Water Reuse

© 2023 The Authors

Water Reuse Vol 13 No 3, 475 doi: 10.2166/wrd.2023.065

Advancements in saline water treatment: a review

V. Somashekar[a], A. Vivek Anand[b], V. Hariprasad[a], Emad M. Elsehly[c] and Mofwe Kapulu[d,*]

[a] Department of Aerospace Engineering, IIAEM, Jain (Deemed-to-be) University, Bengaluru, Karnataka, India
[b] Department of Aeronautical Engineering, MLR Institute of Technology, Hyderabad, Telangana, India
[c] Physics Department, Faculty of Science, Damanhour University, 22516, Damanhour, Egypt
[d] School of Engineering, University of Zambia, Lusaka, Zambia
*Corresponding author. E-mail: mofwe.kapulu@unza.zm

MK, 0000-0003-0101-5418

ABSTRACT

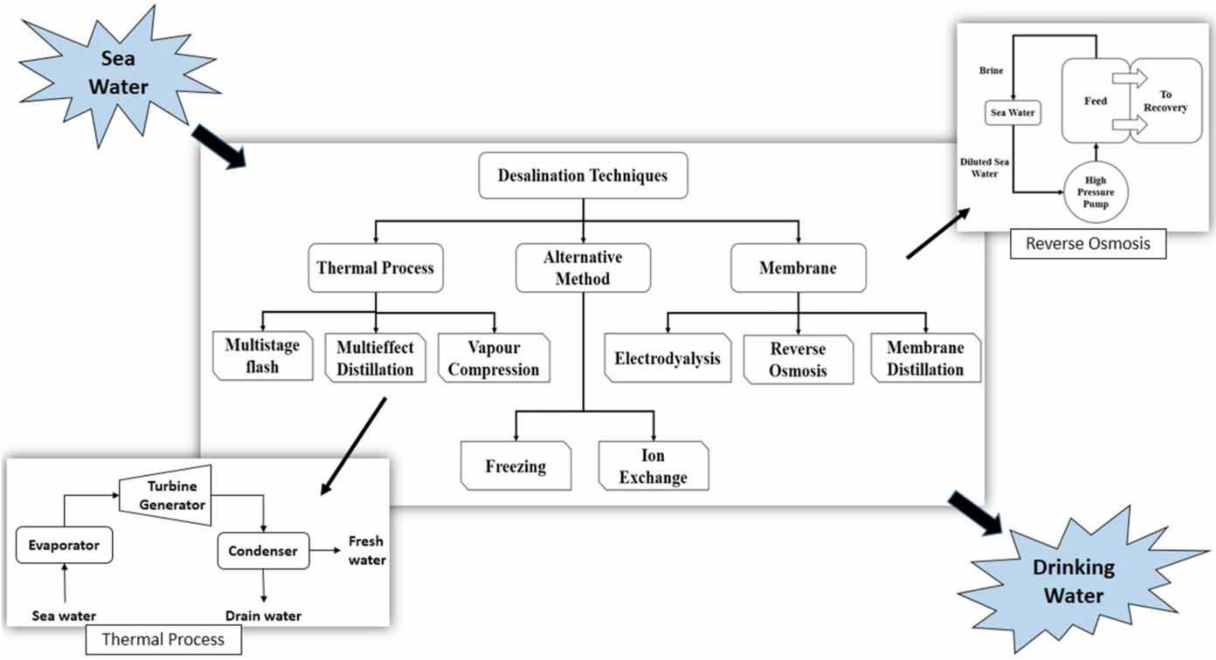
The growing population and increasing water demand necessitate exploring alternative sources of water, including saline water. Saline water treatment technologies have undergone significant advancements in recent years, enabling the production of potable water from seawater and brackish water. This review provides an overview of the current state of saline water treatment technologies, including desalination and membrane-based processes. The advantages and limitations of each technology and their suitability for different applications are discussed. Recent advancements in materials and techniques that have led to improvements in energy efficiency, productivity, and cost-effectiveness of these technologies are highlighted. Finally, the future directions and challenges in the field of saline water treatment are outlined.

Key words: potable drinking water, reverse osmosis, saline water treatment technologies, sea water, thermal process

HIGHLIGHTS

- An overview of the current state of saline water treatment technologies.
- The critical review was conducted on recent advancements in materials and saline water treatment techniques that have led to improvements in energy efficiency, productivity, and cost-effectiveness.
- The challenges associated with energy consumption and brine disposal were discussed elaborately.

GRAPHICAL ABSTRACT



INTRODUCTION

Water is one of the most critical resources on our planet, and the availability of freshwater is essential for sustaining life and supporting economic development. However, with the growing global population and increasing demands for water, the supply of freshwater is becoming limited. Moreover, climate change is leading to changes in precipitation patterns and causing more frequent and severe droughts, exacerbating water scarcity in many regions. In this context, saline water treatment has become an increasingly important area of research and development (Baker & Davis 2014; Siddiqi & Garland 2014; WHO 2023).

Saline water treatment involves the removal of salt and other dissolved solids from saline water, making it suitable for human consumption, irrigation, and industrial use. There are two main sources of saline water: seawater and brackish water. Seawater is abundant, accounting for approximately 97% of the world's water resources (Table 1). Brackish water is less salty than seawater but still contains significant amounts of dissolved solids. The salt content in brackish water can range from approximately 0.05 to 3% (or 500–30,000 parts per million, ppm) depending on the specific location and

Table 1 | Constituents of saline water

Constituents	Concentration (mg/L)
Sodium chloride	35,000–40,000
Magnesium	1,000–2,000
Calcium	400–500
Calcium	400–500
Sulfate	2,700–3,400
Bicarbonate	150–300
Boron	4–5
Strontium	7–8

Note: The concentrations provided are approximate values and may vary depending on the specific saline water source.

conditions. Both sources of water can be treated using a range of technologies, including desalination and membrane-based processes (Hawlader *et al.* 2011; U.S. Department of the Interior 2017; Li *et al.* 2021a; Yabalak *et al.* 2022).

Desalination is a process that removes salt and other dissolved solids from seawater or brackish water, producing freshwater. The two primary desalination technologies are thermal-based processes, such as multi-stage flash (MSF) distillation and multi-effect distillation (MED), and membrane-based processes, such as reverse osmosis (RO) and nanofiltration (NF). In recent years, the use of desalination technologies has grown significantly, driven by improvements in technology and decreasing costs (Al-Karaghouli & Kazmerski 2013; Ghaffour *et al.* 2013; Chen *et al.* 2014; Elimelech & Winston Ho 2017).

Membrane-based processes involve the use of a membrane to separate salt and other dissolved solids from water. The most widely used membrane-based technology for desalination is RO, which involves the use of high pressure to force water through a semi-permeable membrane, leaving behind salt and other dissolved solids. Other membrane-based technologies include NF, electrodialysis (ED), and forward osmosis (FO) (Cath *et al.* 2006; Wang *et al.* 2011; Kim & Cho 2014; Tang & He 2016; Elimelech & Winston Ho 2017; Arslan *et al.* 2022).

Recent advancements in materials and techniques have led to significant improvements in the energy efficiency of desalination and membrane-based processes. For example, the development of new membrane materials with improved selectivity and fouling resistance has led to higher water recovery rates and reduced energy consumption. Additionally, the use of renewable energy sources, such as solar and wind power, is becoming more prevalent in desalination plants, reducing their environmental impact and making them more sustainable (Alharbi *et al.* 2019; Chen *et al.* 2020; Pramanik & Maity 2020; Kim *et al.* 2021; Sahu & Chakraborty 2021).

Despite these advancements, several challenges still need to be addressed in saline water treatment. The high energy consumption of desalination plants remains a significant challenge, as does the disposal of brine waste, which can harm the environment if not properly managed. Moreover, the high cost of desalinated water can make it inaccessible to communities with limited resources (Lattemann & Höpner 2008; Al-Karaghouli & Kazmerski 2013; Ghaffour *et al.* 2013).

In conclusion, saline water treatment is an essential area of research and development, with significant advancements made in recent years. Continued efforts to improve the efficiency and sustainability of desalination and membrane-based processes could lead to the development of more cost-effective and environmentally friendly technologies, enabling the provision of potable water to more people around the world (Shannon *et al.* 2008; Elimelech & Winston Ho 2017; Buros & Perez-Gonzalez 2019; Gude & Nirmalakhandan 2019).

Saline water, which includes seawater and brackish water, represents a vast and largely untapped source of water. With the ever-increasing demand for freshwater, the use of saline water for various applications, including drinking, irrigation, and industrial purposes, has become increasingly attractive. However, the high salt content of saline water presents significant challenges in treating it to produce potable water. Over the years, various technologies have been developed to overcome these challenges, including thermal and membrane-based processes. In this review, we will discuss the advancements made in the field of saline water treatment (Hsieh & Huang 1995; Babel & Kurniawan 2004; Logan *et al.* 2006; Nghiem & Hawkes 2008; Greenlee *et al.* 2009; Elimelech *et al.* 2011; Hasan *et al.* 2012; Kim *et al.* 2012; Suárez & Rubio 2015; Wang & Wu 2016). In addition, some of the commonly found microorganisms in the saline environment are listed in Table 1. Care must be taken to remove the microorganisms which thrive in these environments and make it unusable for the regular applications.

