Water, Energy, Food and Environment Journal
*An International Journal*

http://dx.doi.org/10.18576/wefej/050201

# Reverse Osmosis and Beyond: A Review of Desalination, Brine Management, and the Pursuit of Zero Liquid Discharge

*Sohair Ahmed Darwish*[1], *Ibrahim Mohamed Ismail*[1*] *and Amr Abdelkader*[2]

[1] Chemical Engineering Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt.

[2] Mechanical Engineering Department, Faculty of Engineering, British University in Egypt, El-Sherouk 11837, Cairo, Egypt.

Received: 5 Feb. 2024, Revised: 18 April. 2024, Accepted: 21 Jun. 2024.
Published online: 1 Jul. 2024.

**Abstract:** Desalination has become essential in addressing global freshwater scarcity. However, the generation of concentrated brine remains a major environmental and operational challenge, especially as water recovery targets increase. This review provides a comprehensive overview of current desalination technologies, brine disposal methods, and emerging strategies targeting Zero Liquid Discharge (ZLD).

The paper first explores thermal, pressure-driven, and electrically driven desalination processes, with a focus on Reverse Osmosis (RO) as the industry's leading technology. Common brine disposal methods are evaluated, alongside their environmental limitations.

Advanced brine treatment technologies are then discussed, including thermal, membrane-based, and electrically driven systems. These technologies are then extensively evaluated and compared in terms of specific energy consumption and salinity limits.

Finally, the review analyses advanced RO-based ZLD configurations, including tandem RO, chemically enhanced stages, and RO-hybrid systems with electrodialysis or crystallisation. While high recovery rates have been demonstrated, most systems remain limited by energy demand, operational complexity, and cost.

This review highlights the critical need for integrated, efficient, and scalable solutions to bridge the gap between freshwater production and sustainable brine management.

**Keywords:** Desalination, Reverse Osmosis, Brine Management, Zero Liquid Discharge, Hybrid Desalination Systems.

## 1 Introduction

With the continued depletion of freshwater resources, desalination has become an indispensable strategy for meeting global water demand [1]. Today, more than 95 million $m^3$ of water is produced daily by over 16,000 desalination plants around the globe [2]. Among the available desalination technologies, Reverse Osmosis (RO) is the most dominant desalination route, which alone makes up approximately 70% of the total global desalination capacity [3].

Correspondingauthore-mail: dr_ismail@icem-group.org

Despite RO's energy efficiency and scalability, it generates a substantial amount of concentrated brine, most often in quantities that exceed the volume of freshwater produced, as shown in Figure 1. Global desalination operations are estimated to generate approximately 141.5 million $m^3$/day of brine [4]. This by-product typically possesses a salinity nearly double that of seawater [5] and contains four to seven times the concentration of contaminants found in the original feedwater [6]. This brine is typically discharged without further treatment, raising serious environmental concerns and undermining the long-term sustainability of desalination operations [7].

