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Analysis of Seawater Desalination Research Data: Trends and Perspectives

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Projections of water availability in the near future are increasingly worrisome due to climate change. It is, therefore, high time to seek and develop technologies that would guarantee water availability in the future. In this respect, desalination of seawater is one of the most important alternatives, as specific attention needs to be directed at improving the existing techniques of it. This is why updating information about new achievements for researchers is so important in improving such technologies. This comprehensive review article analyzes advancements in seawater desalination through a bibliometric study encompassing 8523 scientific papers published from 1966 to 2023. The analysis identifies eight key research areas, highlighting significant improvements in energy efficiency and membrane technology. The review examines innovative approaches, including the application of nanoparticles and hydrogels, as well as the integration of renewable energy sources. Additionally, it addresses persistent challenges such as biofouling and brine management. A compilation of costs of different technologies of the last decade has been carried out in order to serve as a baseline for future research or technological developments. This study serves as a valuable resource for researchers and policymakers, aiming to promote sustainable water solutions and enhance future water security. By synthesizing decades of research, this review provides a foundation for further advancements in desalination technology and policy development, ultimately contributing to the global effort to secure water resources for future generations.

Keywords: crystallization, entrainment solutions, forward osmosis, hydrogels, membranes, reverse osmosis, solar still.

Introduction

This review provides a comprehensive analysis of recent developments in seawater desalination, focusing mainly on improving efficiency and incorporating emerging technologies. It addresses the main challenges, identifies key research gaps and aims to guide future research and inform policy decisions related to sustainable water management. By conducting a bibliometric analysis, the study ranks recent developments, with particular emphasis on the role of nanomaterials and innovative pretreatment processes. It also highlights a significant knowledge gap on the long-term environmental and economic impacts of these technologies, underlining the need for integrated treatment strategies. The research shows possible future directions for developing more sustainable and efficient solutions to mitigate global water scarcity.

Seawater desalination is the removal of dissolved salts in seawater to produce water that is potable or of suitable characteristics for irrigation (Wang, 2018). It is also a promising alternative to address the global water crisis due to increasing freshwater scarcity and droughts aggravated by climate change. However, large-scale desalination that is cost-effective and sustainable, i.e., minimizing energy use, is still a challenge, and more research is needed to improve these technologies while minimizing environmental impacts (Liponi et al., 2022; Panagopoulos and Giannika, 2022; Xu et al., 2023).

According to a report by the World Health Organization (WHO) for the year 2020, 2 billion people in the world still do not have access to safely managed drinking water services; of this total, 1.2 billion have basic services, 282 million have limited services, 367 million use unimproved sources and 122 million drink surface water. The causes of this situation are diverse, but one of the main ones is the lack of investment in infrastructure and technology for water management (WHO and UNICEF, 2019). The consequences of the lack of water are serious, affecting both the health of people and the economic and social development of communities.

In addition, climate change is also affecting the availability of water in the world. Water scarcity, given the uneven distribution of rainfall, will be exacerbated by changing climatic conditions. While droughts in Latin America are more frequent and intense, water stress indices in China are improving due to increasing water availability and are expected to continue to improve (Huang, 2023; Jurgen et al., 2020; Desbureaux et al., 2019).

The literature review aims to compile and analyze the existing scientific literature on seawater desalination, to provide a comprehensive overview of this area of research and the challenges it faces. The analysis leads to desalination technologies, such as multiple evaporation distillation and reverse osmosis, and highlight emerging technologies that can improve performance and reduce costs and environmental footprints. By summarizing key findings and proposing research directions, this review aims to provide a comprehensive overview of seawater desalination. It is hoped that this review will help researchers, policy, and decision-makers to better understand desalination as a solution to the water crisis and to develop effective strategies for its implementation.

Future research in desalination should focus on assessing long-term environmental and economic impacts, technology integration, pretreatment optimization, energy efficiency through renewable energy sources, biofouling mitigation, and brine management. Developing integrated strategies that combine desalination methods with other water treatment processes is crucial to maximize efficiency. Research should inform policy frameworks that align technological advancements with sustainable water management practices, thus addressing global water scarcity and enhancing sustainability in the field of desalination.

Methods

A total of 8523 scientific articles were filtered from the Scopus database using “Seawater desalination” as keywords. The selected articles date from 1966 to 2023, and belong to 1376 different sources and 16117 authors. The search was performed on March 19th, 2023.

VOSviewer and Bibliometrics software were used for the bibliometric analysis. In VOSviewer, 12 occurrences were used as the minimum number of a keyword, where out of 13286 keywords, 251 met the threshold using the normalized method of association. Of the 251 items, 8 were removed for being repetitive, leaving 243 for analysis grouped into 8 clusters.

The AI-based academic search engine Consensus for the collection of cost data and research on novel materials was required. The prompt used was: “show me costs about ...", and a specific desalination process between the ellipsis. The topics of the costs associated were reverse osmosis, multiple-effect distillation (MED), multi-stage flash distillation (MSFD), electrodialysis and solar distillation. This analysis gives researchers a very useful cost benchmark that can be used to highlight potential ways in which costs could be lowered.

Results and Discussion

Fig. 1a shows the co-occurrences by keyword association and *Fig. 1b* shows that in the last years, the topics related to nanotechnology are being strongly addressed, being the keywords for this last period: graphene, chitosan, graphene oxide, carbon nanotubes, electro-spinning, hydrogel; as well as energy utilization in the keywords of solar steam generation, photothermal generation, and solar evaporation.

Table 1 shows the clusters obtained with the VOSviewer software by color and by number of items.

Cluster 1 (Red color – biofouling)

Of the total number of articles, 130 mention biofoulings from 1992 to 2023. This subject, which has been widely addressed for decades, is still a scientific and technological challenge. Biofouling causes corrosion in the marine structures of desalination plants or clogging of reverse osmosis membranes (Kurihara et al., 2001; Malik et al., 1996). Biofouling has its origin in the formation of biofilms composed of carbohydrates, and proteins and with the presence of α-proteobacteria, phylum Firmicutes, and Planctomycetes (Lee et al., 2009). To counteract biofouling, bactericidal agents such as TaTe2 QDs, haloperoxidases, iron nanoparticle coatings, proposed membranes resistant to biofilm formation, antifoulants, pretreatment with air flotation and/or UF before RO, improvements in backwash cycles and cleaning in situ have been proposed (Armendáriz-Ontiveros et al., 2022; Liu et al., 2022a; Winters et al., 2022; Roo-Filgueira et al., 2022).