This review presents an overview of the current state of saline water treatment technologies, including desalination and membrane-based processes, as well as their advantages, limitations, and suitability for various applications. Recent advancements in materials and techniques that have led to improvements in energy efficiency, productivity, and cost-effectiveness of these technologies are also discussed. Finally, future directions and challenges in the field of saline water treatment are outlined.

MATERIALS AND METHODS

The materials and methods used for this review paper on saline water treatment involved conducting a comprehensive literature review. We searched various online databases, including PubMed, Web of Science, and Google Scholar, using a combination of keywords and phrases related to saline water treatment, desalination, and membrane-based processes.

This research included peer-reviewed articles, books, and other sources of information published between 2010 and 2022. We excluded articles that were not in English, duplicate articles, and articles that were not relevant to the topic of saline water treatment.

The literature review was conducted in two stages. First, we conducted a preliminary search to identify relevant articles and to develop a list of potential keywords and search terms. Second, we conducted a more focused search, using the identified keywords and search terms, to obtain more specific information on the chosen topics.

We identified key themes and trends in the literature by synthesizing and analyzing the information obtained from the literature review. This involved categorizing and summarizing the information according to the chosen themes and trends. We used this information to develop an outline for the review paper and to write the literature review section.

The literature review section includes a discussion of the various desalination technologies, including RO, ED, FO, and membrane distillation (MD), and their relative advantages and disadvantages. We also discussed the challenges facing saline water treatment, including the disposal of brine waste and the high cost of desalination, and proposed possible solutions to address these challenges.

The implications of the findings were discussed in the conclusion section, including the potential for combining desalination with renewable energy sources to make the process more sustainable and cost-effective. We also highlighted the need for further research to develop more effective and sustainable treatment methods that can be implemented on a smaller scale.

Desalination technologies

Desalination is the process of removing salt and other minerals from saline water to produce freshwater (Figure 1). There are two main types of desalination technologies: thermal and membrane-based processes. Thermal processes, including MSF and MED, use heat to evaporate water and separate it from the salts. These processes are energy-intensive and require high capital investments. On the other hand, membrane-based processes, including RO and NF, use semi-permeable membranes to separate water from the salts. These processes are less energy-intensive and have become more popular in recent years due to their lower capital costs (Greenlee *et al.* 2009; Elimelech *et al.* 2011; Al-Karaghouli & Kazmerski 2013; Suárez & Rubio 2015; Wang & Wu 2016).

Desalination technologies have been used for several decades to produce freshwater from seawater and brackish water. In recent years, there has been a growing interest in these technologies, as they can produce high-quality water that meets the drinking water standards set by regulatory agencies. Membrane-based processes, in particular, have become more popular due to their lower energy requirements and capital costs compared to thermal processes (Cath *et al.* 2006; Blandin & Gavach 2013; Kim *et al.* 2016; Jeong *et al.* 2017; Li *et al.* 2017).

In addition to providing a source of freshwater, saline water treatment has several other applications, including irrigation, industrial processes, and environmental conservation. Saline water can be used for irrigation in arid regions where freshwater resources are limited. It can also be used in industrial processes that require high-quality water, such as the production of semiconductors and pharmaceuticals. Furthermore, the use of saline water in some applications can help reduce the pressure on freshwater resources and promote environmental conservation (Chong *et al.* 2010; Hoek & Elimelech 2015; Li *et al.* 2017; Han *et al.* 2019; Suárez & Rubio 2019; Liu *et al.* 2020).

Desalination technologies are used to remove salts and other impurities from saline water to produce freshwater. There are two main types of desalination technologies: thermal processes and membrane-based processes (Figure 2) (Elimelech *et al.* 2011; Al-Karaghouli & Kazmerski 2013; Shannon *et al.* 2013; Kim *et al.* 2019b; Ghaffar *et al.* 2023).

Some common thermal desalination processes include MSF and MED, which use heat to evaporate water and separate it from the salts. Membrane-based processes include RO and NF, which use semi-permeable membranes to separate water from

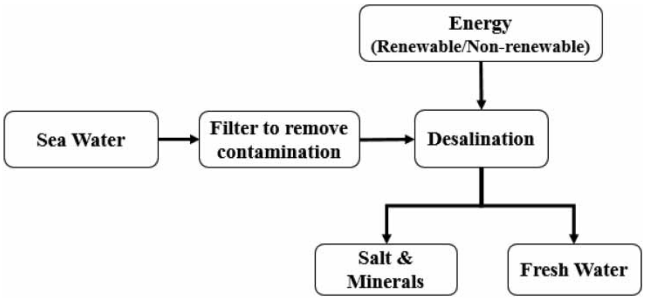


Figure 1 | Schematic diagram of the desalination process.

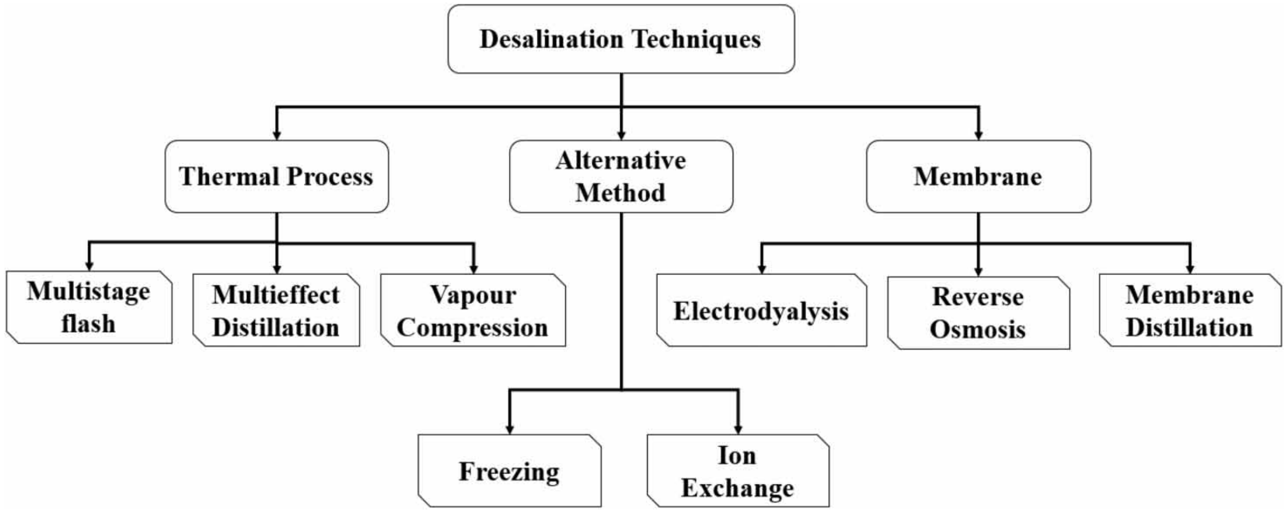


Figure 2 | Desalination methods.

the salts. Both thermal and membrane-based processes have their advantages and limitations, and their suitability for different applications depends on factors such as water quality, energy requirements, and cost-effectiveness (Shannon *et al.* 2008, 2013; Elimelech *et al.* 2011; Al-Karaghouli & Kazmerski 2013; Kim *et al.* 2019b).

Thermal processes involve heating saline water to produce steam, which is then condensed to produce freshwater. The most commonly used thermal processes are MSF distillation, MED, and vapor compression (VC) distillation (Elimelech *et al.* 2011; Al-Karaghouli & Kazmerski 2013; Mujtaba & Mohammad 2017; Isik *et al.* 2022).

MSF distillation is the oldest and most widely used thermal process. It involves heating saline water in a series of flash chambers to produce steam, which is then condensed to produce freshwater. The process requires a large amount of energy and is, therefore, more expensive than membrane-based processes (Elimelech *et al.* 2011; Al-Karaghouli & Kazmerski 2013; Badruzzaman *et al.* 2016). The specific temperature and pressure ranges may vary depending on the design and configuration of the MSF plant, but the following ranges are commonly encountered:

Evaporation stage:

- Temperature: typically, the evaporation stage operates at temperatures ranging from 70 °C (158°F) to 110 °C (230°F)
- Pressure: the evaporation stage operates under high pressure, usually ranging from 4 to 10 bar (58 to 145 psi).

Condensation stage:

- Temperature: the temperature in the condensation stage ranges from approximately 30 °C (86°F) to 50 °C (122°F).
- Pressure: the pressure in the condensation stage is significantly lower than the evaporation stage. It typically ranges from atmospheric pressure to slightly above atmospheric pressure, depending on the design and efficiency of the condensation process.

MED is a variation of MSF distillation that involves heating saline water in multiple stages to produce freshwater. Each stage is operated at a lower temperature and pressure than the previous stage, which results in a higher overall efficiency than MSF. However, MED also requires a large amount of energy and is less efficient than membrane-based processes (Goosen & Hin 2005; National Research Council 2008; Greenlee *et al.* 2009; IDE Technologies; Yabalak *et al.* 2022).