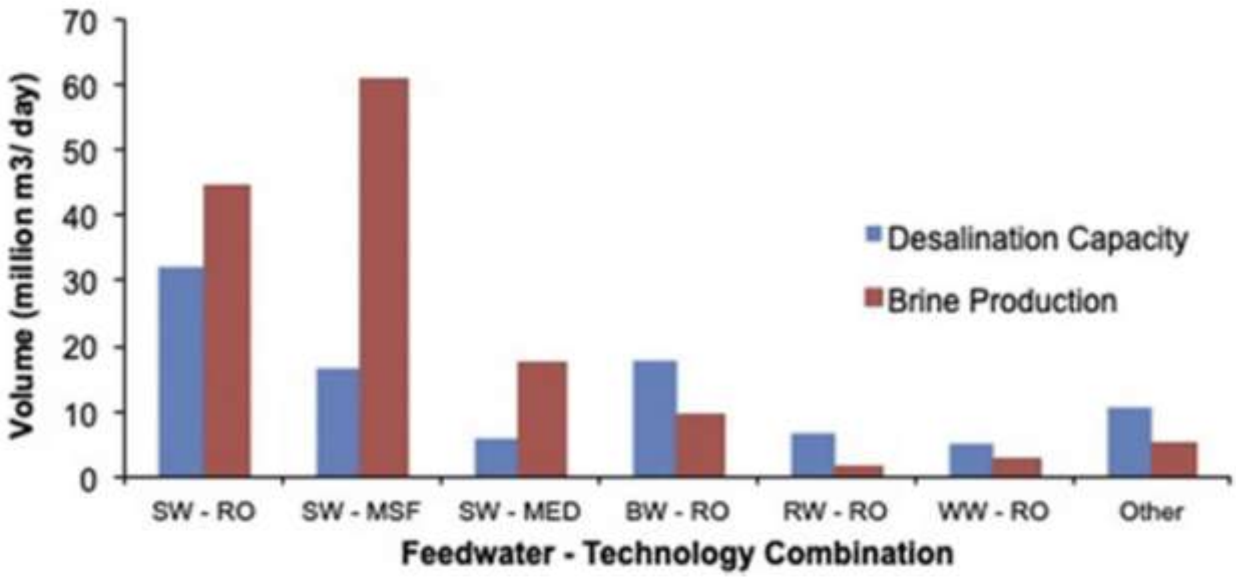


**Fig. 1:** Total desalination capacity and volume of brine produced by the major desalination technologies [15].

The characteristics, both quantity and quality, of the brine vary according to the desalination technology, feed quality, required treated water specifications, the nature of pre- and post-treatment processes, and maintenance practices such as equipment cleaning. Therefore, brine may contain chemicals used throughout the desalination stages, such as antiscalants, flocculants, and coagulants, introduced during pretreatment, membrane cleaning, or post-treatment [8]. Current practices typically involve either direct disposal or volume reduction prior to discharge. A substantial body of literature has emerged reviewing various brine management strategies and technologies [4,5,8,9,10,11,12,13,14].

Most desalination facilities are designed to treat brackish water or seawater which together account for over 80% of feedwater sources. However, less than 1% of facilities target brine treatment directly [8]. This reveals a major gap in the current desalination landscape: while freshwater production has advanced considerably, brine management and valorisation remain underdeveloped.

In response, increasing attention is being directed toward advanced brine treatment processes, including concentrating and crystalising technologies, and other advanced hybrid systems that aim for Zero Liquid Discharge (ZLD). These approaches not only address the challenges of brine disposal but also enable the recovery of additional freshwater and valuable salts, supporting circular water economy [8].

Over the past decades, desalination technologies have evolved considerably, with numerous technologies developed to meet growing global water demands. Yet, no single approach fully resolves the interconnected challenges of water recovery, energy efficiency, environmental impact, and economic viability. This paper offers a critical review of a wide range of desalination technologies, classifying them according to their driving mechanisms and highlighting their key advantages and limitations. Subsequently, brine management strategies, including disposal and concentration routes, are discussed in detail, with special emphasis on the concept of ZLD and an overview of emerging technologies deployed in conjunction with RO.

## 2 Water Desalination Technologies

Desalination refers to the separation of salts and water from saline water, aiming to produce fresh water, suitable for drinking, agriculture, or industrial applications. With increasing water demand and scarcity, especially in dry regions, desalination has emerged as an essential water supply solution [16]. However, the process generates a hyper-saline waste stream (commonly referred to as brine, reject, or concentrate) whose management poses operational and environmental challenges [8].

Desalination technologies can be grouped according to different criteria. Figure 2 shows two commonly used categorisations: by their main driving force, or according to the element separation mode (i.e., if water or salt is the element being separated) [17].