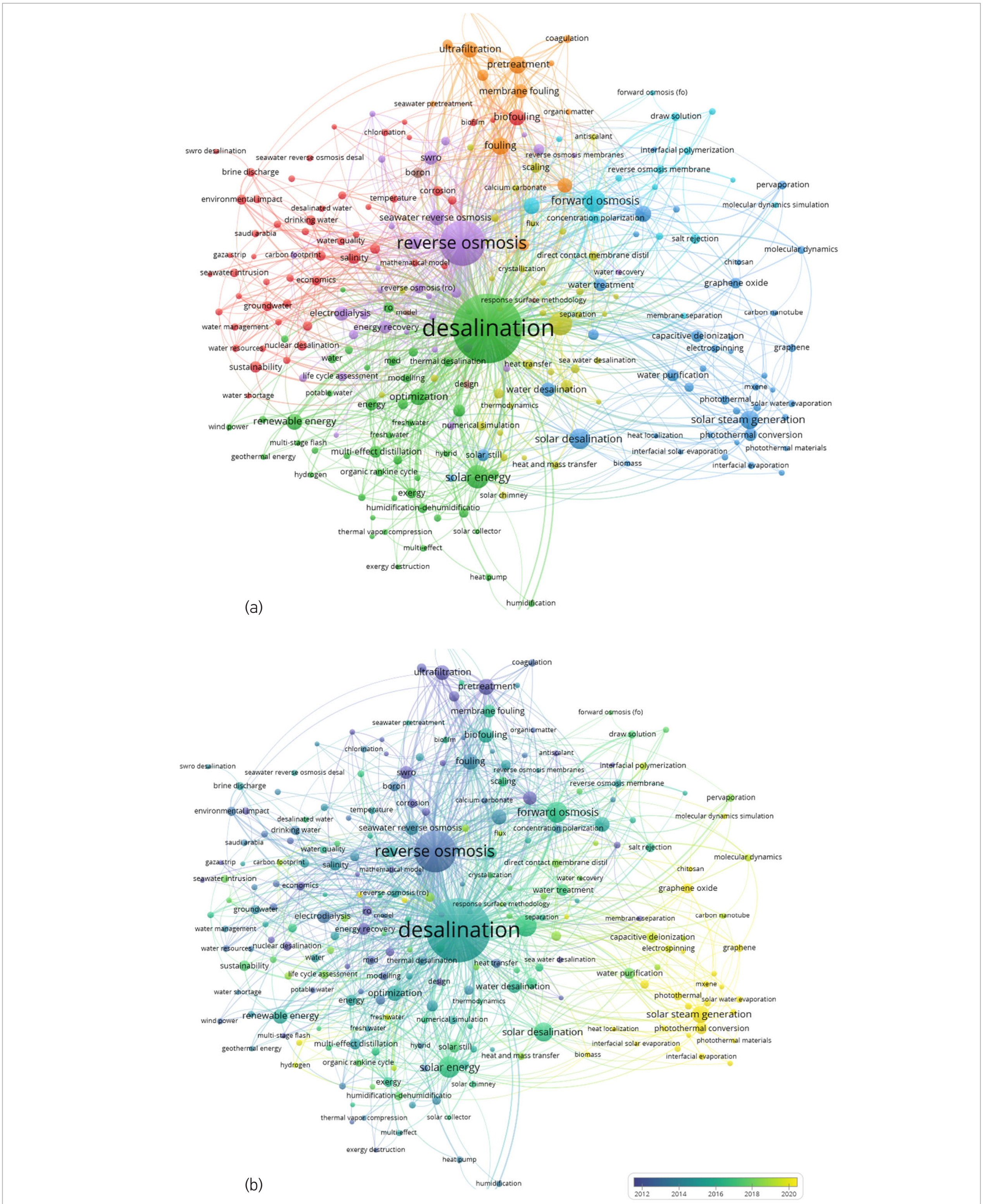
Cluster 2 (Green color – desalination, solar energy, renewable energy, costs)

Although desalination is a keyword in almost 50% of the articles evaluated in this review, the two associated keywords: solar energy and renewable energy have been selected for the respective analysis. A total of 241 articles uses these keywords. Modeling and simulations of desalination plant systems or combined systems using membranes and solar distillation are very useful for selecting the best configurations that allow better removal efficiencies and, therefore, lower costs (Kalmykov et al., 2020; Khaled et al., 2020; Salcedo et al., 2012).

Table 1. *Cluster interpretation elaborated in VOSviewer for the associated keywords of the 523 articles extracted from the Scopus database for the period 1966–2023*

Cluster	Color	Items	Comment
1. Biofouling	Red	50	Technological and scientific challenge due to the formation of biofilms that cause corrosion in marine structures and clogging of reverse osmosis membranes.
2. Solar and Renewable Energy	Green	49	Models and simulations improve the configuration of desalination plants to reduce costs. Innovative materials such as hydrogels are explored to improve heat exchange.
3. Forward osmosis (FO)	Light Blue	42	Use of entrainment solutions to reduce solute polarization, avoiding the use of high pressure. Composite membranes with nanotechnology improve performance.
4. Membrane Distillation (MD)	Yellow	36	Improved modeling and simulations, with modified membranes that offer greater resistance to fouling and higher vapor fluxes.
5. Reverse Osmosis (RO) and Energy Recovery	Purple	31	Process optimization through the integration of FO and energy recovery, with improvements in the efficiency of energy use.
6. Nanofiltration (NF)	Blue	16	Nanofiltration with chitosan and graphene membranes to improve salt rejection efficiency and water recovery.
7. Ultrafiltration (UF) pretreatment	Orange	14	Ultrafiltration processes to improve the durability of membranes in RO, reducing scale formation.
8. Neural Network Design	Brown	5	Optimization of desalination plant design using artificial neural networks and fuzzy logic.

Fig. 1. *(a) Cluster map for 8523 scientific articles, 1966 - 2023, analyzed from the Scopus database with VOSviewer (12 co- occurrences, 13286 keywords, 251 at threshold, normalized method of association). (b) Cluster map of associated keywords as a function of time produced in VOSviewer*



Solar distillation seems a promising alternative especially if it can be harnessed in a better way, for this purpose parabolic trough solar collectors have been tested (Bagheri et al., 2021) and membranes have been integrated for better results (Frikha et al., 2017); however, optical collectors require large size or surface area for better performance. The development of materials capable of improving heat exchange by direct contact is a step forward in the technology of conventional shell and tube or plate equipment. Currently, the development of hydrophilic hydrogels or gels is capable of evaporating seawater at low temperatures. While the current cost could be high (Sayer et al., 2018), less expensive hydrogels such as natural biomass polysaccharides are being pursued (Luo et al., 2022). The study of new membranes that are less expensive, more efficient, and capable of withstanding a high number of cycles and aggressive acidic or alkaline media continues (Han et al., 2021). Another innovative water desalination proposal is that of Zamen et al. which uses solar panels to heat seawater, then transports it to an air humidifier and finally dehumidifies this air using an air-cold air condenser obtained from the ventilation of a greenhouse (Zamen et al., 2023).