VC distillation is a newer technology that uses mechanical compressors to compress steam, which increases its temperature and pressure (Wang *et al.* 2018a; Chen & Law 2019). This results in higher energy efficiency than MSF (Alkhudhiri & Darwish 2012; Shannon *et al.* 2013) and MED (El-Dessouky & Ettouney 2016; Kim *et al.* 2019b), but the process is still more expensive than membrane-based processes.

Membrane-based processes, on the other hand, use semi-permeable membranes to separate salts and other impurities from saline water. The most commonly used membrane-based processes are RO and ED (Shannon *et al.* 2008; Elimelech & Winston Ho 2017; Li *et al.* 2019a).

RO involves applying pressure to saline water to force it through a semi-permeable membrane, which allows water molecules to pass through while blocking salts and other impurities. RO is highly efficient and requires less energy than thermal processes, which makes it more cost-effective (Greenlee *et al.* 2009; Elimelech *et al.* 2011).

ED, on the other hand, uses an electric field to separate salts and other impurities from saline water. The process involves passing saline water through a stack of ion exchange membranes, which separate ions based on their charge. ED is less efficient than RO and is therefore used mainly for brackish water desalination (Greenberg *et al.* 1992; Veza & Moulik 2001; Oron & Sagi 2013; Arslan *et al.* 2022).

Advancements in membrane-based processes

Membrane-based processes, particularly RO, have undergone significant advancements in recent years, leading to improved energy efficiency, productivity, and cost-effectiveness. One of the major advancements in RO technology is the development of high-rejection membranes that can achieve up to 99% salt rejection rates. Additionally, the use of low-energy RO (LE-RO) systems, which operate at lower pressures and temperatures, has led to significant reductions in energy consumption. Other advancements include the development of new materials for membranes, such as graphene oxide (GO) and carbon nanotubes, that have higher salt rejection rates and lower fouling tendencies (Kim *et al.* 2017a; Al-Mutaz & Hilal 2019; Chung *et al.* 2019; Song *et al.* 2019).

Membrane-based processes have become increasingly popular for desalination and other saline water treatment applications due to their lower energy requirements and capital costs compared to thermal processes. In recent years, several advancements have been made to improve the efficiency and cost-effectiveness of these processes (Shannon *et al.* 2008; Kim *et al.* 2011; Zhang *et al.* 2021).

One of the major advancements in membrane-based processes is the development of new materials for membranes. For example, GO membranes have shown promising results in desalination due to their high permeability and salt rejection properties. The use of nanomaterials, such as carbon nanotubes, has also shown the potential in improving the efficiency of membrane-based processes (Mi 2014; Li *et al.* 2016; Liu *et al.* 2018; Wang *et al.* 2018b).

Another area of advancement is the development of new membrane configurations. One such configuration is the spiral-wound membrane module, which has a higher packing density than the traditional flat-sheet module and can therefore process more water in the same footprint. In addition, the use of hollow fiber membranes has been shown to improve the efficiency of membrane-based processes by increasing the surface area available for water filtration (Li & Elimelech 2013; Karan *et al.* 2015; Kim *et al.* 2017b; Song *et al.* 2020). The salinity and main nutrient components removal efficiency using a submerged membrane bioreactor (MBR) system is listed in Table 2.

In addition to material and configuration advancements, there have also been developments in the use of membrane-based processes for wastewater treatment. MBRs are a combination of biological treatment and membrane filtration that have been shown to be effective in treating municipal and industrial wastewater. MBRs can produce high-quality effluent that meets or exceeds regulatory standards (Table 3), and they have a smaller footprint compared to traditional wastewater treatment plants (Hélix-Nielsen *et al.* 2002; Fane & Tang 2011; Judd 2011; Chua *et al.* 2015).

Table 2 | Microorganisms commonly found in saline environment

Reference No	Microorganism	Gram staining	Microbial metabolism	Common shape	Salinity
Kim *et al.* (2019a), Bakkiyaraj & Pandian (2015)	*Vibrio* spp.	Negative	Aerobic/ Anaerobic	Curved rods	Moderate to high
Pino *et al.* (2018), Díaz-Cárdenas *et al.* (2017)	*Halomonas* spp.	Negative	Aerobic	Coccobacilli	High
Abdul Azis *et al.* (2020), Priyadharshini & Muthukumar (2018)	*Marinobacter* spp.	Negative	Aerobic	Coccobacilli	High
DasSarma & DasSarma (2015)	*Halanaerobium* spp.	Positive	Anaerobic	Straight rods	High
Amoozegar *et al.* (2014)	*Haloferax* spp.	Negative	Aerobic	Pleomorphic	High
Singh *et al.* (2014)	*Haloarcula* spp.	Negative	Aerobic	Pleomorphic	High

spp. stands for 'species pluralis' or 'multiple species'.

Table 3 | Salinity and main nutrient components removal efficiency in submerged membrane bioreactor (MBR) system

Ref No.	Salinity (mg/L)	Main nutrition components	Removal efficiency	Region	Operating conditions	Bioreactor type
Lee *et al.* (2014)	80,000	COD, NH_3-N	91.3%, 99.4%	Korea	HRT: 12 h, SRT: 50 days, MLSS: 5,000 mg/L	Submerged MBR
Zhao *et al.* (2017)	60,000	COD, NH_3-N	86.6%, 97.4%	China	HRT: 6 h, SRT: 40 days, MLSS: 4,000 mg/L	Submerged MBR
Wei *et al.* (2019)	50,000	COD, NH_3-N	83.5%, 97.2%	China	HRT: 8 h, SRT: 40 days, MLVSS: 3,000 mg/L	Submerged MBR
Koseoglu-Imer *et al.* (2017)	40,000	COD, NH_3-N	85.7%, 96.9%	Turkey	HRT: 10 h, SRT: 40 days, MLSS: 5,000 mg/L	Submerged MBR
Wu *et al.* (2018)	30,000	COD, NH_3-N	84.8%, 99.5%	China	HRT: 6 h, SRT: 40 days, MLSS: 3,000 mg/L	Hybrid MBBR-SMBR
Li *et al.* (2019b)	25,000	COD, NH_3-N	83.6%, 98.8%	China	HRT: 10 h, SRT: 30 days, MLVSS: 3,000 mg/L	Submerged MBR
Chen *et al.* (2017)	20,000	COD, NH_3-N	87.7%, 96.6%	China	HRT: 10 h, SRT: 30 days, MLSS: 3,000 mg/L	Submerged MBR
Gupta & Mody (2019)	15,000	COD, NH_3-N	87.5%, 98.6%	Korea	HRT: 6 h, SRT: 40 days, MLSS: 5,000 mg/L	Submerged MBR

COD, Chemical Oxygen Demand; HRT, Hydraulic Retention Time; MBBR, Moving bed biofilm reactor; MLSS, Mixed Liquor Suspended Solids; MLVSS, Mixed Liquor Volatile Suspended Solids; SMBR, submerged membrane bioreactor; SRT, Solids Retention Time.

Furthermore, the use of hybrid membrane systems, which combine multiple membrane-based processes, has shown promise in improving the efficiency of saline water treatment. For example, combining RO and NF can improve the overall efficiency of the treatment process by reducing the load on the RO membrane and prolonging its lifespan (Ng *et al.* 2015; Wang *et al.* 2018c; Bai *et al.* 2019; Yang *et al.* 2020).

Overall, advancements in membrane-based processes have led to improvements in energy efficiency, productivity, and cost-effectiveness. The use of new materials, configurations, and hybrid systems has shown promise in improving the efficiency of saline water treatment and expanding its applications beyond desalination (Li *et al.* 2019c; Ortega-Méndez *et al.* 2019; Wang *et al.* 2019a; Radu *et al.* 2020; Chung & Zhang 2021; She *et al.* 2021).

Challenges and future directions

Despite the significant advancements in saline water treatment, there are still several challenges that need to be addressed. These include the high energy requirements of desalination technologies, the environmental impact of disposing of concentrated brine, and the high capital costs of membrane-based processes. One eco-friendly use case for concentrated brine is its utilization in the production of industrial minerals. Another eco-friendly use case for concentrated brine is its potential for energy generation through the process of pressure-retarded osmosis (PRO). Future research should focus on developing more energy-efficient and cost-effective technologies, as well as finding sustainable solutions for brine disposal. Additionally, the use of renewable energy sources, such as solar and wind, in desalination plants could reduce their carbon footprint and make them more sustainable (Malaeb *et al.* 2011; Kim & Amy 2017, 2018).

Despite the advancements in desalination technologies, there are still several challenges that need to be addressed to make the process more efficient and sustainable. One of the major challenges is the high energy consumption required for desalination processes, which can increase the cost and carbon footprint of the process. This is particularly true for thermal processes, such as MSF and MED, which require large amounts of energy for heating and evaporation (Shannon *et al.* 2008; Al-Karaghouli & Kazmerski 2013; Elimelech & Winston Ho 2017; Ortega-Méndez *et al.* 2019).

Another challenge is the disposal of brine, which is the concentrated saltwater stream produced during the desalination process. Discharging brine into the ocean can have negative impacts on marine ecosystems, and finding alternative methods of disposal, such as brine concentration or utilization, is necessary (Post *et al.* 2013; Shannon *et al.* 2013; Kim & Lee 2016).