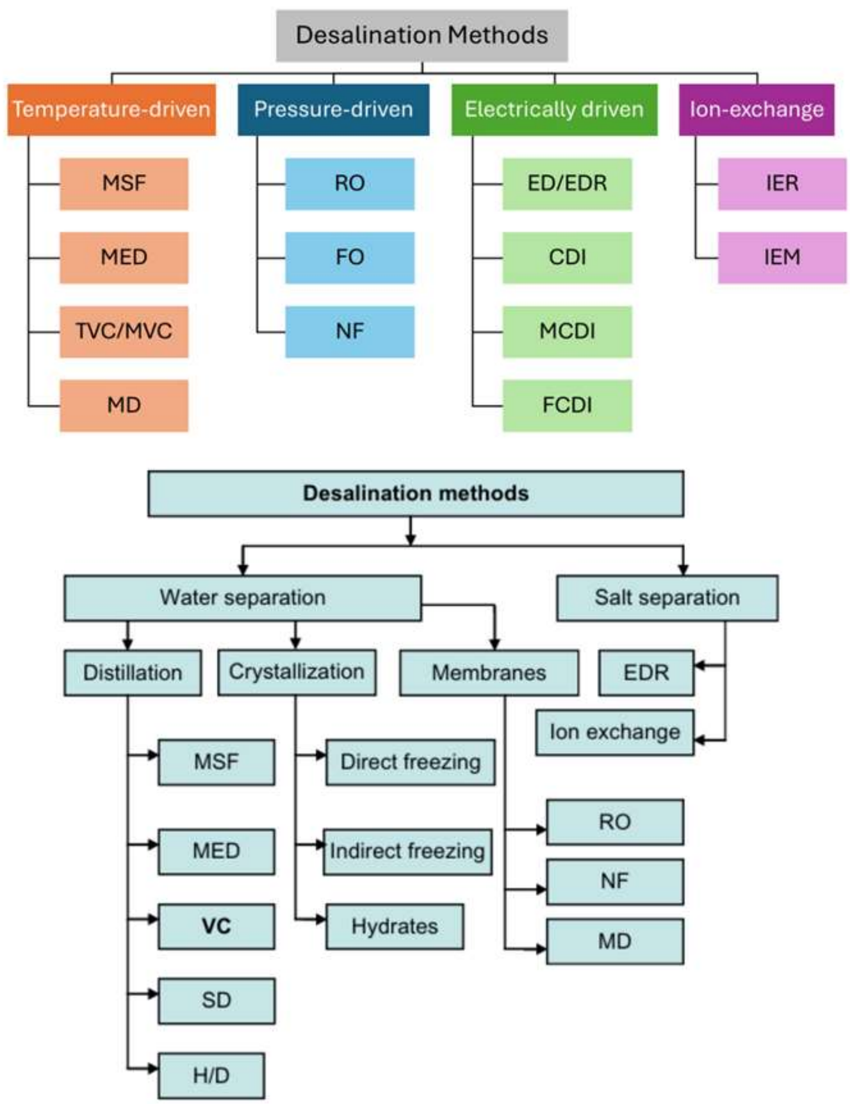


**Fig. 2:** Flow-sheet of desalination technologies according to a) driving force of separation the b) the separation of water or of salts [17].

A short overview of conventional desalination technologies will be presented in this section, categorized into: (1) Temperature-driven distillation processes, (2) pressure-driven membrane processes, (3) ion-exchange and (4) electrically driven processes. Each of these conventional technologies' operational mechanisms, advantages, and challenges will be discussed. While this review provides a general introduction to the topic, detailed and application-specific insights can be found in specialised reviews and research articles available in the literature [18,19,20,21].

### 2.1 Temperature-driven Distillation Processes

Temperature-driven distillation processes utilise phase change to separate salts from saline water by converting water into vapour, which subsequently condenses into fresh water [17]. These technologies replicate the natural water cycle, where water is evaporated then condensed yielding freshwater [8].

#### 2.1.1 Multi-Stage Flash Evaporation (MSF)

Multi-Stage Flash (MSF) distillation is a widely used temperature-driven desalination technology. MSF is widely implemented in regions with limited freshwater resources but abundant seawater availability, particularly in the Middle East [16]. In fact, it ranks as the second most commonly deployed desalination technology after RO [18]. Preheated saline water is fed into multiple chambers, each maintained at successively lower pressure. This pressure drop causes the water to rapidly expand and then evaporate, or "flash" into steam. This steam later condenses to ultimately produce freshwater. This latent heat of condensation is re-integrated and gained by incoming feedwater, improving energy efficiency [17]. The residual brine is passed through subsequent stages, continuing the flashing process until final discharge [16].

The process is valued for its durability and capacity to handle fluctuations in feedwater quality, making it well-suited for large-scale applications. However, MSF systems are extremely energy intensive, with total energy demand of 19-28 kWh per cubic metre of desalinated seawater. The use of high operating temperatures and repeated flashing promotes scale formation on heat exchange surfaces, necessitating regular maintenance and cleaning to sustain performance [18].