Cluster 3 (Blue color – forward osmosis)

Direct osmosis allows the removal of some solutes from water, although not all, but its advantage lies in the fact that it does not use high pressure; however, it needs to be complemented by some other process that guarantees the removal of the remaining contaminants. Therefore, there are hybrid systems of direct osmosis and RO (Choi et al., 2009), or hybrid processes of FO with crystallization and RO (Kim et al., 2018). Analysis of closed loop RO (PRO) combined with RO, FO-RO, and RO-PRO configurations through computational simulations indicates that FO-RO consumes lower energy compared to the other two (Altaee et al., 2015). An improvement of the process involves the use of entrainment solutions to avoid solute concentration polarization in the membranes, for example, from highly soluble gases (ammonia and carbon dioxide) sodium chloride can be removed between 95% – 99% (McCutcheon et al., 2006). Hydrocobaltose and ferric complexes have also shown good performance and ease of regeneration producing high water rates; cobaltous complexes are hydrophilic, can dissociate in water, and form a multi charged anion and sodium cations; moreover, their expanded structures decrease reverse solute flow (Ge et al., 2014). Other drag agents developed are the highly porous, three-dimensional, and stable sodium alginate-graphene oxide (SA-GO) aerogel (Yu et al., 2017); as well as, the development of an easy-to-regenerate hyaluronic acid-graphene oxide/polyvinyl alcohol (HA-GO/PVA) hybrid monolith (Yu et al., 2020). In terms of membrane development, thin-film composite (TFC) hollow fiber membranes consist of a selective polyamide layer on a hollow polyethersulfone (PES) fiber support with a spongy morphology (Sukitpaneenit and Chung, 2012). Likewise, membranes have been simulated with carbon nanotubes whose potential lies in resistance to clogging and good mechanical properties (Jia et al., 2010). The incorporation of silver nanoclusters into membranes forms a thin film that prevents bacterial accumulation (Guo et al., 2019).

Cluster 4 (Yellow color – membrane distillation, vacuum membrane distillation)

Utilizing waste heat as an energy source, vacuum MD technology is promoted as a novel and effective way to clean oily wastewater. This technique is a desirable alternative for the industry, particularly in oil fields, because it has been shown to generate up to 10 liters of desalinated water per square meter of membrane every hour (Cui et al., 2020). Janus composite membrane silver - polyvinylidene fluoride - polydimethylsiloxane (Ag-PVDF-PDMS) with a silver coating improves the oil resistance and flux of the membrane. This membrane has improved mechanical properties and long-term stability, with 85% flux recovery after 10 hours of treatment (Yue et al., 2021). Additionally, a Janus membrane with hydrophilic and hydrophobic surfaces was developed to optimize membrane desalination, maintaining a steady flux of 11 $L/m^2 \cdot h$ over 60 hours and demonstrating strong resistance to fouling and wetting. This membrane operates efficiently even in the presence of contaminants such as sodium dodecyl sulphate and propylene glycol (Nambikkattu and Kaleekkal, 2023).

The optimization of mixed-matrix hollow fiber membranes improves resistance to wetting and demonstrates efficient permeation of up to 11.95 $kg/m^2 \cdot h$, with a salt rejection rate of 99.96% when utilizing PVDF and nano-fumed silica (NFS) particles under specific conditions (Alsebaeai et al., 2023). The application of an electric field influences desalination efficiency in a capacitive deionization membrane distillation (CDIMD), which employs activated carbon felt electrodes and conductive membranes. This system achieves notable improvements compared to conventional MD (Liu et al., 2023). Additionally, MD in multi-envelope modules, using an enhanced vacuum system, emerges as an alternative to thermal desalination technologies. The response surface methodology (RSM) was applied to model and validate permeate productivity and condenser outlet temperature (TCO) across three different module designs (Andrés-Mañas et al., 2022).

Cluster 5 (Color purple – reverse osmosis, electrodialysis, energy recovery)

Since the 1970s, improvements in equipment designs have been analyzed for greater energy efficiency in seawater purification, such as the use of vertical tubes in distillation, coupling with flash distillation, and crystallization. Also, RO and electrodialysis, which compete in cost, achieve good water quality (Savage, 1970). The evaluation of equipment configurations to reduce operating costs is necessary so that combinations of direct osmosis with RO, as well as RO with delayed pressure RO, appear to be a good option (Wan and Chung, 2018). Energy recovery, especially from thermal power plants, is useful for MED systems to lower costs; however, even achieving this integration the high capital cost of the cogeneration plant and pumping seawater inland are major obstacles to making it price competitive with other desalination methods (Hoffmann and Dall, 2018); novel methods integrate two rigidly linked cylinders under an electrohydraulic system, wherein one cylinder energy is recovered for RO to be performed in the other cylinder (Li et al., 2020). The use of efficient energy in plant design is important to obtain competitive costs, such is the case of the proposals for solar poly generation plants for the production of thermal and cooling energy, electricity, and desalinated water (Proposal 1: Concentrated photovoltaic/solar thermal collectors - Absorption chiller - Mediterranean; Proposal 2: Photovoltaic field - RO unit - Heat pump) (Calise et al., 2020).

Knowledge about the mechanisms of osmosis considering membrane properties, ions, solutions, multiscale phenomena such as nanoscale interactions, mesoscale concentration gradients, macroscale conditions (flux, modular geometry), and performance (surface partitioning, internal diffusion, water flux, and rejection) will enable a new level of development of state-of-the-art membranes with improved performance (Nickerson et al., 2023). An improvement for the membranes is the incorporation of NC-LAP nanoclay dispersed with polyethylene glycol in a thin film membrane. Tests showed 98.18% salt rejection for brackish water desalination at 20 bar and 25 ± 1°C. The water permeability is 53% higher than conventional thin film composite membranes (Zhao et al., 2020). The search for membranes with better characteristics is a challenge, such as the case of the polyamide thin film composite membrane for RO (TW30-2540) (Bouchareb et al., 2019). Another example, concerning membranes, is a RO pretreatment of water, where the biofilm formed by protobacteria and planctomycetes favors the removal of Assimilable Organic Carbon (AOC) between 50–55%. After this pretreatment, microfiltration continues under a hydraulic residence time (HRT) of 24 hours. The results indicate that water production increases and water quality improve (Ranieri et al., 2023). Saltwater pretreatment, by softening and flocculation, removes scale-causing calcium and magnesium ions, as well as bacteria and suspended solids. This configuration allows greater durability and operation of the membranes in RO (Yadai and Suzuki, 2023). Concerning process optimization, it is convenient to test different configurations using material and energy balance. The closed-loop reverse osmosis (PRO) process configuration with FO predilution results in the lowest costs for seawater desalination. This configuration significantly reduces the capital expenditure (CapEx) and operating expenditure (OpEx) of the desalination process (Wan and Chung, 2018). The rejected water or brine that is eliminated from desalination processes is a challenge due to the environmental problems it could cause. An industrial pilot plant using the FFFC (falling film freeze crystallization technology) process to concentrate RO brine was tested and evaluated. Crystallization experiments achieved a salt rejection rate and water recovery rate of 56.6% and 49.8%, respectively, using a feed stage and at a heat transfer medium (HTM) temperature of –6°C at the final operating point (Ahmed et al., 2020). The return of brine to the sea has negative effects on the ecosystem of a region of the Persian Gulf producing eutrophication. If solar panels are used, 10% of the electricity generated from natural gas can be replaced. With the SimaPro software, the four main impacts of industrial and potable water production were reduced by 2% – 5.19% (Fayyaz et al., 2023).