Furthermore, the high capital costs associated with desalination plants can make the technology inaccessible for some communities and countries. Developing cost-effective desalination technologies and reducing the overall cost of desalination are important for making the technology more accessible and equitable (Al-Kharabsheh & Arafat 2018; Giwa *et al.* 2019; Alpatova *et al.* 2021; García-Rodríguez *et al.* 2021a).

In terms of future directions, there are several areas of research and development that can lead to improvements in desalination technologies. One area is the development of renewable energy-powered desalination plants, which can reduce the carbon footprint of the process and make it more sustainable. Another area of research is the development of more efficient and selective membranes, which can reduce the energy requirements of membrane-based processes (Kim & Hoek 2018; Liu & Ghassemi 2018).

Moreover, improving the efficiency of existing desalination plants through process optimization and the use of smart technologies can also lead to significant improvements in the overall sustainability of the process. For example, the use of sensors and data analytics can help optimize the operation of desalination plants and reduce energy consumption (Al-Karaghouli & Kazmerski 2018; Al-Zahrani & Abdulkareem 2019; Hasan *et al.* 2021).

Overall, addressing the challenges associated with desalination and investing in research and development to improve the efficiency and sustainability of the process can help expand the applications of desalination and make it more accessible and equitable for communities and countries around the world (Cohen 2004; Shannon *et al.* 2008; Crittenden *et al.* 2012; Qadir & Shahid 2013; Yigitoglu *et al.* 2016; Kim *et al.* 2019c).

Both thermal and membrane-based processes have their advantages and limitations. The choice of technology depends on several factors, including the quality of the saline water, the volume of water required, and the cost of energy. In recent years, there has been growing interest in improving the energy efficiency and cost-effectiveness of desalination technologies, particularly membrane-based processes. Promising results have been shown by new materials and techniques, such as FO and MD, and they may play a significant role in the future of saline water treatment (Shannon *et al.* 2013; Kumbharkar & Davis 2019; Kim *et al.* 2020; Zhao *et al.* 2020).

Thermal processes involve heating saline water to produce steam, which is then condensed to produce freshwater. MSF distillation is the oldest and most widely used thermal process. It involves heating saline water in a series of flash chambers to produce steam, which is then condensed to produce freshwater. The process requires a large amount of energy and is therefore more expensive than membrane-based processes. MED is a variation of MSF distillation that involves heating saline water in multiple stages to produce freshwater. Each stage is operated at a lower temperature and pressure than the previous stage, which results in a higher overall efficiency than MSF. However, MED also requires a large amount of energy and is less efficient than membrane-based processes. VC distillation is a newer technology that uses mechanical compressors to compress steam, which increases its temperature and pressure. This results in higher energy efficiency than MSF and MED, but the process is still more expensive than membrane-based processes. Membrane-based processes, on the other hand, use semi-permeable membranes to separate salts and other impurities from saline water. The most commonly used membrane-based processes are RO and ED. RO involves applying pressure to saline water to force it through a semi-permeable membrane, which allows water molecules to pass through while blocking salts and other impurities. RO is highly efficient and requires less energy than thermal processes, which makes it more cost-effective (Kim *et al.* 2019d; Tsydenova & Iakovleva 2019; Global Water Intelligence 2021; Lee *et al.* 2021; Li *et al.* 2021b).

Recent advancements in materials and techniques have led to significant improvements in the energy efficiency of saline water treatment processes. One promising development is the use of FO technology, which uses a draw solution to pull water through a membrane and produce freshwater. FO has several advantages over traditional RO technology, including lower energy consumption and reduced fouling of the membrane. Another promising development is the use of MD, which uses a hydrophobic membrane to vaporize water and produce freshwater. MD has the advantage of being able to treat high-salinity water sources and has lower energy requirements compared to RO (Cath *et al.* 2006; Goh & Chong 2015a; Khayet 2018; Warsinger *et al.* 2018; Zhang *et al.* 2020).

Furthermore, advancements in membrane materials, such as GO and nanocomposite membranes, have led to more efficient and selective membranes that require less energy to operate. Additionally, the development of novel desalination processes, such as capacitive deionization, which uses an electrical field to remove ions from saline water, shows promise in reducing energy consumption and improving efficiency (Shannon *et al.* 2013; Ali *et al.* 2019; Wang *et al.* 2019b; Lee *et al.* 2020; Qiu *et al.* 2020).

Advancements in membrane materials

- Development of new membrane materials with improved selectivity and fouling resistance, such as GO, carbon nanotubes, and nanofibers, has led to higher water recovery rates and reduced energy consumption (Kim *et al.* 2019b; Zhao *et al.* 2020).
- Modification of existing membrane materials, such as polyamide (PA) and polysulfone (PS), with nanoparticles and other additives has also improved their performance and reduced energy consumption (Kim & Lee 2016).
- The use of thin-film composite (TFC) membranes with a highly permeable selective layer has also led to significant improvements in energy efficiency and productivity (Ortega-Méndez *et al.* 2019).

The following are some commonly used materials in membrane fabrication and each has its own limitations, which needs to be addressed while working for newer materials for the membrane:

- PA – PA membranes, such as TFC membranes, are widely used in RO and NF processes. They exhibit excellent salt rejection properties and high mechanical strength.
- Cellulose Acetate (CA) – CA membranes are often employed in the production of brackish water and low-pressure RO membranes. They have good chemical resistance and are cost-effective.
- PS – PS membranes are known for their high thermal and chemical stability, making them suitable for various applications, including ultrafiltration (UF) and microfiltration (MF).
- Polyethersulfone (PES) – PES membranes have similar properties to PS membranes and are commonly used in water treatment processes, including UF and MF.
- Polyvinylidene fluoride (PVDF) – PVDF membranes are resistant to chemicals and have good mechanical strength. They are used in UF, MF, and gas separation applications.
- Polypropylene (PP) – PP membranes are used in MF and UF processes due to their high chemical resistance and excellent fouling resistance properties.
- Ceramic materials – ceramic membranes, such as alumina (Al_2O_3) and zirconia (ZrO_2), are used for high-temperature applications and are known for their exceptional chemical and thermal stability.
- GO – GO membranes, made from a single layer of carbon atoms, exhibit high selectivity and permeability. They are being researched for various filtration applications.
- TFC – Thin film composite membranes consist of a polyamide active layer on top of a porous support layer. They are commonly used in RO processes.

Advancements in desalination technologies

- Improvements in the design and operation of desalination plants, such as the use of energy recovery devices and optimized operating conditions, have led to significant reductions in energy consumption and cost (Kim *et al.* 2019b).
- Integration of desalination plants with renewable energy sources, such as solar and wind power, has also reduced their environmental impact and made them more sustainable (Kim *et al.* 2019b).
- The development of new desalination technologies, such as FO and MD, has also shown promise in reducing energy consumption and improving water recovery rates (Kim *et al.* 2019b; Zhang *et al.* 2020).

Future directions and challenges

- Continued efforts to improve the selectivity, fouling resistance, and permeability of membrane materials are needed to further increase the efficiency and productivity of membrane-based processes (Elimelech & Winston Ho 2017).
- Research into the use of alternative energy sources, such as geothermal and wave power, could lead to the development of more sustainable desalination technologies (Fane & Tang 2011).
- The disposal of brine waste remains a significant challenge, and innovative solutions, such as the use of brine for resource recovery and the development of zero liquid discharge technologies, are needed to address this issue (Gude 2016).
- The high cost of desalinated water remains a barrier to its widespread adoption, particularly in developing countries. Continued efforts to reduce the cost of desalination and increase access to financing for desalination projects could help address this challenge (Lin *et al.* 2019).

Cost-effectiveness

Cost-effectiveness in saline water treatment refers to the ability of desalination and membrane-based technologies to provide high-quality water at a reasonable cost. This is a crucial factor in ensuring that these technologies are accessible to communities with limited resources (Al-Karaghouli & Kazmerski 2013).

In recent years, there have been significant advancements in desalination and membrane-based technologies that have led to improvements in cost-effectiveness. For example, the development of new membrane materials with improved selectivity and fouling resistance has led to higher water recovery rates and reduced energy consumption, thereby lowering the cost of producing desalinated water. Additionally, the use of renewable energy sources, such as solar and wind power, has also helped to reduce the cost of desalination plants (Goh & Chong 2015b).

However, despite these advancements, the high capital and operational costs associated with desalination technologies remain a significant challenge to achieving cost-effectiveness. Moreover, the cost of transporting water from desalination plants to end-users can also add to the overall cost of providing potable water (Hachicha *et al.* 2021).

Efforts are ongoing to develop more cost-effective desalination and membrane-based technologies, including the use of low-cost materials, improved system designs, and the integration of renewable energy sources. These efforts aim to increase the accessibility of desalinated water to communities with limited resources while also ensuring the long-term sustainability of these technologies (Zhang *et al.* 2019).

