejection (>99.99 % for 35 and 70 g/L NaCl solutions) [143]. Furthermore, also in DCMD, omniphobic PTFE membranes have been shown to perform better than conventional hydrophobic PTFE membranes in terms of the surfactant sodium dodecyl sulfate due to wetting resistance. Due to hydrophobicity, surfactant molecules interact with the membranes surface and inhibit its nature, which causes a decrease in salt rejection, however, in the case of omniphobicity, surfactant molecules are not able to do so, thus, there are no observable effects on flux or salt rejection [142].

As with other membrane processes, fouling and scaling are also present in MD. Three main types of MD fouling exits: Inorganic, organic, and biological, with their composition depending on the feed. In desalination, inorganic fouling comprises mostly of ionic salts such as $CaCO_3$, $CaSO_4$, Na_2SO_4, NaCl, $MgCl_2$, Na_2CO_3, and $CaCl_2$. Meanwhile, in desalination, organic fouling consists of natural organic matter deposition such as humic substances and carbohydrates. As for biological fouling (or biofouling), bacteria, fungi, and sludge (in membrane distillation bioreactors) can be present [105,171]. As mentioned in Section 3.3.1, ions related to hardness (Ca^{2+} and Mg^{2+}) can be dealt with through NF pretreatments, while microalgae and other organisms can be removed through MF and UF membranes. Regarding scaling, calcium carbonate is also present, as in RO, due to its low solubility. Antiscalants are employed, with the most effective against $CaCO_3$ and $CaSO_4$ being GHR (pH between 1.8 and 2), GLF (pH between 9.8 and 10.2), and GSI (pH between 9.8 and 10.2) [105].

Regarding economic viability, DCMD has been compared economically to MED, MSF, and RO. By analyzing and optimizing the process in terms of energy and exergy, the cost of desalinated water through DCMD was estimated to be 1.17 USD/m^3 (in 2008), which was comparable to MED and MSF prices (1.00 and 1.40 USD/m^3, respectively, in 2008). Nevertheless, when compared to RO (0.50 USD/m^3 in 2008), the authors concluded that decreasing the cost of DCMD through low-grade thermal energy sources, its price can approach RO's [80]. Even though this may still be the case, implementations of carbon taxes in desalination technologies may still play a role. By taking a reference of a 30,000 m^3/day, the authors calculated that if the Australian government implemented a 23-dollar tax per ton of carbon emitted, depending on steam prices and electrical efficiency, at times MD can produce lower than MED and RO [151].

As demonstrated, MD is also affected by fouling as MF, UF, NF, and RO, however, if such filtration types are used as pretreatments, biofouling and inorganic fouling can be avoided. Scaling, which was also present in RO, can be dealt with by using antiscalants. SWD through MD alone is feasible process-wise, however, economic viability depends on steam price, electrical efficiency, and economic factors as carbon credits, which can, at times, produce desalinated water with fewer costs.

3.3.5. Solar desalination

Coupling desalination systems with environmentally friendly energy production has been broadly proposed in terms of solar energy [26,89,92,112,113], geothermal energy [26,89,92], wind energy [89,92,112,113], wave energy [92,113], and blue energy [92]. Considering the scope and the prominence of solar energy in the bibliometric analysis, we will focus exclusively on discussing solar energy. According to the articles found through the refined search prompts, two main categories of solar desalination are present: hybrid solar desalination and solar evaporation systems.

Among the hybrid solar desalination systems, RO, MD, and HDH applications have been studied. As with general desalination, RO also has been widely employed in this context, in power and thermal energy sources such as photovoltaic panels RO (PV-RO), solar collectors (SC-RO), solar dishes (SD-RO), and solar organic Rankine cycles (SORC-RO) [172]. Similarly, membrane distillation moduli have also been coupled in similar systems, mainly PVMD (photovoltaic-powered MD), SDMD (solar collector-powered MD), and SORCMD (solar Rankine cycle-coupled MD) [66,173].