Cluster 6 (Light blue color – nanofiltration, chitosan, graphene)

The FO process demonstrated high fouling ion rejection rates, efficiency, and cost-effectiveness with low energy consumption and production cost. However, the cost is sensitive to water flux and membrane expenses (Hafiz et al., 2023). Pretreatment with direct osmosis improves thermal efficiency, reducing energy consumption by 44% and heat transfer area by 21%. The Forward Osmosis-Multi-Effect Distillation (FO-MED) system also reduces saline water discharge by 40% and the water footprint by 36%. Although it has a higher water levelized cost than the stand-alone MED system, the need for high-performance membranes is suggested to improve its economic viability (Ortega-Delgado et al., 2022). Therefore, a new infinite desalination process based on Hollow Fiber Forward Fiber Osmosis (HFFO) is proposed as an environmentally friendly and energy-efficient alternative to overcome the limitations of the conventional Seawater Reverse Osmosis (SWRO) process. In the present research, a comparative evaluation of the energy costs between the concept of Direct Hollow Fiber Osmosis and a hybrid process of Forward Osmosis - Seawater Reverse Osmosis (FO-SWRO) is carried out. The high dilution rate of the direct hollow fiber osmosis process allows for efficient operation of the downstream seawater RO process, generating significant annual energy revenues (Im et al., 2021). Similarly, a high-performance NF membrane with self-doping sulfonated polyaniline (SPANI) nanofibers in an intermediate layer allow adjustments with different alkaline solutions to obtain various surface layer morphologies during interfacial polymerization. The resulting membrane shows excellent Na_2SO_4 and $MgSO_4$ flux and retention capabilities (Guo et al., 2023). Considering the comprehensive modeling method for flat sheet and spiral wound NF configurations in seawater desalination allows tuning the membrane characteristics and studying their impact on the process. The reliability of the model was confirmed by validation with data from a large-scale desalination plant (Roy et al., 2015).

Research conducted with thermo-sensitive amphiphilic non-ionic amphiphilic copolymers used as carry-over solutes in direct osmosis for high salinity water recovery focuses on poly(ethylene oxide) and poly(propylene oxide) (PEO-PPO-PEO) copolymers, especially Pluronic® L35, which shows good performance and stability after multiple regeneration cycles. Although membrane fouling is observed due to the copolymer, it does not significantly affect the FO flux in high-salinity water (Xu et al., 2022). The NF type direct osmosis process also showed higher water flux and passage of monovalent salts, making it a better choice for seawater pretreatment. The study provides valuable information on the design of FO membranes for this application (Yao et al., 2019).

From membrane desalination and the use of Liquid Chromatography for Organic Carbon Detection (LC-OCD) to quantify organic matter and bacteria in a pilot plant, the effective removal of bacterial cells (99.7%), but not TOC (Total Organic Carbon), was achieved. On the other hand, NF removed both TOC (95%) and bacteria, although the NF permeate showed a higher organic concentration than the original seawater (Rehman et al., 2020).

The proposed ionized GO membranes for seawater desalination by NF is a method that utilizes an external electric field and improves solute rejection in the ionized GO membrane, achieving complete rejection at E = 0.6 V/Å and a water flux of 0.071 $kg/cm^2/s$. The study highlights the potential of ionized GO as a novel material for desalination membranes (Dahanayaka et al., 2020).

The method is proposed to separate Mg^{+2} and SO_4^{-2} from seawater, including low monovalent ions, which employs cation ion exchange, NF and semi-batch diananofiltration, with resin regeneration using the permeate from the nanofiltered desalination retentate, which is cost-effective in cost analysis, with a value of approximately \$1.6 per kg of separated Mg^{+2}, making it cost-effective for large-scale production and beneficial for water-scarce industries and communities (Tang et al., 2018).

The effect of ultrasound on direct osmosis desalination with magnesium sulfate and copper sulfate effectively reduces internal concentration polarization (ICP), significantly improving water flux by up to 34.6% and 43.9% for magnesium sulfate and copper sulfate, respectively, suggesting that ultrasound is a promising technique for improving the efficiency of direct osmosis. However, ultrasound increases the flux of reverse extraction solutes (Qasim et al., 2020).

The FO process was evaluated at an elemental scale, using real wastewater for 36 days, studying the initial contaminants (high molecular weight hydrophilic organic molecules) and their transport influenced by water and reverse salt fluxes. Strategies to improve the rejection of organic molecules in direct osmosis membranes based on cellulose triacetate (CTA) are proposed (Im et al., 2020).

Cluster 7 (Color orange – pretreatment, ultrafiltration)

New ultra-fast pretreatment processes have been developed for seawater desalination using RO membranes, combining traditional softening with ballasted flocculation. These processes effectively remove blocking substances from raw seawater, improve sludge treatability and demonstrate successful removal of Mg^{2+} and Ca^{2+} ions, suspended solids, and bacteria (Yadai and Suzuki, 2023), among other contaminants specific to seawater. Biofouling behavior in seawater desalination can be detected and biofilm formation on RO membrane surfaces can be monitored by measuring adenosine triphosphate (ATP) to monitor biofilm growth and bacterial cell shedding in the RO seawater desalination process, among other factors that influence membrane fouling in the RO seawater desalination process (Nakaya et al., 2021; Jamieson et al., 2021). The conceptual layout and basic design of RO drinking water desalination plants can be designed and optimized using decision algorithms and computer programs (Khodabandehloo and Farhadi, 2021). In addition, novel approaches have been suggested for seawater desalination that can produce quality drinking water while reducing energy consumption and cost, making use of hybrid processes of FO, NF, and RO. The FO-NF-RO process with a FO membrane similar to NF can be an efficient and cost-effective approach to seawater desalination (Wang et al., 2021).

Although coagulation and microfiltration are effective methods of seawater pretreatment, it has been shown that microfiltration can be an environmentally benign alternative to coagulation in seawater treatment, effectively removing suspended solids and organic matter from seawater. This is presented as an alternative to coagulation in the pretreatment of seawater (Shaheen and Czéfalvay, 2022; Bar-Zeev et al., 2021).

In UF, low-fouling UF membranes have been developed for water purification and desalination, investigating for example, how permeation flux affects the fouling resistance and desalination efficiency of a hybrid PSf/TNT-SO_3H ultrafiltration membrane fouled by a specific type of fouling such as sodium alginate, finding that the addition of TNT-SO_3H to the membranes improved the water penetration fluxes and surface hydrophilicity of the fabricated membranes (Alsohaimi, 2022). However, future research could cover other types of fouling or operating conditions. Robust porous UF membranes, such as polytetrafluoroethylene-co-hexafluoropropylene (FEP) membranes, obtained by electrospinning-sintering technology, have also been designed and manufactured. These membranes have excellent mechanical properties, high porosity, and good separation performance, making them suitable for various applications such as wastewater treatment, protein separation, and blood plasma filtration (Chen et al., 2022).