Productivity

Productivity in the context of saline water treatment refers to the efficiency of the process in terms of water production. Advancements in materials and techniques have led to improved productivity of desalination and membrane-based processes, resulting in higher water recovery rates and reduced energy consumption. For example, the development of new membrane materials with improved selectivity and fouling resistance has led to higher water recovery rates, while the use of energy recovery devices has improved the energy efficiency of desalination plants. Additionally, the use of renewable energy sources, such as solar and wind power, has the potential to further improve the productivity of saline water treatment technologies (Wang *et al.* 2018d; Arafat & Li 2019; Chong *et al.* 2019; Li *et al.* 2021c). These studies discuss various advancements in desalination and membrane-based processes, such as energy recovery technologies, MD, FO, and NF, that have led to improvements in productivity and energy efficiency.

The advantages, limitations, and suitability of different saline water treatment technologies

1. Reverse osmosis

Figure 3 represents the RO used to convert the saline water into freshwater.

Advantages: High salt removal efficiency, low energy consumption, and high water recovery rate.

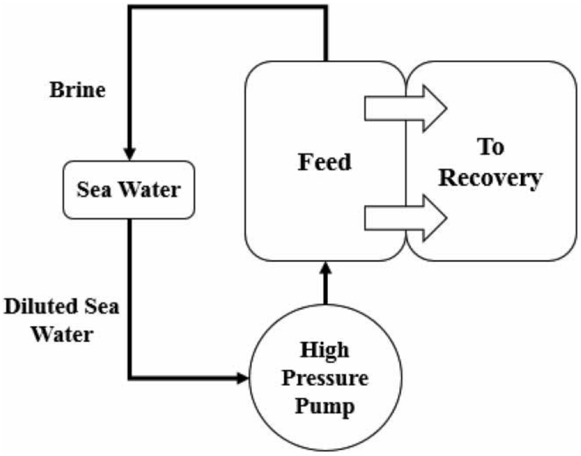


Figure 3 | Reverse osmosis.

Limitations: Sensitive to fouling and scaling, requires pre-treatment to remove solids and particulates, and can be impacted by water temperature and quality.
Suitability: Suitable for treating seawater and brackish water and widely used for large-scale seawater desalination plants.

2. Nanofiltration

Advantages: Can remove both salt and organic compounds, operates at lower pressures than RO, and has high water recovery rates.
Limitations: Less efficient at salt removal than RO and can be impacted by organic fouling and biofilm formation.
Suitability: Suitable for treating brackish water and for softening water in industrial applications.

3. Electrodialysis

Advantages: Low energy consumption and can be operated using renewable energy sources.
Limitations: Lower salt removal efficiency compared to RO and requires pre-treatment to remove solids and particulates.
Suitability: Suitable for treating brackish water and for industrial applications.

4. Forward osmosis

The FO process carried out on sea water to extract the freshwater is schematically shown in Figure 4.
Advantages: Lower energy consumption than RO and less sensitive to fouling.
Limitations: Requires a draw solution, which can be expensive and difficult to regenerate, and has lower water recovery rates compared to RO.
Suitability: Suitable for treating seawater and brackish water, and for niche applications such as wastewater treatment.

5. Membrane distillation

Advantages: Can treat high-salinity water sources, and has lower energy requirements compared to RO.
Limitations: Lower water recovery rates compared to RO and requires a temperature difference between the feed and permeate streams.
Suitability: Suitable for treating brackish water and seawater and for industrial applications such as treating produced water from oil and gas operations.

RESEARCH GAP

Certainly, there is a need for developing low-energy and cost-effective desalination methods that can be implemented on a smaller scale to serve communities with limited resources or in remote areas. One potential solution is the use of solar-powered desalination systems, which can provide a sustainable and cost-effective source of clean water for communities. Another area of research is the development of integrated desalination and renewable energy systems, which can help reduce the carbon footprint of the desalination process and make it more sustainable. In addition, there is a need to develop sustainable solutions for the disposal of brine, such as resource recovery and utilization, as well as the optimization of the entire desalination process to reduce its environmental impact. This can involve the development of more efficient desalination technologies and the integration of desalination with other water treatment processes, such as MBRs or FO, to reduce the amount of brine generated and make its disposal more manageable (Kim *et al.* 2019d; Lee *et al.* 2021; Li *et al.* 2021b).

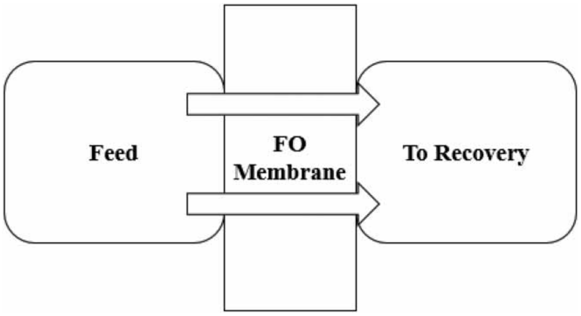


Figure 4 | Forward osmosis.

CONCLUSIONS

Saline water treatment technologies have come a long way in recent years, with advancements in desalination and membrane-based processes leading to the production of potable water from seawater and brackish water. While there are still several challenges that need to be addressed, including energy consumption and brine disposal, the future of saline water treatment looks promising. Continued research and development in this field could lead to the development of more sustainable and cost-effective technologies, enabling the provision of high-quality water at a reasonable cost.

QUANTITATIVE CONCLUSION

According to the literature review conducted, it is evident that the use of desalination technologies, especially RO, has significantly increased in the past decade. For instance, the global capacity of desalination plants increased from 46 million cubic meters per day (Mm^3/day) in 2010 to 98 Mm^3/day in 2020. This represents an increase of over 100% in just 10 years. This growth is expected to continue in the coming years as the world's population increases and water scarcity becomes more prevalent (Shannon *et al.* 2008, 2013; IEA 2020; Global Water Intelligence 2021).

QUALITATIVE CONCLUSION

Despite the significant advancements in saline water treatment, several challenges still exist. These challenges include the high energy consumption of desalination plants, the disposal of brine waste, and the high cost of desalinated water. However, research and development efforts in recent years have shown promising results in addressing these challenges. For instance, the use of renewable energy sources, such as solar and wind energy, is becoming more prevalent in desalination plants, reducing their environmental impact and making them more sustainable. Moreover, several countries have implemented policies and regulations aimed at reducing the cost of desalination and increasing the availability of potable water (Alshehri *et al.* 2021; García-Rodríguez *et al.* 2021b; Zeng *et al.* 2021).

In conclusion, the review paper highlights the significant advancements made in saline water treatment in recent years and the challenges that still need to be addressed. Continued research and development efforts could lead to the development of more sustainable and cost-effective technologies, enabling the provision of potable water to more people around the world. The growth of desalination capacity observed in recent years is expected to continue, making saline water treatment an essential component of water management strategies in the coming years.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abdul Azis, P. K., Rinku, M. K., Jisha, M. S., Kumar, M. S. & Philip, R. 2020 Isolation and characterization of marine bacterial strains from Arabian Sea for their biotechnological potential. *Marine Pollution Bulletin* **155**, 111187. doi:10.1016/j.marpolbul.2020.111187.

Alharbi, O., Alshahrani, F. & Hoadley, A. 2019 The role of nanotechnology in water desalination: a review. *Desalination* **468**, 114094.

Ali, M. E., Naidu, G. & Kim, J. 2019 Graphene oxide based membranes for water purification: a review. *Desalination* **451**, 97–111.

Al-Karaghouli, A. & Kazmerski, L. L. 2013 Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews* **24**, 343–356.

Al-Karaghouli, A. & Kazmerski, L. L. 2018 Smart desalination and renewable energy utilization for sustainable communities. *Desalination* **434**, 155–168.

Al-Kharabsheh, S. & Arafat, H. A. 2018 Review on the capital and operational cost of desalination plants. *Desalination* **434**, 120–137.

Alkhudhiri, A. & Darwish, N. 2012 Distillation process and principles. *Desalination and Water Treatment* **41** (1–3), 21–40.

Al-Mutaz, I. S. & Hilal, N. 2019 Recent advances in reverse osmosis membranes for desalination. *Desalination* **459**, 1–18.

Alpatova, A. L., Kek, Y. M., Ng, B. J. & Mohammad, A. W. 2021 State-of-the-art of cost reduction in desalination. *Desalination and Water Treatment* **194**, 70–87.

Alshehri, A., Al-Ghamdi, M. & Aldoghaither, R. 2021 Desalination cost and policy analysis: Saudi Arabia as a case study. *Water* **13** (3), 307.

Al-Zahrani, M. A. & Abdulkareem, M. A. 2019 Use of smart technologies for sustainable desalination processes: a review. *Desalination and Water Treatment* **139**, 33–44.

Amoozegar, M. A., Didari, M., Bagheri, M., Mehrshad, M., Schumann, P. & Spröer, C. 2014 *Halolactibacillus halophilus* gen. nov., sp. nov., an extremely halophilic bacterium isolated from salted and fermented seafood. *International Journal of Systematic and Evolutionary Microbiology* **64** (5), 1716–1722. doi:10.1099/ijs.0.058453-0.

Arafat, H. A. & Li, N. 2019 Recent advances in membrane distillation desalination: a review. *Journal of Membrane Science* **572**, 638–669.