As of 2003, for a 5000 m^3/day capacity plant, the water production cost of PV-RO was estimated to be 2 USD/m^3, which is approximately 2.5 times higher than a standalone RO plant (0.7 USD/m^3 in 2003) [149]. Similarly, studies with PV-RO and wind turbines in the context of Saudi Arabia were also performed. Optimizations in the number of wind turbines, solar panels, and batteries, found a minimum energy cost of 0.624 USD/kWh at 2, 40, and 16, respectively. However, water costs generated through these means have costs between 3.693 and 3.812 USD/m^3 [140]. Nevertheless, photovoltaic power costs have been declining since 2003, from 5.19 to 0.26 USD/W in 2022 [174], thus PV-RO could have become more feasible, even so, it is likely to require higher investments.

As of 2020, SC-RO in the form of evacuated tube heat pipe collectors obtained maximum energetic and exergetic efficiencies at 50 °C. When applied to Encontech engine-driven RO, simulations point to an exergy efficiency of 52.5 % achieved through a heat transfer coefficient of 1 W/m^2.K, with upper efficiency values being found for similar condenser and absorber areas (A_{co} and A_{abs}, respectively, such that $\frac{A_{co}}{A_{abs}} = 1$ causes maximum efficiency) [175]. More recently, modified evacuated tube collectors have been employed to further concentrate RO brine. Experiments demonstrated that an average 4.58 ± 0.12 L/m^2 can be produced daily with <100 ppm of total dissolved solids [176].

SD-RO has been assessed recently through simulations of a dish-Stirling system, which generates electricity in tandem with RO operation. Given the weather conditions of the Mediterranean Sea, the authors calculate that the electricity generated can account for 48 % of the power consumed by RO, with a levelized water cost of €1.03/m^3 of fresh water [177]. Furthermore, solar dishes can also be employed in conjunction with ORCs. Recently, an SORC-RO system was also evaluated in a system powered by a solar Scheffler dish with a steam Rankine cycle on top of an organic Rankine cycle. The highest overall efficiency (14.08 %) was obtained for the R1234yf working fluid (trans-1,3,3,3-trifluoroprop-1-ene), with treated water costs estimations varying from 0.89 to $0.924/m^3 [178].

Membrane distillation has also been coupled with solar panels with the capability to increase water recovery. Even though PVMD has been proven feasible, the costs of water production are higher when compared to PV-RO [91]. However, as pointed out in [115], the energy consumption and water production costs of MD systems had been highly variable at the time, from 1 to 9000 kWh/m^3 and from 0.3 to 130 USD/m^3. Given that there was and still is a lack of standardized cost analysis methods in these systems, as well as high capital investments for membrane MD modules, PVMD also has the same economic barriers as PV-RO [115].

Still, given the high energy demand of MD, solar concentrators such as solar dishes have also been employed. In a simulation study tailored to the Moroccan-like climates, DCMD systems coupled with large-scale parabolic through collector plants can produce freshwater at a cost of 0.84, 0.98, and $1.20/m^3 for the cities of Dakhla, Saidia, and Agadir, respectively [179]. Co-generation through parabolic collectors and wind farms has also been analyzed as an alternative for renewable RO. In a hybrid system also containing MED, TVC, and a SORC, the optimal design prevents the emission of 52 kton of CO_2 per year. Nevertheless, this system produces freshwater at a cost of $3.08/m^3, a higher price if compared to standalone RO Despite this, the system achieved an RO water recovery rate of 32.05 %. However, the flow rates for feedwater, permeate, and concentrate have not been addressed [180].

Given the discussed forms of solar desalination, freshwater cost also varies greatly. When compared to standalone RO, some options appear more feasible, such as SDMD in Moroccan-like climates. Furthermore, SORC-RO options also display potential. Nevertheless, as with all solar technology, these costs also tend to fluctuate depending on solar irradiance, which is influenced by weather patterns. One example of such is the variability in freshwater cost obtained for the cities of Dakhla and Agadir, with a 43 %. Another challenge concerning the use of solar energy in SWD, are the conflicts between consolidating an environmentally friendly process and the freshwater cost. As demonstrated in [180], even though SORC hybrid systems are feasible and prevents emission of 52 kton of CO_2 per year, the freshwater cost is still above standalone RO [86]. Further, analysis of solar RO and MD systems is discussed in Section 3.3.6.