Devices have also been designed and tested to separate and desalinate saline-alkaline water from farmland in arid areas, which proved to be effective in reducing the salinity and alkalinity of the water, making it suitable for irrigation (Yang et al., 2022).

Cluster 8 (Brown color – neural network, design)

Artificial neural network mechanisms have been developed to optimize the water treatment process with the most common desalination techniques (Taloba, 2022), providing decision algorithms and software that can help design and optimize, for example, RO plants for both seawater and brackish water supply (Wang et al., 2021; Amokrane and Sadaoui, 2021). Thus, we have explored the use of soft computing techniques to manage the modeling, simulation, and optimization of the real-time performance of seawater RO desalination plants using neural networks and fuzzy logic to predict optimal process conditions. The models were trained using four input parameters (feed temperature, feed pressure, feed flow rate, and feed total dissolved solids) and two output parameters (permeate flow rate and permeate total dissolved solids) (Mahadeva et al., 2021).

Compared centrifugal reverse osmosis (CRO), a novel and energy efficient membrane process, versus conventional single-stage reverse osmosis (SSRO) and how it can help address the global water crisis, highlighting the advantages of CRO over SSRO, such as higher energy efficiency and lower operating costs, having the potential to reduce the cost of renewable biofuel production from biomass technologies (Krantz and Chong, 2021).

A dynamic simulator of the water-energy system was developed with a new approach for the optimal sizing of an autonomous solar-wind RO desalination system, using the design of experiments method. It includes the energy equations of each element, climatological data, and energy management over a year, and also presents intelligent modeling using metamodels that replace the dynamic simulator to predict the optimal configuration of the water-energy system (Cherif et al., 2021). In addition, we have investigated how to reduce energy consumption in desalination and present the results obtained from the analysis of the energy consumption of a small-scale RO seawater desalination plant and its application in small marine vessels. By applying an artificial neural network model to optimize plant performance, the result of the research is a potential solution to reduce energy consumption in the desalination of small marine vessels (Marichal Plasencia et al., 2021). Minimizing energy consumption in seawater desalination can also be achieved by optimizing a simple hybrid system of MED and RO permeate reprocessing processes (Al-hotmani et al., 2021).

The analysis of the exergy performance of a seawater RO plant and possible ways to improve its efficiency. Using recent correlations of seawater properties and a non-ideal solution model, it was shown that the maximum exergy destruction took place in RO pumps and modules. They were followed in order by losses in dual media filters and mixers. The second law efficiency of the plant was found to be only 29.4%, revealing its insufficient level. Therefore, several measures for its improvement were proposed, focused on reducing the input energy and controlling losses during the operation of the process. A limitation of the study is that it only analyzes the performance of a specific plant, and the results may not be generalizable to other plants (Al Ghamdi and Mustafa, 2022).

The influence of temperature on the estimation of boron concentration in desalinated seawater for agricultural irrigation has also been investigated by providing a simple linear regression analysis to estimate boron concentration at different temperatures. The research found that the correlation between temperature and boron concentration in desalinated seawater is high, but decreases with time due to membrane aging and compaction. The study also found that, under the working conditions tested, it was impossible to reach the boron concentration value of 0.3 mg/L which guarantees the absence of toxicity to crops (Escarabajal-Henarejos et al., 2021).

Fig. 2 shows the production of articles related to seawater desalination by country and year (1966–2023). It can be seen that since the year 2000, interest in this topic has grown almost exponentially due to the need to solve the problem of current and future shortages in the world. The country with the highest participation in the development of this research is China, followed by the USA and Korea. In fact, to date, 142 seawater desalination projects have been installed in China, which is highly effective in alleviating the pressure of freshwater scarcity in coastal cities but has limited impact on inland areas, i.e., there is still an underlying problem of water distribution (Ai et al., 2022).

Fig. 2. *Production of articles by country (alone or in collaboration with other countries) and annual scientific production, elaborated with bibliometrics*

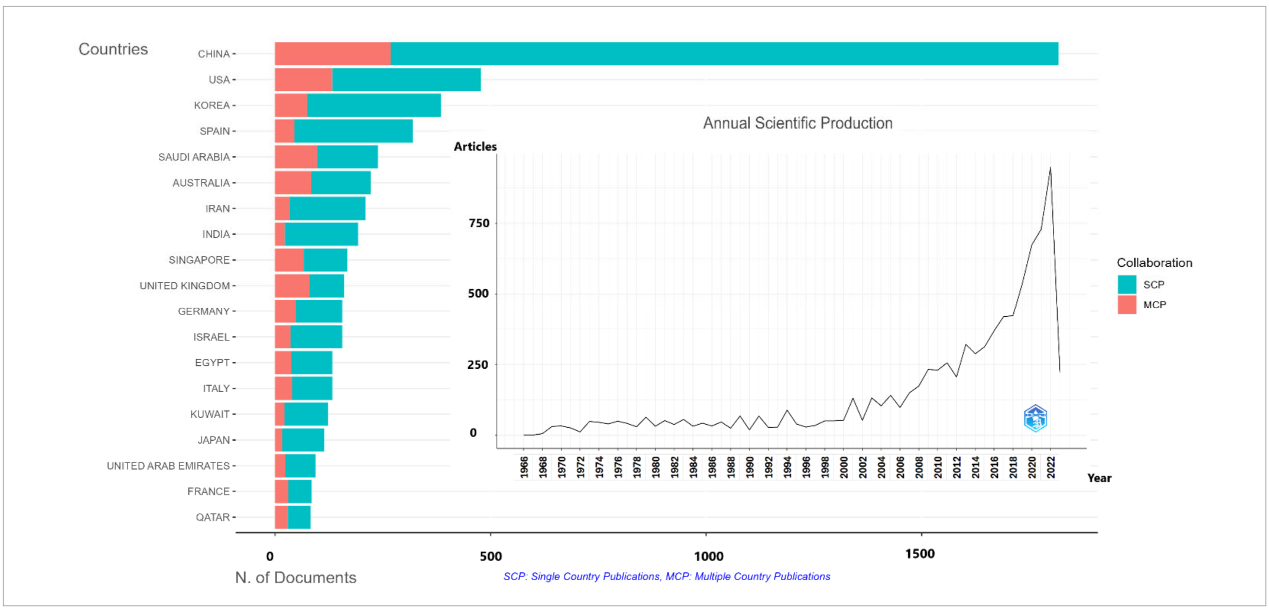


Fig. 3 shows a classification tree by keywords, showing that the focus on desalination (21%), seawater (12%), RO (6%), and seawater desalination (4%) together occupy a percentage of 43%. Some topics such as membranes (2%), evaporation (2%), energy utilization (1%), solar energy (2%), solar power (1%) and costs (1%) should be highlighted, which despite the low percentage of study are new or emerging topics.