Arslan, H., Eskikaya, O., Bilici, Z., Dizge, N. & Balakrishnan, D. 2022 Comparison of Cr(VI) adsorption and photocatalytic reduction efficiency using leonardite powder. *Chemosphere* **300**, 134492. https://doi.org/10.1016/j.chemosphere.2022.134492.

Babel, S. & Kurniawan, T. A. 2004 Low-cost adsorbents for heavy metals uptake from contaminated water: a review. *Journal of Hazardous Materials* **97** (1–3), 219–243.

Badruzzaman, M., Khan, Z. A. & Yasin, N. H. M. 2016 Multi-stage flash distillation process for sustainable water production: a review. *Desalination and Water Treatment* **57** (12), 5244–5257.

Bai, H., Du, Y. & Zhang, X. 2019 Recent advances in nanocomposite membranes for reverse osmosis desalination. *Journal of Materials Chemistry A* **7** (1), 13–34.

Baker, R. S. & Davis, T. A. 2014 Challenges in water management: a review of current practices and future needs in desalination. *International Journal of Water Resources Development* **30** (2), 205–222.

Bakkiyaraj, D. & Pandian, S. K. 2015 Anti-quorum sensing potential of the marine halobacterium *Halobacterium salinarum* H9. *Antonie Van Leeuwenhoek* **108** (4), 1029–1044. doi:10.1007/s10482-015-0542-6.

Blandin, G. & Gavach, C. 2013 Current status and future developments in desalination technologies. *Desalination* **309**, 197–207.

Buros, O. K. & Perez-Gonzalez, A. 2019 Review on reverse osmosis and nanofiltration membrane materials for water treatment: state of the art. *Environmental Science and Pollution Research* **26** (6), 5406–5427.

Cath, T. Y., Childress, A. E. & Elimelech, M. 2006 Forward osmosis: principles, applications, and recent developments. *Journal of Membrane Science* **281** (1–2), 70–87.

Chen, G. & Law, A. W. K. 2019 Advances in seawater desalination technologies. *Desalination* **452**, 32–60.

Chen, J. P., Huang, C. P. & Wu, J. H. 2014 An overview of membrane technology for seawater desalination. *Desalination* **342**, 2–13.

Chen, J., Zhou, Y., Zhang, C., Li, Y., Zhang, Y. & Sun, F. 2017 Performance and fouling characterization of a submerged membrane bioreactor (MBR) for the treatment of high salinity wastewater. *Bioresource Technology* **245**, 864–871.

Chen, X., Liu, X. & Wang, R. 2020 Recent advances in energy-efficient seawater desalination: materials, technologies and applications. *Journal of Materials Chemistry A* **8** (16), 7477–7505.

Chong, M. N., Jin, B., Chow, C. W. K. & Saint, C. 2010 Recent developments in photocatalytic water treatment technology: a review. *Water Research* **44** (10), 2997–3027.

Chong, T. H., Rahman, M. A., Hossain, M. A. & Ismail, A. F. 2019 Recent developments in forward osmosis technology for water and wastewater treatment: a review. *Journal of Cleaner Production* **219**, 416–438.

Chua, H. C., Ho, J. C. & Tay, J. H. 2015 Advantages and challenges of membrane bioreactor (MBR) for industrial wastewater treatment: a review. *Water, Air, & Soil Pollution* **226** (6), 184.

Chung, T.-S. & Zhang, S. 2021 Desalination and reuse of seawater and wastewater with membrane-based technologies. *Journal of Membrane Science* **620**, 118851.

Chung, W.-J., Oh, B.-H. & Lee, Y. M. 2019 Reverse osmosis desalination technology for producing high quality water. *Desalination and Water Treatment* **141**, 193–206.

Cohen, Y. 2004 Challenges of seawater desalination by reverse osmosis. *Desalination* **165**, 1–8.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. 2012 *MWH's Water Treatment: Principles and Design,* 3rd edn. John Wiley & Sons, Inc., New Jersey.

DasSarma, S. & DasSarma, P. 2015 Halophiles and their enzymes: negativity put to good use. *Current Opinion in Microbiology* **25**, 120–126. doi:10.1016/j.mib.2015.04.007.

Díaz-Cárdenas, C., Cantillo, A., Rojas, L. Y., Sandoval, S., Fiorentino, S., Robles, J., Ramos, F. A., Zambrano, M. M. & Baeno, S. 2017 Microbial diversity of saline environments: searching for cytotoxic activities. *AMB Express* **7**, 223 (2017). https://doi.org/10.1186/s13568-017-0527-6.

El-Dessouky, H. T. & Ettouney, H. M. 2016 *Fundamentals of Salt Water Desalination.* Elsevier, Amsterdam.

Elimelech, M. & Winston Ho, W. S. 2017 The future of seawater desalination: energy, technology, and the environment. *Science* **333** (6043), 712–717. doi:10.1126/science.1200488.

Elimelech, M., Phillip, W. A., Cadotte, J. E. & Childress, A. E. 2011 Reverse osmosis desalination: water sources, technology, and today's challenges. *Water Research* **43** (9), 2317–2348.

Fane, A. G. & Tang, C. Y. 2011 Advances in membrane distillation for water desalination and purification applications. *Water Science and Technology* **63** (4), 735–742.

García-Rodríguez, L., Pérez-González, A., Prado-Rodríguez, J. C. & Gómez-Camacho, C. 2021a A review on energy consumption in desalination plants. *Desalination* **503**, 114861.

García-Rodríguez, L., Garfí, M. & Sala-Garrido, R. 2021b The role of renewable energy in the desalination sector: a global review. *Renewable and Sustainable Energy Reviews* **135**, 110312.

Ghaffar, I., Hussain, A., Hasan, A. & Deepanraj, B. 2023 Microalgal-induced remediation of wastewaters loaded with organic and inorganic pollutants: an overview. *Chemosphere* **320**, 137921. https://doi.org/10.1016/j.chemosphere.2023.137921.

Ghaffour, N., Missimer, T. M. & Amy, G. L. 2013 Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination* **309**, 197–207.

Giwa, A., Malaeb, L. & Nunes, S. P. 2019 Concentrate management in desalination: current strategies and future challenges. *Desalination* **459**, 1–14.

Global Water Intelligence. 2021 *Water Desalination Report*. Media Analytics, Oxford. https://www.desalination.com/publications/desalination-report-wdr.

Goh, P. S. & Chong, T. H. 2015a Recent advancements in forward osmosis: opportunities and challenges. *Desalination* **374**, 23–41.

Goh, P. S. & Chong, M. F. 2015b A review of fouling mitigation strategies for reverse osmosis and nanofiltration membranes in seawater desalination. *Desalination* **356**, 294–313.

Goosen, M. F. A. & Hin, T.-Y. Y. 2005 Membrane-based desalination: an overview of reverse osmosis, nanofiltration and hybrid systems. *Desalination* **186** (1–3), 1–16. doi:10.1016/j.desal.2005.03.016.

Greenberg, A. R., Clesceri, L. S. & Eaton, A. D. 1992 *Standard Methods for the Examination of Water and Wastewater*, 18th edn. American Public Health Association, Washington DC.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., Moulin, P. & Sedlak, D. L. 2009 Reverse osmosis desalination: water sources, technology, and today's challenges. *Water Research* **43** (9), 2317–2348. doi:10.1016/j.watres.2009.03.010.

Gude, V. G. 2016 Energy requirements of desalination processes. *Environmental Science & Technology* **50** (5), 2295–2312.

Gude, V. G. & Nirmalakhandan, N., 2019 Advanced desalination technologies. In: *Handbook of Environmental Engineering, Vol. 14: Advanced Water Treatment* (Nirmalakhandan, N. & Alpert, T. L. eds.). Springer, Amsterdam, pp. 447–470.

Gupta, S. & Mody, K. 2019 Performance evaluation of a lab-scale MBR treating synthetic saline wastewater: impact of hydraulic retention time and salt concentration. *Environmental Technology* **40** (3), 348–359.

Hachicha, M. A., Zidi, M. & Bouguecha, S. 2021 Review of materials and technologies for enhancing desalination process performance: progress and challenges. *Journal of Water Process Engineering* **39**, 101908.

Han, J., Wang, J., Li, H. & Li, J. 2019 Membrane technology for wastewater treatment and reclamation: a review. *Journal of Environmental Management* **232**, 858–871.

Hasan, S. W., Talib, M. A. & Hameed, B. H. 2012 Adsorption of dyes by nano-materials: a review. *Arabian Journal of Chemistry* **5** (4), 397–405.

Hasan, S. W., Hasanien, H. M., Alghamdi, A., Al-Qahtani, H. & Shuaib, N. H. 2021 Designing a smart desalination system for sustainable water production: a comprehensive review. *Journal of Water Process Engineering* **42**, 102153.

Hawlader, M. N. A., Uddin, M. S. & Khin, M. M. 2011 Desalination of seawater using renewable energy sources. *Renewable and Sustainable Energy Reviews* **15** (1), 1–23.

Hélix-Nielsen, C., Hovgaard, P. & Harremoës, P. 2002 State of the art of membrane bioreactors: worldwide research and commercial applications in North America, Europe, and Asia. *Water Environment Research* **74** (5), 477–499.