Moreover, interesting results are also obtained when membrane modifications are employed in solar desalination. In brackish water desalination systems such as PV-NF/RO, solar irradiance fluctuations lead to changes in concentration polarization and scaling [181]. However, little research has been done into membrane modifications in solar SWRO systems, nevertheless, solar MD membrane modifications demonstrate how photothermal energy can be incorporated into the process. Surface coatings can provide commercial MD membranes with nanophotonic properties, which enhances solar energy absorption. When applied to seawater or high salinity brines, a SGMD system can provide a reliable removal of total dissolved solids, achieving an average flux of at least 0.75 L m^{-2} h^{-1} [182].

In addition, titanium compounds (TiC and TiO_2) can also be used as a surface spray in commercial flat sheet PVDF membranes applied to VMD. When compared to the solar-free process, a flux increment of 0.64 kg m^{-2} h^{-1} can be achieved at 1000 W m^{-2} of solar irradiation. Furthermore, high salt rejection (above 99.95 %) can be maintained for 156 h of operation with a 70 g/L NaCl and $CaCl_2$ feed solution [183]. Further investigation into titanium coatings ($Ti_3C_2T_x$ MXene sheets) has been conducted on metallic spacers and PVDF membranes. In an AGMD system, the photothermal spacers implemented were able to enhance water flux up to 0.36 kg m^{-2} h^{-1} under one sun irradiation for a feed salinity of 35 g/L, with an energy conversion efficiency of 28.3 % [184]. Therefore, as surface modifications in commercial membranes become more accessible, they can be directly applied in solar MD to partially meet the energy demands of AGMD, SGMD, and VMD systems. However, given the temperature ranges of MD, surface coatings must be securely bound to the membrane surface and possess high thermal stability in high-humidity conditions. Consequently, this underscores the necessity for long-term studies on the potential detachment of these coatings.

Solar evaporators (SEs) also use solar absorption to desalinate water, which makes them an interesting substitute for solar-powered hybrid systems, with the most recent research focusing on membrane improvements. SEs work by absorbing sunlight through a membrane, which is in contact with seawater, then, due to the temperature difference between the membrane and the seawater, heat is transferred, and steam is generated. As a result, the steam passes through the membrane while the salts remain in the solution, producing two separate streams: one for steam output and another for brine output. Although this eliminates some issues with solar panels, roadblocks such as poor solar absorption and salt accumulation are present [127].

One approach to increasing solar absorption is modifying the membrane in the field of photovoltaics and solar absorbers, absorption is highly dependent on irradiance, given by the amount of energy per time per square meter. The solar constant, which is the total irradiance given by the sun after reaching earth's atmosphere, is approximately 1360.8 W m^{-2}. At times, authors will conduct experiments with greater values than one sun irradiance (i.e., two sun irradiance or 2721.6 W m^{-2}). Furthermore, a Ti_2O_3 layer combined with a cellulose membrane can achieve evaporation rates of 1.32 and 5.03 kgm^{-2} h^{-1} over 1- and 5-kW. m^{-2} solar irradiances, respectively, which correspond to 2.65 and 4.18 times higher than pure water evaporation [125]. Similarly, solar evaporator with a membrane produced from pristine natural wood cut transversely were also studied. The authors achieved a solar absorption of approximately 99 % at 10 sun irradiation and non-observable salt accumulation through this method. At 1 kW m^{-2}, an evaporation rate of approximately 1 kg m^{-2} h^{-1} was observed. At a 5-sun irradiation, a 5.5 kg m^{-2} h^{-1} evaporation rate was observed [127]. Moreover, energy loss has also been addressed through 3D materials made of a mixture of metal oxides, which achieved an evaporation rate of 2.04 kg m^{-2} h^{-1} under one sun irradiation [128]. Other results also include hybrid hydrogels, which achieved low costs (14 USD/m^2) and a high evaporation rate of 3.2 kg m^{-2} h^{-1} under one sun irradiation [155].

Consequently, solar evaporators have been evolving to mitigate poor solar absorption and salt accumulation, still, it is also possible to conclude that the scalability of solar evaporators can be another obstacle. For example, if one sun irradiation is assumed, the evaporation rates listed are considered, for the production capacity of an RO plant like Sydney's (250 million liters per day [185] or 10.41 kton/h), areas of 7.88, 10.41, 5.10, and 3.25 km^2 would be needed for Ti_2O_3, pristine wood, mixed metal oxides, and hybrid hydrogels, respectively. This corresponds to 30.15 %, 39.79 %, 19.51 %, and 12.44 % of the total area of Sydney itself (26.15 km^2 [186]), respectively.