Fig. 4 shows a dendrogram of the seawater desalination keywords 1966–2023. This figure shows 8 clusters in the turquoise cut-off line which we can associate with the following idea: The supply of fresh or potable water by seawater desalination is achieved by optimized treatments, with membranes, adequate energy expenditure, cost verification, and energy efficiency. One of the most widely used processes is RO and the emerging processes are those that use solar energy. All of this will lead to achieving adequate water management and the development of other controlled studies will favor the fulfillment of this great objective. Following is a dendrogram showing hierarchical clustering of several water-related terms, which have been grouped together by their similarities. High-level branching of terms into topics involves desalination processes, water purification techniques, energy utilization, and management of water quality. The closer the cluster is, the closer related it is. Thus, "Water purification" is closer to "Water management," whereas "Sea water" clusters with "Sodium chloride" and "Salinity". It would, thus, be useful to show how various concepts in water treatment, desalination, and environmental sustainability are related and provide the most important themes on which research into water is focused.

Fig. 5 shows a general outline of the scientific and technological advances being developed for seawater desalination. Due to the complex composition of seawater, some of the above-mentioned research has implemented a pretreatment that may involve any of the following sub-stages: coagulation-flocculation, softening, flotation, UF, NF. The treatment would consist of the different operations existing today, such as those using membranes like FO, RO and electrodialysis. FO does not remove all contaminants from salt water, but it has the advantage of working at low pressure, which is why it can be used prior to RO treatment. Membranes are often fouled by biofouling or fouling and require chemicals for cleaning; therefore, they must be chemically resistant to cleaning agents or bactericides. For RO, new materials are being investigated such as hollow fiber membranes, at the simulation level membranes with carbon nanotubes, inclusions, or nanoparticle coatings with specific or bactericidal effects. For FO membranes, entrainment solutions are being developed to avoid the concentration polarization that hinders their operation. Conventional distillation plants tend to consume a lot of energy; if this energy could come from some other source where it is being wasted, the operation would be less costly. An alternative could be solar distillation; however, it

Fig. 3. *Distribution tree of keywords on seawater desalination, 1966–2023, elaborated in bibliometrics*

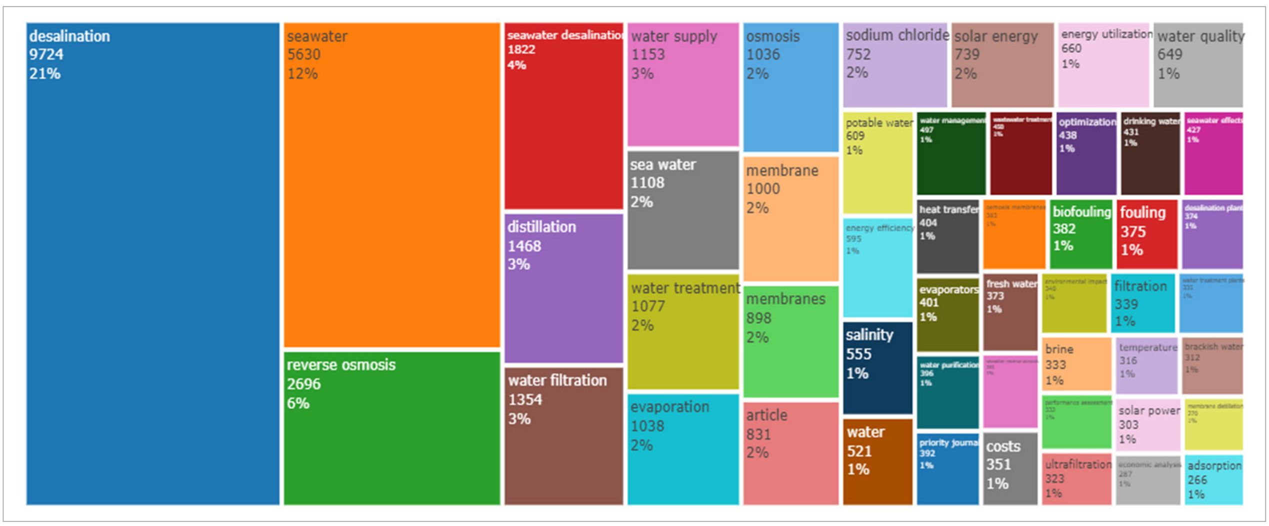


Fig. 4. *Dendrogram of the keywords on seawater desalination 1966–2023, elaborated with bibliometrics*