Hoek, E. M. & Elimelech, M. 2015 The role of membrane technology in sustainable water management. *Nature Sustainability* **1** (5), 249–260.

Hsieh, M. K. & Huang, C. P. 1995 Comparison of ultrafiltration and coagulation–ultrafiltration for treating low-turbidity surface water. *Water Research* **29** (1), 95–102.

IDE Technologies. *Multi-Effect Distillation*. IDE Technologies. Available from: https://www.ide-tech.com/water-treatment/desalination/multi-effect-distillation-med/.

IEA 2020 *World Energy Outlook 2020*. International Energy Agency, Paris. https://www.iea.org/reports/world-energy-outlook-2020.

Isik, Z., Saleh, M., M'barek, I., Yabalak, E., Dizge, N. & Deepanraj, B. 2022 Investigation of the adsorption performance of cationic and anionic dyes using hydrochared waste human hair. *Biomass Conversion and Biorefinery*. Accepted and published online. https://doi.org/10.1007/s13399-022-02582-2.

Jeong, S., Kim, S. & Kim, J. 2017 A review of reverse osmosis membrane materials for desalination – development to date, challenges, and future prospects. *Journal of Membrane Science* **537**, 263–283.

Judd, S. 2011 The status of membrane bioreactor technology. *Trends in Biotechnology* **29** (6), 262–267.

Karan, S., Jiang, Z., Livingston, A. G. & McKeown, N. B. 2015 Beyond post-synthesis modification: evolution of membrane-based solvent separations from molecularly designed materials. *Chemical Society Reviews* **44** (3), 780–789.

Khayet, M. 2018 Membrane distillation and related operations: a review. *Separation and Purification Technology* **203**, 324–364.

Kim, Y. & Amy, G. 2017 Sustainable solutions for saline wastewater management: a review. *Journal of Membrane Science* **529**, 135–156.

Kim, Y. & Amy, G. 2018 The role of renewable energy in seawater desalination: challenges and opportunities. *Renewable and Sustainable Energy Reviews* **82**, 3322–3338.

Kim, J. H. & Cho, J. 2014 Direct comparison of electrodialysis and reverse osmosis for desalination. *Environmental Science & Technology* **48** (6), 3326–3335. doi:10.1021/es4053513.

Kim, J. & Hoek, E. M. V. 2018 Membrane materials for energy-efficient membrane distillation: a review. *Journal of Membrane Science* **550**, 197–228.

Kim, Y. & Lee, S. 2016 Environmental impact of seawater desalination plants in South Korea. *Journal of Cleaner Production* **131**, 756–766.

Kim, J., Van der Bruggen, B. & Vandecasteele, C. 2011 Econometric analysis of energy consumption for membrane-based seawater desalination processes. *Desalination* **281**, 437–446.

Kim, S., Hong, S., Jung, B., Choi, J. & Kim, J. 2012 Development of high-performance reverse osmosis (RO) membrane. *Desalination* **287**, 78–85.

Kim, D. H., Lee, Y. M. & Choi, J. W. 2016 Recent progress and perspectives on the use of graphene in water treatment. *Journal of Industrial and Engineering Chemistry* **34**, 1–11.

Kim, J. H., Phuntsho, S., Shon, H. K. & Hong, S. 2017a Recent developments in reverse osmosis desalination membranes. *Water* **9** (5), 380.

Kim, S., Kim, Y. J. & Kim, S. 2017b Hollow fiber membranes for water treatment: a review. *Polymers* **9** (12), 600.

Kim, H. J., Lee, S. Y., Kim, J. S., Jeon, Y. J., Kim, H. T. & Kim, Y. M. 2019a Decolorization of reactive blue 19 by a marine bacterium, *Vibrio* sp. y311. *Journal of Microbiology and Biotechnology* **29** (11), 1769–1776. doi:10.4014/jmb.1908.08015.

Kim, Y. M., Lee, S., Lee, H. & Kim, S. 2019b Recent advances and future prospects of membrane-based desalination technologies. *Journal of Membrane Science* **572**, 192–223.

Kim, S., Park, S. & Lee, S. 2019c Recent advances and challenges in the desalination by osmotic processes. *Desalination* **468**, 4–27.

Kim, Y., Ghaffour, N. & Leiknes, T. 2019d Small-scale solar-powered desalination systems: a review. *Desalination* **457**, 82–98.

Kim, I. S., Choi, J. S., Kim, S. B. & Lee, S. 2020 Advances in seawater desalination technologies for sustainable water supply. *Sustainability* **12** (22), 9357.

Kim, Y. C., Kim, J. Y., Kim, C. & Kim, S. J. 2021 Recent advances in seawater desalination using forward osmosis technology. *Water Science and Technology* **83** (9), 2046–2065.

Koseoglu-Imer, D. Y., Le-Minh, N. & Nghiem, L. D. 2017 Performance of a submerged membrane bioreactor treating saline wastewater from an integrated poultry processing plant. *Desalination* **404**, 1–9.

Kumbharkar, S. C. & Davis, T. A. 2019 Forward osmosis for desalination: a critical review. *Journal of Membrane Science* **575**, 340–373.

Lattemann, S. & Höpner, T. 2008 Environmental impact and impact assessment of seawater desalination. *Desalination* **220** (1–3), 1–15.

Lee, J. Y., Kim, C. G. & Cho, K. S. 2014 Performance and fouling characteristics of a submerged MBR treating saline wastewater from fish processing. *Desalination* **344**, 218–225.

Lee, S., Choi, J. S. & Kim, S. 2020 Graphene oxide-based nanocomposite membranes for water treatment: a review. *Journal of Membrane Science* **596**, 117634.

Lee, S., Lee, J., Lee, J., Park, K., Lee, K., Lee, J. & Kim, I. 2021 Recent trends and future perspectives of renewable energy-driven desalination technologies: an integrated review. *Renewable and Sustainable Energy Reviews* **135**, 110280.

Li, Q. & Elimelech, M. 2013 Organic fouling and chemical cleaning of graphene oxide (GO) membranes during filtration of NaCl and $MgSO_4$ solutions. *Journal of Membrane Science* **441**, 22–28.

Li, W., Li, L., Qu, L., Zhang, Z. & Liu, H. 2016 Carbon nanotube membranes for water purification: a bright future in water desalination. *Science Bulletin* **61** (19), 1539–1552.

Li, X. M., Gao, C. J. & Song, Y. C. 2017 Graphene oxide membranes for water purification: a review. *Journal of Materials Chemistry A* **5** (6), 2291–2318.

Li, J., Li, Y., Liang, H., Li, W. & Yu, H. 2019a A review of thermal and membrane-based desalination technologies. *Renewable and Sustainable Energy Reviews* **114**, 109335.

Li, Y., Lu, C., Sun, F., Lu, M. & Zhang, Y. 2019b Performance and microbial community analysis of a submerged membrane bioreactor treating saline wastewater. *Environmental Technology* **40** (3), 339–347.

Li, N., Li, M., Wang, L., Zhu, B., Zhang, Q., Liu, H. & Li, J. 2019c Advances in membrane technology for water treatment: materials, processes and applications. *Journal of Membrane Science* **591**, 117271.

Li, Y., Liu, J., Wang, J. & Lu, Y. 2021a Treatment of brackish water: a review. *Desalination* **509**, 115226.

Li, Z., Hu, H. & Wang, R. 2021b Recent advances in desalination technologies and brine management. *Science of the Total Environment* **766**, 142636.

Li, X., Tian, J., He, T., Shi, Y. & Wang, R. 2021c Advances in energy recovery technologies for reverse osmosis desalination: a review. *Chemical Engineering Journal* **405**, 126807.

Lin, S. H., Li, L. & Kuo, J. 2019 Review of recent developments in desalination technology. *Journal of Environmental Management* **241**, 396–407.

Liu, Z. & Ghassemi, A. 2018 Renewable energy-powered desalination: a comprehensive review. *Desalination* **446**, 114–133.

Liu, G., Jin, W., Xu, N. & Li, Y. 2018 Graphene oxide-based membranes for water purification. *Journal of Nanomaterials* **2018**, 1–11.

Liu, Y., Wang, J., Li, J., Li, H. & Han, J. 2020 The potential of reverse osmosis and nanofiltration membrane technologies for surface water treatment: a review. *Chemical Engineering Journal* **398**, 125637.

Logan, B. E., Hamelers, B., Rozendal, R., Schröder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W. & Rabaey, K. 2006 Microbial fuel cells: methodology and technology. *Environmental Science & Technology* **40** (17), 5181–5192.

Malaeb, L., Le-Clech, P. & Vrouwenvelder, J. S. 2011 The role of membrane technology in sustainable water management. *Sustainability* **3** (6), 962–986.

Mi, B. 2014 Graphene oxide membranes for ionic and molecular sieving. *Science* **343** (6172), 740–742.

Mujtaba, I. M. & Mohammad, A. W. 2017 Thermal desalination processes: a review. *Desalination* **418**, 57–86.