Nevertheless, other technologies such as molten salts and liquid metals can boost solar absorption performance due to their high thermal conductivity [187,188]. Systems utilizing molten salts as heat transfer fluids have been proposed such as CCHP system (Combined cooling, heating, and power), which combines parabolic trough solar collectors, proton exchange membrane electrolyzers, and an organic Rankine cycle [189]. Furthermore, molten-salt systems have been proposed for SWD through hybrid moduli, with RO and MED, with RO presenting the best performance of energy utilization and a higher upper limit of water production when compared to MED [190]. Consequently, by coupling these highly conductive materials, solar desalination can be possible. However, additional research in this area remains necessary. As demonstrated, even though solar hybrid desalination systems have economic roadblocks in their implementation, they are still feasible for large-scale execution, which is not possible for solar evaporators at the moment. SEs are still favorable for low scale uses such as desalination in remote areas, however, scalability is still a challenge. Nonetheless, solar hybrid solar desalination moduli can be coupled with highly conductive materials such as molten salts and liquid metals, which can supply SWD's energy needs.

3.3.6. Environmental challenges, economic considerations, and social impacts

As with many industrial processes, seawater desalination deals with challenges with respect to environmental issues, economic restrictions, and social repercussions. The environmental impact of desalination processes has been widely documented in literature reviews, case studies, and life cycle analyzes (LCAs). Desalination processes such as membrane technologies (SWRO and NF/RO modules [16,17,108,147,148]), thermal technologies (MSF, MED, and VC [16,17,108,147,148]), and emerging technologies (FO, ED, CDI, and hybrid systems [16]) have been reviewed. Primary concerns outlined in literature reviews regarding desalination include the substantial energy requirements for these processes, which are linked to GHG emissions [16], as well as brine disposal and chemical discharge challenges [17]. In addition, thermal technologies like MSF, MED, thermal VC (TVC), and mechanical VC (MVC) typically require significantly higher electricity consumption compared to membrane technologies such as SWRO, ED, and BWRO.

Furthermore, these membrane technologies also have the potential for large-scale production. Nevertheless, given that most of the desalination is currently provided through RO [11], it is possible that the scale of SWRO plants overshadows the energy requirements of thermal technologies. For example, if the best-case scenario is assumed (minimal total electricity consumed and maximal production for all processes), based on the data from [111], it is possible to calculate an estimate for an ideal daily total electricity consumption. Based on these assumptions and the data, it is possible to point out that, even in the best-case scenario, due to the process scale of SWRO, it can consume more electricity daily when compared to some thermal technologies. Therefore, this leads to more indirect GHG emissions when considering the process scale [147]. The energy demand comparisons for these desalination technologies are illustrated in the Supplementary Material.

Furthermore, indirect GHG emissions can be avoided through environmentally friendly energy sources. Solar power control management systems can be used to offset energy needs in RO, reducing the specific energy consumption up to 18 % [191]. Moreover, standalone solar-powered RO can be coupled with excess energy recovery systems. Under the Saudi Arabian weather conditions (Al-Khobar city), photovoltaic arrays (total of 158 kW) can save 131 tons of CO_2 emissions per year [192]. Nevertheless, as initially discussed in Section 3.3.5, often the inclusion of renewable sources tends to increase the water production costs. In [192], the levelized cost of water for only battery and only water tank storage systems are 2.892 and $2.647/m^3, respectively. Still, when a hybrid battery/water-tank storage system is used, costs drop to $1.874/m^3. Other hybrid desalination systems, such as MDC-HDH-RO powered by solar-wind cogeneration, when optimized, can not only reduce the solar field area needed, but also improve the overall environmental impact and electricity cost. Still, the optimum design for this system has a $3.02/m^3 levelized cost of water [193].

However, when similar optimization strategies are implemented in MED-RO systems, such as those based on the combined-cycle power plant in Shahid Salimi Neka, Iran, water production costs can be reduced from 1.342 to $0.948/m^3 [194]. Thus, there is a trend with renewable energy sources coupled with RO, where they exhibit lower specific energy consumption but higher water production costs [195], with similar patterns also present in solar membrane distillation [115]. Consequently, solar desalination, especially SDRO and SORCs coupled with both RO and MD, have great potential when it comes to offsetting the energy needs of SWD. Still, economic constraints such as the levelized cost of water are challenges in this front.