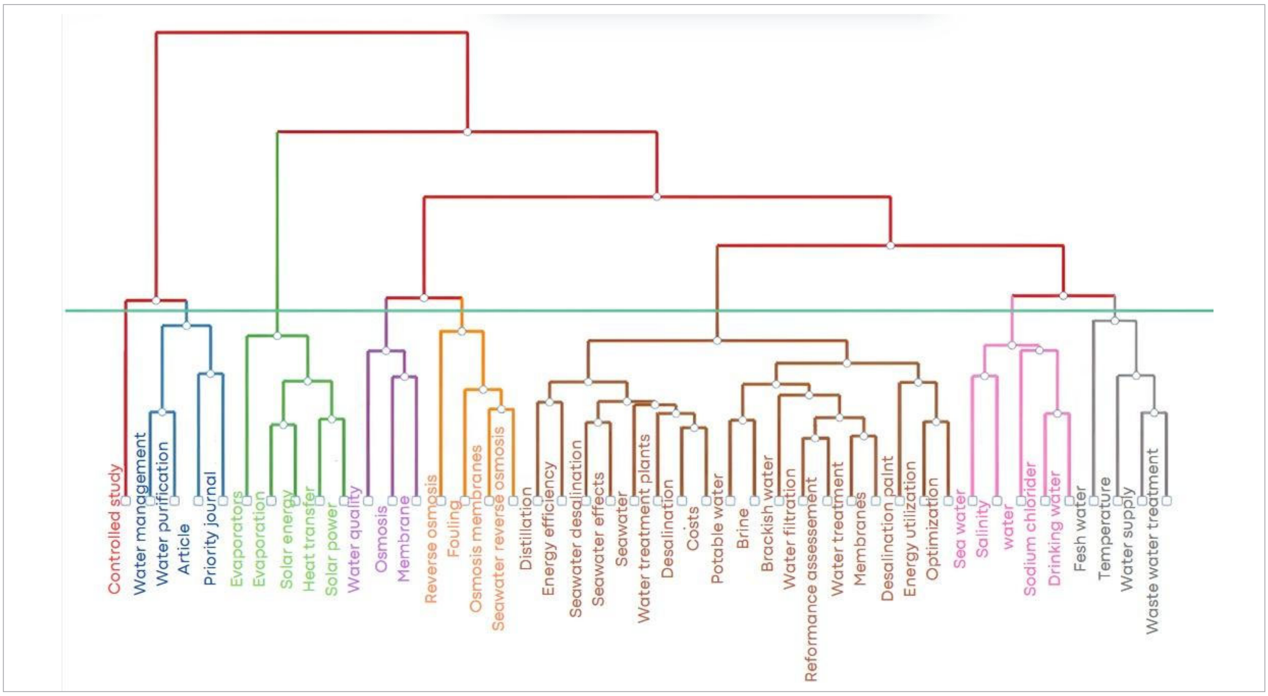
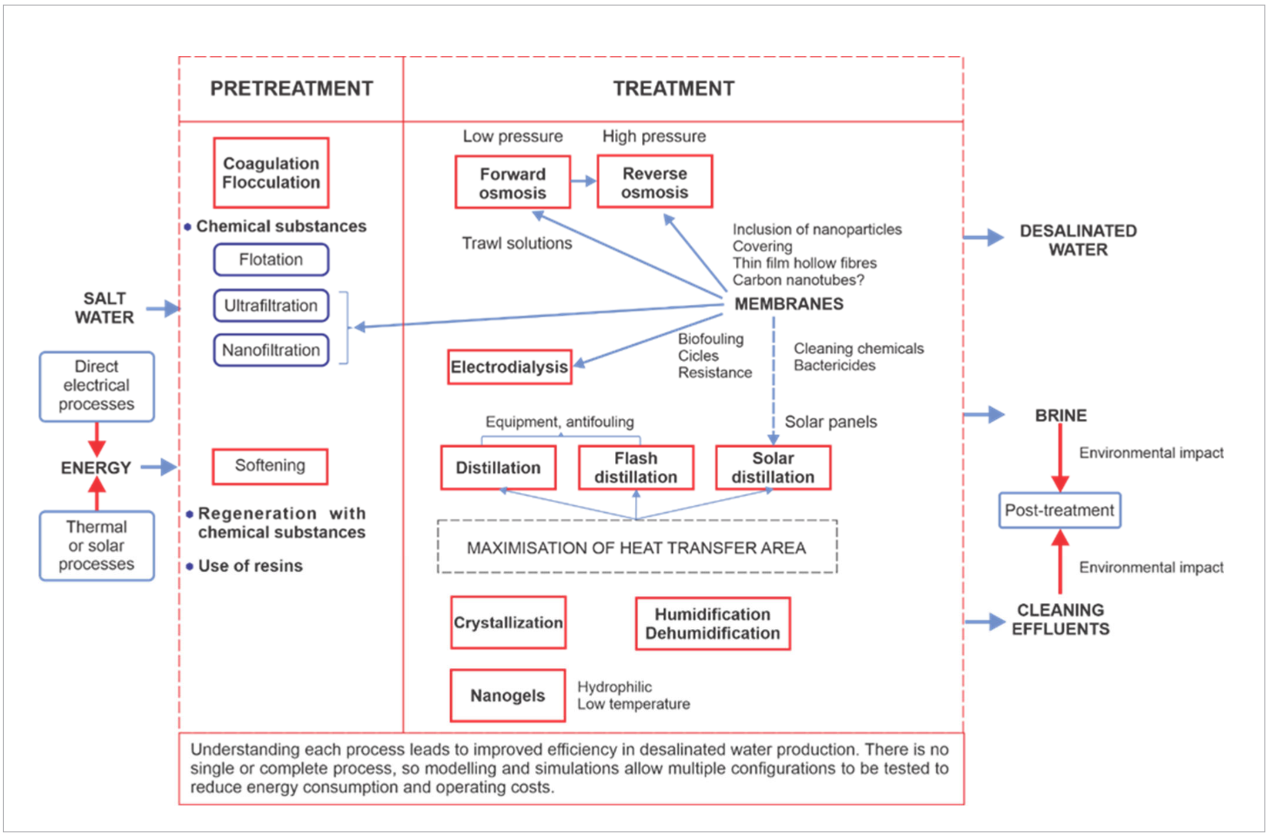


Fig. 5. *General outline of scientific and technological advances in seawater desalination*



still requires expensive solar panels. Distillation operations need a high heat transfer area to be successful; however, indirect heat transfer has limitations. Crystallization has been evaluated as a way to desalinate seawater, but energy consumption is high. Humidification and dehumidification may be simpler alternatives and require a combination with other processes to be operationally and economically feasible. Hydrophilic nanogels could revolutionize seawater purification as they are direct contact media for heat transfer causing the water to evaporate at lower temperatures with much lower energy consumption compared to other processes.

Economic perspectives, challenges and costs

The current analysis of seawater desalination shows a complex scenario. Although the growing need for potable water is driving the development of this technology, high energy costs and the required infrastructure remain major obstacles. From an economic point of view, the initial expenses in the construction of desalination plants, together with operating and maintenance costs, as well as intensive energy consumption, make desalinated water expensive. In addition, there are environmental challenges, such as brine waste management, and a heavy dependence on non-renewable energies that hinder its expansion. However, the development of cheaper materials, the use of renewable energies and improved process efficiency can reduce these costs and make desalination more affordable and sustainable in the long term.

The use of wind energy for seawater desalination, compared to conventional thermal methods, reduces energy consumption by 79.77%. Although 24.97% of the total energy consumption is attributed to construction, the system's 7.2-year payback period highlights its long-term effectiveness and sustainability (Guo et al., 2024). Solar desalination emerges as a decentralized and sustainable alternative to conventional methods, as solar thermal energy is less costly than photovoltaic systems due to its lower storage requirements. By 2030, it is expected to become even more economically viable as solar energy generation and storage costs continue to decrease (Menon et al., 2023). For instance, a study on RO desalination in China revealed a total direct energy consumption of 2.23×10^6 kWh and an embodied energy total of 2.18×10^7 kWh. Through system optimization, energy consumption could be reduced from 79.54% to 26.30%, demonstrating significant energy-saving potential in desalination projects (Liu et al., 2022b). In regions such as the Middle East and North Africa, solar desalination, particularly photovoltaic RO, has emerged as a promising solution to address water scarcity, offering greater efficiency and lower costs compared to traditional methods, while also tackling critical challenges such as aquifer depletion and pollution. This positions it as a sustainable and economically viable alternative (Maftouh et al., 2022). Additionally, innovative approaches like zero liquid discharge desalination, which integrates brine concentrators, high-pressure RO, and membrane-assisted crystallization, have achieved water recovery rates of 97.04%. This system is 3.28 times more cost-effective than traditional methods, with a cost of USD 1.00/m^3, and its profitability is further enhanced by the marketability of both water and solid salts (Panagopoulos and Giannika, 2024).

Ceramic NF membranes offer significant potential in desalination and lithium recovery from seawater brines, although their high cost remains a challenge. Salt rejection efficiency is determined by factors such as Donnan exclusion, steric exclusion, and zeta potential (Kirk et al., 2024). Recent studies on multichannel membrane capacitive deionization (MC-MCDI) have demonstrated advancements in improving desalination efficiency and reducing energy consumption, highlighting the method's advantages over conventional technologies, although challenges remain for its industrial-scale application (Kim et al., 2024). Microbial desalination cells (MDCs) represent a promising solution by combining saltwater desalination with electricity generation and wastewater treatment. Further improvements in their design and efficiency could position them as a competitive alternative to current desalination technologies (Aber et al., 2023).