#### 2.1.2 Multi-Effect Distillation (MED)

Multi-Effect Distillation (MED) was among the earliest technologies employed in thermal desalination; however, it was later overtaken by MSF due to its lower operational costs and reduced scaling issues [18]. MED operates on principles similar to those of MSF, wherein seawater is preheated using the latent heat of the effluent water. In the first stage, pre-heated saline feed is sprayed over tubes heated by pressurised steam, resulting in evaporation. The generated vapour then passes through a series of chambers, referred to as "effects", each operating at a successively decreasing pressure. In each effect, the vapour condenses, releasing latent heat that contributes to evaporating the incoming saline feed in the subsequent stage [17].

A key advantage of MED is its high thermal efficiency, achieved through the sequential reuse of vapour as a heat source across multiple effects. MED systems typically consume around 14 to 22 kWh per cubic metre of desalinated water, which is less than MSF, and also require less maintenance [18]. However, MED is limited in scalability, making it less suitable for applications demanding large water output. Additionally, the capital cost for establishing MED units is relatively high, which hinders widespread adoption. The operational performance of MED systems is also highly dependent on the availability of a stable heat source at the installation site [16].

#### 2.1.3 Vapor Compression

Distillation plants employing vapor compression evaporation utilise the heat produced from compression to evaporate the feed saline water. Two main configurations are used: Mechanical Vapor Compression (MVC) and

Thermal Vapor Compression (TVC). In MVC systems, an electrically driven compressor is used to compress the vapor, while TVC systems rely on a steam jet thermo-compressor to achieve the same effect [18].

As with MSF and MED, TVC and MVC systems begin by preheating the feed saline water using heat exchangers. Inside the evaporator, the preheated seawater undergoes evaporation, and the resulting vapour is compressed to elevate its temperature, allowing it to be reused as a heating source for further evaporation inside the same unit. The concentrated brine remaining in the evaporator is then separated and split into two parts: part of it is recycled and mixed with incoming feedwater, while the rest is discharged as waste [18].

TVC systems typically consume around 16 kWh per cubic metre of desalinated seawater, whereas MVC systems are more energy-efficient, requiring approximately 7-12 kWh/$m^3$ [18]. MVC is considered the most energy-efficient among distillation-based desalination methods and is currently regarded as the leading technology for treating high-salinity water streams, where they are predominantly used in small- to medium-scale applications [22].

### *2.1.4 Membrane Distillation (MD)*

While Membrane distillation (MD) is a membrane-based technology, it relies on a temperature gradient, not pressure, as the driving force of separation, hence it is under temperature-driven desalination technologies. Separation in MD is based on the vapor pressure difference across the membrane surfaces. The membrane is hydrophobic, meaning it prevents liquid penetration by the feed solution and allows only to water vapor through [17]. Typically, one side of the membrane is in direct contact with hot saline water, forming the 'hot side', while the other side is for the with cold freshwater, forming the 'cold side'. Water vapor migrates across the membrane and condenses on the cold side, producing the distillate [23].

MD as not yet achieved energy efficiency levels comparable to those of established thermal desalination technologies. A major operational challenge in MD is membrane wetting, often resulting from fouling, which compromises performance and longevity [24]. Nevertheless, MD offers several advantages, including the capability to handle highly saline feed streams and the capacity to utilise low-grade thermal energy, making it a promising option for specific niche applications [25].