Apart from energy consumption, which is a process-dependent challenge, brine management is a common factor in SWD. Considerations about antiscalants (polycarbonic acids, polyphosphates, and sulfuric acid), coagulants (such as $FeCl_3$), antifoaming agents (polyethylene and polypropylene glycol), and cleaning agents (detergents, such as dodecyl sulfate and dodecylbenzene sulfonate, and oxidants, such as sodium perborate and sodium hypochlorite). Even though the toxicity of all antiscalants is low, eutrophication has been reported in desalination plants that use polyphosphates due to orthophosphate conversion. As for polycarbonic acids and phosphonates, they are stable and have low biodegradability, which can result in long residence times in coastal waters [148]. As for $FeCl_3$, its discharge may cause intense water coloration, however, it has a very low toxic potential. Polyglycols are non-toxic to the environment, nonetheless, also have poor biodegradability, which may also lead to their persistence. Moreover, cleaning chemicals and other additives (biocides and corrosion inhibitors), if discharged without treatment, pose harm to aquatic life, especially in the discharge site [148].

Other angles, such as seawater intake and discharge systems have also been analyzed, in the context of SWRO. Open-ocean intake systems can limit sea fauna and flora near the intake, either by trapping sea life against the intake screens (impingement) or by carrying smaller organisms like plankton, fish eggs, and larvae into the process (entrainment). Velocity-cap intakes and subsurface intake systems can avoid these effects, however, discharge systems need to be designed with proper chemical pretreatment and adequately designed diffusers in order to reduce the environmental impact of SWRO [17].

Among case studies and real-life scenarios, similar concerns were raised over this high energy consumption, especially through the indirect emission of GHGs caused by external sources. The discussion also includes chemical pollution and its negative impacts on the marine environment, particularly due to the discharge of concentrated brine and additives into open waters [145]. Furthermore, another life-cycle analysis applied to Sydney Water also remarked on the high energy consumption of the desalination process (a 27 % increase compared to their base case). If powered by environmentally unfriendly energy sources that advance climate change, desalination can cause a 23 % increase in use. However, in terms of other environmental indicators such as the eutrophication potential, photochemical oxidant formation potential, and human toxicity potential, its implementation produces low impacts (1 %, 5 %, and 1 %, respectively) [133].

In addition to environmental challenges, some economic considerations need to be addressed in SWD. More specifically, desalination and water transportation costs can scale with time and location. Even though desalinized water costs have decreased from 9 USD/m^3 (seawater in 1960) to 1 USD/m^3 (seawater in 2005 by MSF) and 0.6 USD/m^3 (brackish water in 2005 by RO), transporting desalinized water inland increases costs. At the time, the authors estimated 100 m vertical lift is about as costly as a 100 km horizontal transport [97]. Although economic parameters change due to price variation, it seems highly likely that vertical transportation is still more costly than horizontal transportation currently. Additionally, investments are necessary for enhancing system water recovery and enabling resource recovery by applying preprocessing such as MF and NF pretreatments, MD modules, and crystallization for RO, but at the same time water production costs fall [79].

On one hand, advances in desalination technology led to lower costs per cubic meter of clean water. On the other hand, desalinated water costs can increase up to 50 % depending on location (from 0.50 to 1.00 USD/m^3 in 2013). The main parameters influencing desalination costs are geographical location, raw water quality, brine and reject discharges, and process configuration. Geographical location influences additional costs such as water transportation and land acquisition, which impact operating costs and fixed-capital investments. In turn, location influences the raw water quality (i.e., hardness and biofouling), which can decrease membrane life expectancy. As for brine and chemical discharges, adequately treating effluents to match governmental regulations is paramount due to the environmental impact of high-salinity mixtures and additives. In the case of process configuration, hybrid technologies demand higher investments than standalone SWRO [86].

Additionally, social impact is also a factor present in SWD research, having sociological ramifications in countries such as Spain. As of 2005, demands for water-based policies to implement economic, environmental, and public participation [146]. More recently, concerns were raised over health, safety, discrimination, local employment, and fair salaries in a case study regarding a circular desalination plant. Equipment manufacturing and plant construction contributed to concerns in terms of "Health and safety" (of Workers), "Discrimination" and "Local employment" [196].