Table 2 shows the different technologies applied in research, the production of desalinated water and the relationship with its cost. In this way, these costs of approximately the last decade serve as a baseline for the development of new research and/or technologies. Technologies with higher treatment capacity have lower unit costs in $/$m^3$.

Novel materials for seawater desalination

Seawater desalination is a promising solution to the growing scarcity of drinking water, conventional

Table 2. *Cost summary for seawater desalination processes*

	Type	Production	Costs ($\$/m^3$)	Reference
Solar thermal desalination	MSFD system	1000 m^3/day	0.97	Zheng et al. (2019)
	Small-Scale Solar MD desalination systems	500–1000 kg/day	5.16–5.92	Chang et al. (2014)
	Passive solar still	1043 L/year	34	Ranjan et al. (2013)
	Passive solar still modified	1043 L/year	7	Ranjan et al. (2013)
	Double slope passive solar still	1043 L/year	24	Ranjan et al. (2013)
	Solar driven sweeping gas MD desalination system	240 L/day	85	Moore et al. (2018)
	Solar MD	10 m^3/day	15	Karanikola et al. (2019)
	Reusable carbon black based solar evaporator	30 L/day	1.89	Chen et al. (2020)
	Conventional solar still	3.2 kg/day	49	Sharshi et al. (2016)
	Humidification – deshumidification	24.3 kg/day	58	Sharshi et al. (2016)
	Humidification – deshumidification solar still	66.3 kg/day	34	Sharshi et al. (2016)
Electrodialysis	Ten-stage continuous flow electrodialysis	---	22–39	McGovern et al. (2014)
	Electrodialysis reversal (EDR) technique	---	0.57–1.18	Hamdan et al. (2021)
Flash distillation	MSFD	---	0.5–0.9	Alhazmy (2014)
MED	System integrating MED and evaporative crystallization	---	4.17	Chen et al. (2021)
	Multiple effect evaporation and MD hybrid desalination system	---	2.05	Al-Obaidi et al., (2019)
	Thermal vapor compression system	55.20 kg/s	1.73	Fergani et al. (2023)
RO	Integration of hybrid power (wind-photovoltaic-diesel-battery) and seawater RO systems	1 m^3/h	2.20	Gökçek (2018)

methods, such as RO, are often costly due to energy consumption and the need to use specialized materials, such as advanced polymeric membranes or complex filtration systems. For this reason, in recent years, the focus has been on more economical alternatives that can optimize the process without compromising its efficiency, focusing on the incorporation of low-cost materials.

Membranes made from recycled polymers, carbon-based composites, nanomaterials and cellulose membranes are among these materials. They not only reduce production and maintenance costs, but can also increase efficiency.

The following is a review of some research that proposes the use of low-cost materials and inputs for different desalination technologies:

Anti-wetting hollow fibers optimize desalination by MD, achieving high water flux and 99.96% salt rejection (Alsebaeai et al., 2023). The use of MD reduces desalination costs; PVDF membranes, fabricated using the Vapor-Induced Phase Separation (VIPS) method for Air-Gap Membrane Distillation (AGMD), showed higher permeability and salt rejection of more than 99.5% (Shekari et al., 2024). The incorporation of the hydrophilic nanomaterial UiO-66-NH_2 improves the efficiency and long-term stability of cellulose acetate (CA) FO membranes, highlighting its potential to optimize performance and reduce costs in desalination (Li et al., 2022).

4,4'-(hexafluoroisopropylidene)diphthalic anhydride and 2,4,6-trimethyl-m-phenylenediamine (6FDA-TMPD) porous membranes, used for desalination by MD, stand out for their high porosity and efficiency without the need for chemical additives. These membranes have a flux of approximately 18.20 kg/m^2.h and a salt rejection of more than 99.96%, outperforming other commercial alternatives (Obidara et al., 2023). Likewise, GO modified polyamide (PA) membranes for brackish water desalination, after being functionalized and cross-linked, show good mechanical stability and high ion retention after multiple reuses. Their portable and low-cost design suggests high potential for applications in affordable desalination systems (Porangaba et al., 2023).

Table 3 shows some seawater desalination technologies with novel materials in which energy consumption was minimal or nil.

Table 3. *New materials used in seawater desalination technologies*

Desalination method	Main material used	Environmental impact	Energy consumption (kW-h/m^3)	Cost (USD/m^3, m^2)	Reference
Solar thermal desalination	Absorbent layer of Titanium Nitride Oxide (TiNO)	Low emissions; uses renewable energy; minimal waste	0.5	0.50	Chang et al. (2021)
MD	Coaxially electrospun superhydrophobic nanofibers Poly(vinylidene fluoride-*co*-hexafluoropropylene (PVDF- co -HFP) and Dimethylformamide (DMF)	Moderate environmental impact due to energy efficiency and waste reduction.	3.0	0.75	Woo et al. (2021)
Solar thermal desalination	Carbon black	Low environmental impact	No consumption	1.89	Chen et al. (2020)
Solar thermal desalination	Polymer film	Low environmental impact	No consumption	3.00	Ni et al. (2018)
Evaporation	Konjac glucomannan and iron-based photothermal nanoparticles	Low environmental impact	1.0	14.90	Guo et al. (2020)
Solar thermal desalination	Multi-walled carbon nanotubes and bicomponent fabric composed of polypropylene/polyethylene core and core-sheath fibers	Low environmental impact	No consumption	2.40	Zhu et al. (2021)

Conclusions

The following results were reached based on the bibliometric analysis, which took costs, economic perspectives, challenges, and the creation of novel materials into account:

- Review addressed the latest advances in seawater desalination, categorized into 8 clusters (biofouling, solar and renewable energy, FO, MD, RO and energy recovery, NF, UF pretreatment, neural network design) based on bibliometric analysis.
- Technological improvements in conventional equipment (distillation, flash distillation, crystallizers) enhance energy efficiency, but thermal requirements remain high.
- Development of new membranes, entrainment solutions, and hydrogels for RO, direct osmosis, and solar distillation was highlighted.
- Incorporating nanoparticles into membranes shows potential for improving membrane performance.
- Energy reuse from thermal processes and the integration of solar energy are key to future cost reductions.
- Process simulation helps optimize energy costs by analyzing process combinations.
- Pretreatment processes, especially coagulation-flocculation and softening, are crucial for the longevity of RO operations.
- Biofouling remains a major issue for membranes; solutions include bactericides, antifouling agents, and nanoparticle coatings.
- Brine from RO must be treated before disposal to prevent eutrophication in marine environments.
- The costs of technologies, new materials and research work for seawater desalination have been compiled as

a baseline for future research aimed at modifying or developing new processes with the consequent reduction of costs.

The review encourages continued research on cutting-edge topics to promote a circular and sustainable economy in desalination processes.

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