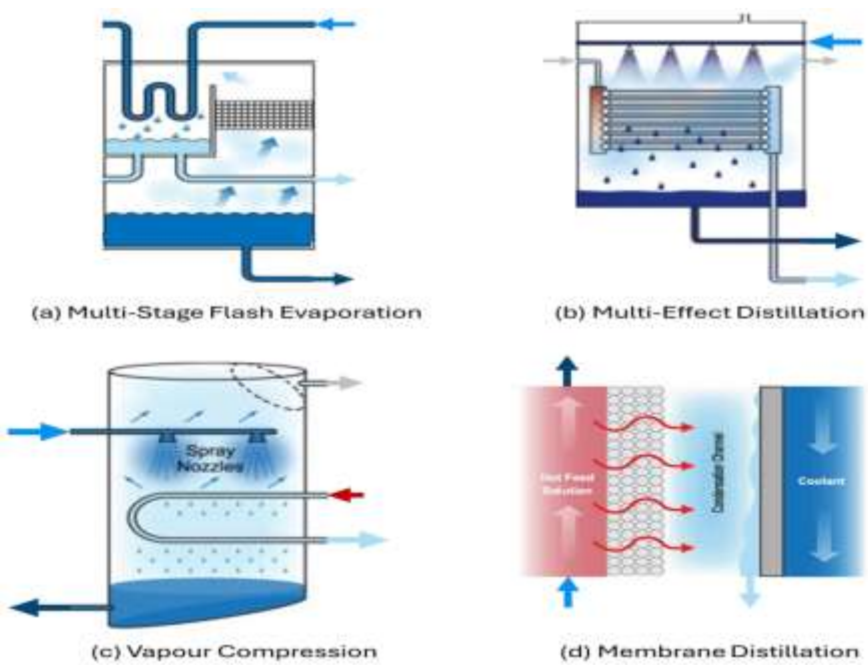


**Fig. 3:** Illustration of the working principles of major temperature-driven desalination processes.

## 2.2 Pressure-driven Membrane Processes

Pressure- and osmotic pressure-driven desalination processes utilise semipermeable membranes to retain salts while only letting purified water to pass through. Separation is achieved by applying large external pressure that overcomes osmotic forces [8]. While the principle of operation is some-what the same, the major difference between all these technologies is the type of membrane used for separation. They range from membranes with micro pores, to dense membranes that can only pass water molecules [25].

### 2.2.1 Reverse Osmosis (RO)

RO is a pressure-driven membrane-based desalination process utilising a membrane that allows the passing of water molecules but not salts and other impurities. RO is a well-developed and widely adopted technology, currently representing the most prevalent method for desalination worldwide [18]. During the RO process, water moves from the high- to the low-pressure side of the semi-permeable membrane, resulting in the production of low-salinity permeate and a concentrated brine on the pressurised side [16].

An RO system is composed of four main stages: pre-treatment, high-pressure pumping, membrane separation, and post-treatment. The pre-treatment stage involves physical and chemical conditioning of the feedwater, including filtration, disinfection, and adding anti-scalants and biocides to mitigate scaling and biofouling. The High Pressure Pump (HPP) supplies the necessary driving force to separate water, with energy demands supplied entirely by electricity. Required operating pressures for brackish water is 17-27 bar, while for seawater 55-82 bar. The membranes, available in various configurations, are designed to achieve a typical permeate salinity of around 500 mg/L. Post-treatment processes include degassing processes such as the removal of hydrogen sulphide and pH adjustment to ensure water quality compliance [18].

Energy consumption in RO processes is strongly influenced by the feedwater salinity and the targeted water recovery rate. Osmotic pressure, which increases with the Total Dissolved Solids (TDS) concentration, dictates the required operating pressure, and thus, energy demand. Consequently, desalinating high-salinity water requires substantially more energy. For typical seawater RO units, electricity consumption ranges from 4 to 6 kWh/ $m^3$, whereas for brackish water it is generally between 1.5 and 2.5 kWh/$m^3$ [18]. The core of any RO system lies in its membrane modules, which can be arranged in various operational configurations, based on the feed characteristics, the desired recovery rate, permeate quality, flow conditions, and the presence of trace contaminants [25].

RO systems offer several advantages. They achieve high salt rejection rates (>99%) and water recovery rates typically between 40-60%. Their modular design enables scalability, allowing application in both small- and large-scale systems. Moreover, RO processes are generally more energy-efficient than thermal methods [16]. RO is a single-phase, low-temperature process, hence requires minimal thermal input, with energy mainly consumed by the HPP [17]. In certain cases, such as discontinuous desalination of small volumes of specialised feedwater, RO systems may operate in batch mod where feedwater is first stored in a tank, from which it is circulated through the membrane module. Permeate is collected, while the concentrate is returned to the tank. This cycle continues until a minimal volume of concentrate remains. During batch operation, membrane conditions continuously change throughout the cycle [26].

However, RO is most commonly designed for continuous operation. Several configurations have been innovated to enhance energy efficiency and product water quality. The most conventional is the single-pass RO system. It is widely adopted due to its operational simplicity and cost-effectiveness. This setup typically achieves a recovery ratio up to 50% and produces permeate concentration between 300 to 500 ppm. When higher water purity is required, a second RO pass is often added, forming a double-pass configuration. To further enhance the desalination performance, multi-stage RO systems are typically used. Multi-stage systems apply varying pressures across different stages, compensating for the rise in osmotic pressure as the feedwater becomes more concentrated. This spatial pressure distribution maintains a more consistent driving force, thus reducing energy waste and enhancing overall efficiency. However, these benefits come with increased capital costs [27].