As demonstrated, even though desalination has the potential to bring clean water to the broad population, environmental challenges such as high energy demands connected to GHG emissions, brine-chemical discharges linked to eutrophication and persistence, and seawater intake causing impingement and entrainment. Moreover, economic considerations like geographical location, land acquisition, raw water quality, and process configuration associated with operating costs and fixed-capital investment, as well as social impacts regarding health, safety, discrimination, local employment, and fair salaries greatly influence SWD.

3.4. Blue energy, "blue carbon", ZLD, and membrane-less processes: a road to the future?

Research has been conducted to address the challenges posed by the high energy demand of RO, indirect GHG emissions, brine discharge, and fouling. Salinity gradient power, also known as blue energy, is an interesting approach that can partially address the high energy demands and brine discharge. Blue energy encompasses two processes: pressure-retarded osmosis (PRO) and reverse electrodialysis (RED). In PRO, two solutions come into contact through a semi-permeable membrane, one with higher concentrations than the other. As in FO, a driving force emerges because of the concentration difference, however, as in RO, pressure is applied in the concentrated solution. Consequently, if the pressure applied by turbine instead of a pump, energy can be harvested [134]. Furthermore, if this process is carried out with concentrated brine, the brine is diluted, which can decrease the environmental impact given by its discharge.

In contrast, RED uses ion exchange membranes as well as two solutions of different salt concentrations. By alternating between cation and anion exchange membranes, cells are created where the solutions can be stored. This enables charge-selective ion transport from positive ions (Na^+) and negative ions (Cl^-) from the brine to cells to the less-concentrated solution cells, which, in turn, generates an electrical potential from the anode to the cathode [134].

Comparisons between PRO and RED provide diverse perspectives, and prior literature comparisons were not equivalent, leading some studies to conclude that both processes are viable when applied to their respective strengths. PRO is suited for use with saline brines due to its higher power density and energy recovery, while RED is more suitable for power generation using seawater and river water [134]. Nevertheless, comparisons in terms of energy efficiency and power density concluded that PRO could achieve greater efficiencies (54–56 %) and power densities (2.4–38 W/m^2) when compared to RED (18–38 % and 0.77–1.2 W/m^2, respectively) [197]. Given these advantages, PRO has been integrated to SWRO plants to create so-called third generation desalination. One notable example is the pilot plant located in U.S., which obtained experimental power densities from 1.1 to 2.3 W/m^2. The RO-PRO system may have reduced the specific energy requirements for desalination by approximately 1 kWh/m^3 [198]. Still, other ways of improving the performance of RED are through the optimization of ion exchange membranes. As an example, synthesized ionic diode membranes can increase the power density to 3.46 W/m^2 in artificial seawater – river water tests [136]. Furthermore, Single-layer MoS_2 nanopores also show a promising research venue, which generates power through a similar process called streaming potential, with an estimated power density of up to 10^6 W/m^2. As stated by the authors, this is a current that can be attributed to the atomically thin membrane of MoS_2 [123].

Even though blue energy has the potential to partially mitigate the high energy demand of RO, which is tied to indirect GHG emissions, other approaches towards carbon neutrality are also present. Very recently, measurements of dissolved CO_2 in desalination brines of a large desalination plant were performed. Since concentrated brines have unique buffering capacities, once the brine plumes are discharged, the CO_2 remains dissolved and sinks due to the higher density. Consequently, the brine acts as a "blue carbon" vector, which has the possibility to remove 3.8 Mton CO_2/year globally [199]. Still, as discussed in Section 3.3.6, brine discharge brings its own set of challenges.

Still, other works involving zero liquid discharge (ZLD) methods aim to reduce and nullify the amount of brine release and any liquid effluents into open waters. Hybrid desalination systems have been studied to make this possible, such as incorporating other membrane separation systems as MD and FO, even so, evaporation ponds are a common solution [111]. As of 2021, comparisons between evaporation ponds and scenarios involving partial brine concentration and crystallization demonstrate potential. In a case study regarding two scenarios the Eastern Mediterranean, these partial implementations are at least 3.18 times cheaper than disposal through evaporation pond, with both scenarios being profitable [200].