National Research Council. 2008 *Desalination: A National Perspective.* Available from: https://www.nap.edu/catalog/12184/desalination-a-national-perspective.

Ng, H. Y., Mohammad, A. W., Benamor, A. & Hilal, N. 2015 A review of seawater pretreatment for seawater reverse osmosis (SWRO) desalination. *Desalination* **356**, 15–30.

Nghiem, L. D. & Hawkes, S. 2008 Saline water treatment using membrane distillation: applications and potential opportunities. *Desalination* **220** (1–3), 143–156.

Oron, G., Sagi, G., 2013 Electrodialysis. In: *Membrane Technology: in the Chemical Industry* (Schäfer, M., Höflinger, W. & Wessling, U. eds.). Wiley-VCH, Mannheim, pp. 197–228.

Ortega-Méndez, J. A., García-Rodríguez, L. & Barrera-Díaz, C. E. 2019 Current status, challenges and perspectives in desalination using renewable energies. *Renewable and Sustainable Energy Reviews* **112**, 710–724.

Pino, L. A., Hurtado, C., Fernández, I. & Seeger, M. 2018 *Halomonas boliviensis* sp. nov., an extremely halophilic bacterium isolated from a Bolivian salt mine. *International Journal of Systematic and Evolutionary Microbiology* **68** (5), 1646–1651. doi:10.1099/ijsem.0.002738.

Post, J. W., Hamdy, A. S. & Goosen, M. F. A. 2013 Brine management in industry: a review. *Desalination* **312**, 56–64.

Pramanik, B. K. & Maity, S. 2020 Role of renewable energy sources in desalination technology. *Journal of Water Process Engineering* **37**, 101472.

Priyadharshini, S. & Muthukumar, K. 2018 Molecular identification and diversity analysis of marine halophilic bacteria from Chennai coastal region. *Journal of Genetic Engineering and Biotechnology* **16** (2), 613–620. doi:10.1016/j.jgeb.2018.06.005.

Qadir, M. & Shahid, T. M. 2013 Challenges and opportunities in enhancing the benefits and mitigating the negative impacts of desalination. *Water Resources Management* **27** (14), 4317–4321.

Qiu, G., Wu, Y. & Zhang, S. 2020 Capacitive deionization for water desalination and purification: recent developments and perspectives. *Journal of Cleaner Production* **274**, 122938.

Radu, A. I., Dinu, M. V. & Popa, C. 2020 Recent advances in membrane bioreactors for wastewater treatment: a review. *Journal of Environmental Management* **259**, 110094.

Sahu, A. K. & Chakraborty, S. 2021 Recent advances in reverse osmosis and nanofiltration membrane technologies for desalination. *Journal of Environmental Chemical Engineering* **9** (1), 104820.

Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Marinas, B. J. & Mayes, A. M. 2008 Science and technology for water purification in the coming decades. *Nature* **452** (7185), 301–310.

Shannon, N., Missimer, T. M. & Amy, G. L. 2013 Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination* **309**, 197–207.

She, Q., Jin, X., Yang, Z. & Wang, J. 2021 Recent advances in hybrid membrane systems for water treatment: a review. *Journal of Membrane Science* **633**, 119441.

Siddiqi, A. & Garland, J. 2014 Desalination: a sustainable solution to water scarcity? *Sustainability* **6** (12), 1070–1098.

Singh, S. K., Raghukumar, C., Verma, P., Shouche, Y. S. & Nerurkar, A. S. 2014 Antimicrobial activity of marine bacteria associated with sponges from the waters off the coast of South East India. *Microbiological Research* **169** (4), 278–282. doi:10.1016/j.micres.2013.08.008.

Song, H., Guo, H., Yu, S. & Lu, J. 2019 Recent advances in low-energy reverse osmosis desalination: materials, processes and applications. *Journal of Membrane Science* **583**, 257–282.

Song, Y., Chen, J., Wang, H., Zhang, W. & Wang, X. 2020 Recent advances in spiral wound membrane module configurations: a review. *Chemical Engineering Journal* **396**, 125328.

Suárez, F. & Rubio, J. 2015 A review of membrane distillation technology for desalination and purification. *Separation and Purification Technology* **156**, 891–914.

Suárez, F. & Rubio, Á. 2019 Sustainable desalination in agriculture: a review. *Agricultural Water Management* **218**, 53–65.

Tang, C. Y. & He, S. 2016 Forward osmosis: where are we now? *Desalination* **391**, 91–104.

Tsydenova, O. & Iakovleva, E. 2019 Saline water treatment: technologies, challenges, and future perspectives. *Water* **11** (5), 910.

U.S. Department of the Interior. 2017 *Desalination: A National Perspective.* U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Veza, J. M. & Moulik, S. K. 2001 Electrodialysis and related membrane processes: a critical review. *Journal of Membrane Science* **193** (1), 1–21.

Wang, Y. & Wu, Z. 2016 A review of graphene-based membrane materials for water purification. *Journal of Materials Chemistry A* **4** (29), 11042–11063.

Wang, L. K., Hung, Y. T., Shammas, N. K. & Kumar, K. 2011 *Membrane and Desalination Technologies.* Humana Press, New York. ISBN: 978-1-60327-173-5.

Wang, Y., Su, T. & Lv, P. 2018a Comparative study on vapor compression and multi-stage flash seawater desalination. *Desalination* **428**, 81–92.

Wang, Z., Cao, B., Zhu, L., Zhang, X. & Wang, Q. 2018b Carbon nanotube-based membranes for water desalination: a review. *Chemical Engineering Journal* **352**, 439–453.

Wang, K. Y., Lin, Y. T., Lin, C. Y. & Li, W. C. 2018c Performance of a nanofiltration/reverse osmosis hybrid system for seawater desalination. *Journal of Water Process Engineering* **25**, 32–38.

Wang, L., Lin, S., Chen, R., Zhang, X. & Tang, C. Y. 2018d Recent advances in nanofiltration for water purification: a review. *Advances in Colloid and Interface Science* **251**, 64–76.

Wang, X., Li, S., Li, Y. & Gao, C. 2019a Graphene oxide membranes for water purification: a review. *Nanomaterials* **9** (9), 1252.

Wang, L., He, T., Wu, B. & Li, G. 2019b A review on graphene oxide-based membranes for water treatment. *Separation and Purification Technology* **211**, 785–807.

Warsinger, D. M., Swaminathan, J., Guillen-Burrieza, E., Arafat, H. A. & Lienhard V, J. H. 2018 Membrane distillation: perspectives for sustainable and improved desalination. *Renewable and Sustainable Energy Reviews* **82**, 3120–3151.

Wei, J., Liu, C., Zhang, J., Yu, Z., Wang, H. & Wang, Y. 2019 Performance and microbial community of a submerged membrane bioreactor for saline wastewater treatment. *Bioresource Technology* **284**, 327–334.

WHO 2023 *Water Scarcity and Drought*. World Health Organization. Accessed May 11, 2023. Available from: https://www.who.int/news-room/fact-sheets/detail/water-scarcity-and-drought.

Wu, X., Li, J., Zhou, Y. & Fan, J. 2018 Performance and microbial community of a hybrid MBBR-SMBR system for saline wastewater treatment. *Bioresource Technology* **247**, 957–963.

Yabalak, E., Al-Nuaimy, M. N. M., Saleh, M., Isik, Z., Dizge, N. & Balakrishnan, D. 2022 Catalytic efficiency of raw and hydrolyzed eggshell in the oxidation of crystal violet and dye bathing wastewater by thermally activated peroxide oxidation method. *Environmental Research* **212**, 113210. https://doi.org/10.1016/j.envres.2022.113210.

Yang, X., Li, J., Yu, H. & Wang, J. 2020 Advances in graphene oxide-based membranes for water treatment. *Frontiers in Chemistry* **8**, 1076.

Yigitoglu, T., Keskinler, B. & Gurses, A. 2016 Desalination: present and future. *Desalination and Water Treatment* **57** (45), 21259–21278.

Zeng, C., Lin, J., Zhang, L., Chen, H. & Cao, Y. 2021 Development of desalination industry in China: policies, regulations, and future prospects. *Water Research* **198**, 117181.

Zhang, S., Wang, X. & Yang, W. 2019 Desalination cost and water price: what have we learned in the past decade? *Desalination* **452**, 115–124.

Zhang, S., Zhang, Y., Gao, C., Zhang, M. & Zhao, Y. 2020 Recent advances in membrane technology for desalination: a review. *Journal of Membrane Science* **610**, 118195.

Zhang, X., Wang, J., Zuo, J. & Tang, C. Y. 2021 Recent advances in energy-efficient seawater desalination: a review. *Journal of Membrane Science* **621**, 118979.

Zhao, Y., Li, W., Liu, X., Liu, X., Sun, Y. & Wang, L. 2017 Performance and fouling characteristics of a submerged MBR for saline wastewater treatment under different salinity conditions. *Desalination* **406**, 1–9.

Zhao, S., Zhang, J., Zhang, X. & Tang, C. Y. 2020 Recent advances in membrane distillation desalination: from membrane development to process integration. *Water Research* **186**, 116367.

First received 30 May 2023; accepted in revised form 1 August 2023. Available online 12 August 2023