Another advanced configuration is Closed Circuit Reverse Osmosis (CCRO), which achieves similar energy improvements by recirculating the concentrate back into the system in a closed loop. In CCRO, the brine exiting the membrane is blended with incoming fresh feed. As osmotic pressure builds up in the loop, the applied pressure is gradually increased. Unlike multi-stage systems, where pressure differences are established spatially across separate physical stages, CCRO achieves this effect temporally and operationally within a single looping system [28]. In addition to system configuration, the use of Energy Recovery Devices (ERD) has significantly improved RO energy efficiency. With the aid of ERDs, modern RO plants can reduce energy requirements to only 1 kWh/m$^3$ of product water, and in some cases, even lower. This efficiency is possible because RO avoids phase change, allowing energy demands to approach the thermodynamic minimum for separation. As a result, RO is not only the most widely implemented but also the best method for desalinating seawater in terms of energy [19,22,29].

Nevertheless, RO technology faces several limitations. Its performance is constrained by the feedwater salinity and the targeted water recovery rate. Higher salinities and recovery rates demand higher feed pressures, which in turn impose limits on system materials and structural components [29]. Furthermore, the brine generated by seawater RO systems (typically around 60 g/L in salinity) is often discharged directly without treatment, raising serious environmental concerns. Brine disposal also makes up a significant portion of RO's operational costs. Another major challenge is membrane fouling and scaling that degrades the performance and necessitates frequent maintenance. To mitigate these issues, extensive pre-treatment of the feedwater is usually required. This not only increases operational complexity and cost but also introduces environmental risks due to the chemicals involved [16].

Moreover, due to the low recovery ratios of RO systems, large volumes of feedwater must be processed and pretreated relative to the amount of product water obtained [22,29]. In response to these challenges, emerging technologies are being explored to enhance recovery and operational efficiency [29,30].

### *2.2.2 Nanofiltration (NF)*

Nanofiltration (NF) is a membrane-based desalination technology that utilises membranes with nanometre sized pores. NF membranes have pore sizes of about 1-10 nm, smaller than ultrafiltration, but slightly bigger than RO membranes. These membranes typically feature a compact active layer, enabling them to separate inorganic salts, differentiate between monovalent and multivalent ions, and retain small organic compounds. NF membranes also provide higher permeate flux than RO membranes.

Industrial membrane applications typically require thousands of square meters of membrane area, necessitating efficient packing strategies to minimise the system footprint. To enhance separation efficiency and achieve component fractionation, NF membranes can be arranged in cascade configurations, similar to those employed in distillation or OARO systems [31].

### *2.2.3 Forward Osmosis (FO)*

Forward osmosis (FO) is another membrane-based desalination technology, but dissimilar to RO, is osmosis-driven to separate water by inducing osmotic gradient [17]. The principle of the mechanism is the use of a draw solution with high osmotic coefficient to extract water molecules from a lower osmotic pressure solution across a semipermeable membrane. This continuously concentrates the feed, while diluting the draw solution which will ultimately need regeneration [4]. Since FO does not rely on applied hydraulic pressure, it generally exhibits lower membrane fouling potential and reduced energy demand in comparison to other membrane-based but pressure-driven technologies such as RO.

Also, unlike pressure-driven technologies that force feed water through the membrane, FO draws water across the membrane via osmotic pressure. As a result, FO places less harsh demands on feed water quality and requires membranes with lower mechanical strength than those used in RO. FO processes have the theoretical capacity to treat water streams across a broad spectrum of salinities and qualities. However, their practical implementation is largely constrained by the energy requirements and economic feasibility, particularly the cost and complexity associated with regenerating the draw solution to its original capacity [22].