As for fouling management, many techniques have been covered in previous sections, nonetheless, flux reduction is a challenge at the heart of any membrane separation process. Attempts to create membrane-less desalination processes are notable, especially if scaling can be avoided. One remarkable approach is the use of concentration polarization in desalination, in which a nanojunction creates an electric field along a stream that repels any charged particle. By using this principle, a stream can be divided into a brine stream and a desalted water stream in a microfluidic device, with a single step removing approximately 99 % of salts and 50 % water recovery [154].

Therefore, as demonstrated, SWD research is actively addressing the issues of high energy demand of RO, indirect GHG emissions, brine discharge, and fouling through blue energy, "blue carbon", ZLD, and membrane-less processes. Whether these technologies can fully overcome these obstacles depends on scalability and investment, a similar issue with solar desalination. Economic commitments and returns on investment are often expected from such processes. From the technologies here discussed, ZLD techniques with emphasis on resource recovery have the best chance of providing returns while decreasing the environmental impact of SWD. Blue energy, PRO, can partially mitigate indirect GHG emissions by recovering some energy from brine, however, some estimates affirm that an investment in PRO is only feasible if it is able to generate at least 5 W/m^2 [198]. "Blue carbon" is an interesting emerging possibility, still, a tradeoff between carbon fixation and brine discharge is made. Therefore, more research is needed to evaluate its long-term effects of as a large-scale policy.

3.5. Research gaps

To further understand the research gaps present, the article keywords “energy”, “solar”, “RO”, “modeling”, “optimization”, “MD”, “fouling”, “NF”, “UF, as well as environmental and economic terms were analyzed in terms of their intersections or lack thereof. The co-occurrence subnetworks for these terms are available in the Supplementary Material. Table 7 demonstrates the connections between them, with green squares demonstrating connections and the red squares demonstrating their absence. Furthermore, in this paper, the lack of intersections has been considered as possible research gaps in SWD, with Fig. 12 expressing these gaps in graphical form.

In Fig. 12, if two or more general article keywords are connected, its means there is little research done regarding such terms. Even so, the links shown demonstrate that there is still substantial research potential in SWD. Particularly, gaps regarding the environmental and economic impacts of fouling, NF and UF uses in solar desalination, and NF and UF uses in MD are interesting research opportunities. Nevertheless, since the terms used in the article keyword re-occurrence have a general meaning, the links displayed in Fig. 12 also demonstrate a general scope of SWD, without nuance or context.

Still, studies regarding ultrafiltration and energy analysis have a weak connection in the dataset, which demonstrates a possible research front in SWD. Pretreatments involving MF and UF also impact processes such as SWRO due to pressure loss in membrane filtration moduli. Consequently, higher pumping pressure or repressurization pumps might be needed in some cases. Furthermore, this extra energy consumed is also responsible for indirect GHG emissions, as discussed previously in Section 3.3.6. In addition, UF and NF pretreatments in solar desalination systems is also a promising investigation area. In this case, the energy needed to perform these pretreatments can be provided by photovoltaic sources, which can offset their energy demand, providing the process with seawater containing low biological matter and ions such as Mg^{2+} and Ca^{2+}. These studies can also involve fouling remarks in a solar context.

Although modeling and optimization are widely used in SWD investigations, little work has been done in terms of UF and fouling. Novel studies can integrate fouling measurements into pretreatment or RO processes, optimizing them simultaneously with the overall flowsheet. One viable way of performing this is through the fouling factor, which increases with membrane age, impacting water quality over time. UF and NF pretreatments should also be applied to MD in SWD. As discussed in Section 3.3.4, scaling in the form of $CaCO_3$ is a major hurdle, thus, NF pretreatments can partially cover the use of antiscalants, which not only decreases operating costs but also lessens chemical discharge.

Environmental and economic effects of UF and NF pretreatments in RO has potential large-scale applications in industry partnerships, especially in SWD fouling control. These analyses can also be applied to MD, although in smaller freshwater production scales. Examples of environmental analyses of UF include its impact in partially mitigating the use of disinfectants such as Cl_2, which causes the formation of hazardous byproducts [201]. As for the use of NF, head loss can be avoided in RO and MD systems due to scaling, which can marginally decrease power use and indirect GHG emissions.