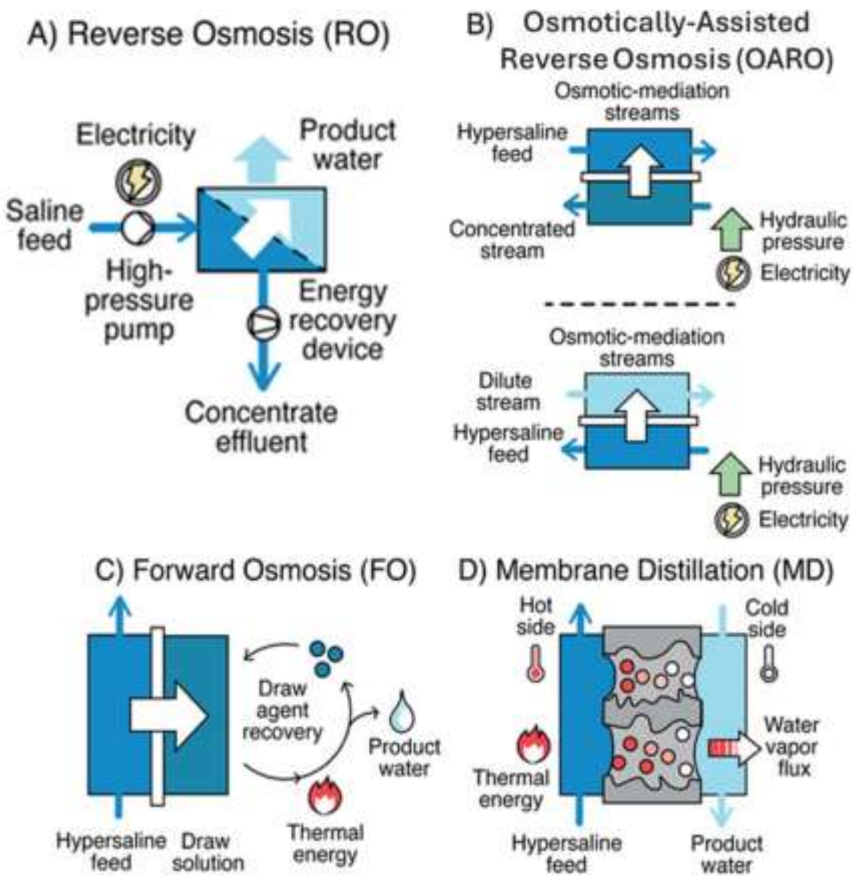


**Fig. 4:** Illustration of the working principles of pressure- and osmotic pressure-driven desalination processes.

## 2.3 Ion-exchange Processes

Ion exchange is a physicochemical method using ion-exchange materials, such as ion-exchange resins (IER) and ion-exchange membranes (IEM), made up of polymers with charged functional groups.

Ion exchange is a physicochemical method using ion-exchange materials, such as ion-exchange resins (IER) and ion-exchange membranes (IEM), made up of polymers with charged functional groups. On the other hand, electrically driven desalination technologies operate based on an applied electric potential gradient. Such processes often also utilise ion-exchange materials. Notable examples of such processes include electrodialysis, capacitive deionization, and their variants.

### 2.3.1 Ion-exchange Resins (IER)

Ion-exchange resins (IER) can be directly utilised for the treatment or desalination of both aqueous and non-aqueous solutions. They are particularly common in the production of purified water [32]. In this process, salt ions in the feedwater are exchanged with hydrogen ($H^+$) and hydroxide ($OH^-$) ions contained within the resin, which effectively desalinate the feed. The basic principle of IER is that cation-exchange resins replace cations in the water with $H^+$ ions, while anion-exchange resins substitute anions with $OH^-$ ions. The released $H^+$ and $OH^-$ ions subsequently combine to form water, resulting in demineralisation [23]. Once the ion-exchange capacity of the resin is exhausted (when most $H^+$ and $OH^-$ ions have been replaced), the resins must either be regenerated using strong acids and bases or disposed of. As such, this method is relatively intensive in terms of chemical usage and material consumption [25].

IER technology is primarily used to treat water with high hardness or low salinity. Although some studies explored its use for seawater treatment, it has not been widely adopted at the industrial scale due to the rapid exhaustion of resin capacity when dealing with high salinity, making the process economically unfeasible. Currently, its primary application in seawater treatment is limited to pretreatment stages with membrane-based technologies, particularly to prevent the formation of hard scale deposits [17].

### *2.3.2 Ion-Exchange Membranes (IEMs)*

Regarding Ion-Exchange Membranes (IEMs), there are two types: Cation-Exchange Membranes (CEM) characterised by fixed negatively charged (anionic) functional groups, and Anion-Exchange Membranes (AEM) that contain fixed positively charged (cationic) groups, [32]. As shown in Figure 5, when an IEM comes into contact with an electrolyte, these fixed charges enable the selective transport of counter-ions (cations through CEMs and anions through AEMs), while co-ions (those carrying the same charge as the membrane's) are repelled and largely excluded from transport. This mechanism enables ion separation and selective transport [33].