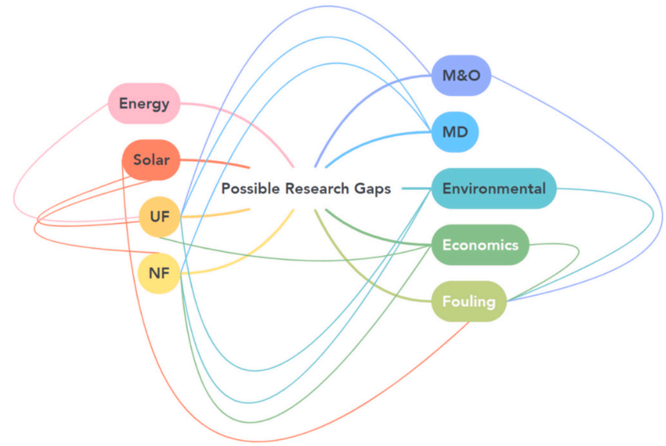


Fig. 12. Possible research gaps according to the article keywords co-occurrence network obtained in this study.

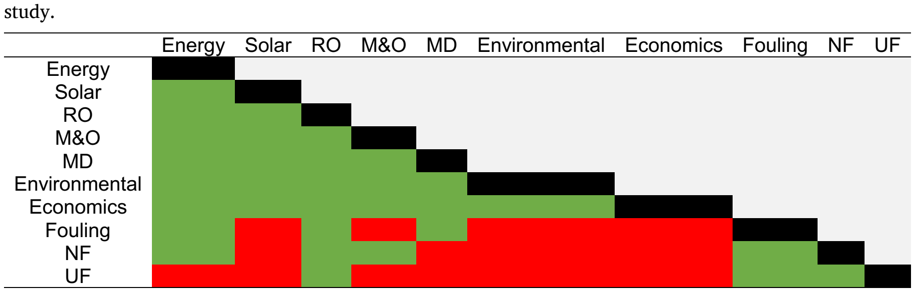
Consequently, SWD research has many fronts and gaps for future study, with exciting potential regarding the effects of fouling on economic and environmental analyses, as well as the incorporation of pretreatments in modeling and optimization of SWD systems.

4. Conclusions

In this bibliometric study we have analyzed 11,000+ papers in terms of article keywords, and abstracts and titles. Further analysis was conducted once long-lasting motor themes were established. Based on the bibliometric analysis and literature assessed, the following was concluded:

- Co-citation and geographical analyses indicate a significant contribution from Chinese and North American institutions in SWD research, highlighting regional research strengths and collaborations.
- Research focus in SWD has evolved from process design in the early 2010s to membrane fabrication and the use of renewable energy sources, especially solar energy, in the early 2020s, reflecting technological advancements and sustainability trends.
- RO remains the predominant technique for seawater desalination despite its high energy demands and associated greenhouse gas emissions, with ongoing research exploring alternatives like FO and MD to improve efficiency and reduce costs.
- Solar desalination, including hybrid systems like PV-RO and SPMD, shows technical viability but faces challenges related to prohibitive costs and scalability, driving ongoing research into enhancing solar absorption and energy efficiency.

Table 7
Highly cited keyword connections according to the article keywords co-occurrence network obtained in this study.



*Green squares indicate intersections, while red squares indicate lack thereof.

- RO and MD technologies coupled with solar dishes and solar organic Rankine cycles have exciting potential when it comes to offsetting the energy needs of SWD, yet economic constraints such as the levelized cost of water are challenges in this front.
- Environmental and economic considerations, such as brine and chemical discharges, indirect GHG emissions, and process configurations, alongside social impacts like worker health and local employment, are crucial in assessing the sustainability and feasibility of desalination technologies, with emerging research areas focusing on blue energy, ZLD, and membrane-less processes to mitigate these impacts.
- Research gaps regarding the effects of fouling on economic and environmental analyses, as well as the incorporation of pre-treatments in modeling and optimization of SWD systems are promising fronts.

CRediT authorship contribution statement

Gustavo Leite Dias Pereira: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Visualization. **Veeriah Jegatheesan:** Supervision, Project administration, Writing – review & editing, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 3.5 to improve readability, clarity, and language coherence throughout the text. After using ChatGPT 3.5, the authors have reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2024.118029.

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