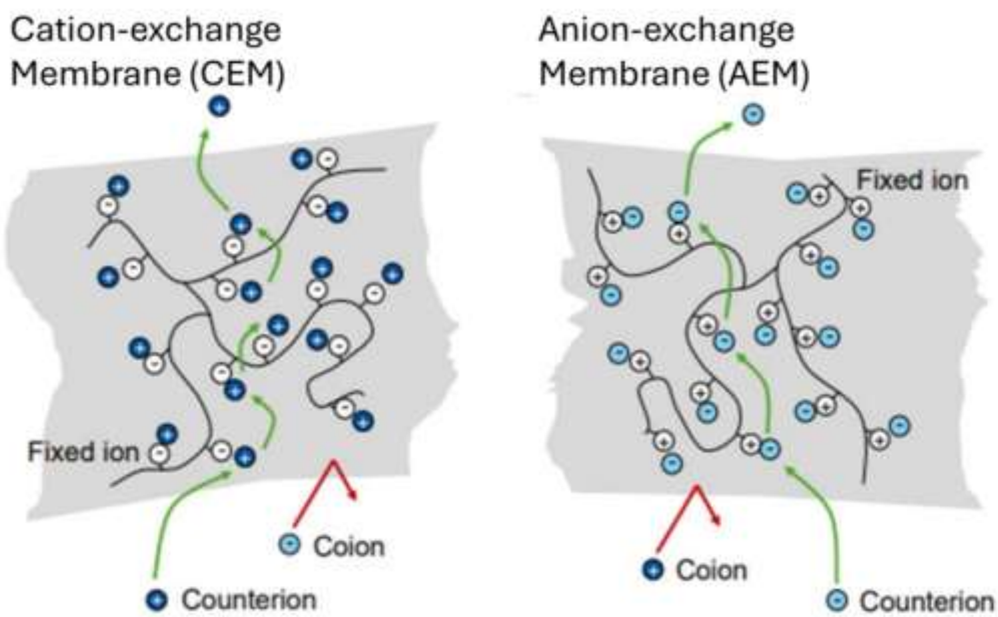


**Fig. 5:** Principle of ion-exchange membranes (IEM) [25].

IEMs can be categorised based on their structural composition. Heterogeneous IEMs are formed by dispersing IER particles within a polymeric binder, whereas homogeneous IEMs are entirely composed of polymers with charged functional groups. To enhance mechanical strength, some homogeneous membranes are reinforced with woven or non-woven polymeric fibres. The specific properties required of an IEM depend on its intended application; however, key performance criteria typically include low electrical resistance, high ion selectivity, and high stability, all at a reasonable cost [32].

### 2.4 Electrically driven Processes

Electrically driven desalination technologies operate based on an applied electric potential gradient. Such processes often also utilise ion-exchange materials. Notable examples of such processes include electrodialysis, capacitive deionization, and their variants.

#### 2.4.1 Electrodialysis (ED)

Electrodialysis (ED) is an electrical desalination technology that utilises IEM and operates under atmospheric pressure. It is a well-established large-scale technology, having been employed for over five decades, mostly for brackish water desalination [4]. The basis of operation of ED involves applying a Direct Current (DC) to a system containing alternating AEMs and CEMs, positioned between a pair of electrodes within a saltwater-filled compartment. Spacers, either placed between or integrated into the membranes, serve to create flow channels for water [34]. Upon application of the potential gradient, dissolved ions in the feed migrate toward their respective oppositely charged electrodes: anions move through AEMs toward the anode, while cations pass through CEMs toward the cathode. This selective ion transport causes the formation of alternating channels: one in which ions accumulate, forming a concentrated brine stream, and another from which ions are removed, producing desalinated fresh water [32].

ED relies solely on electricity as its energy source, utilising DC to power the electrodes and either alternating current or DC to operate the pumps [18]. When used to feedwater with salinity levels below 5000 mg/L, ED proves to be more economically favourable than other desalination methods due to its energy efficiency. However, the economic viability of ED declines significantly with increasing salinity, limiting its practical application primarily to brackish water treatment [23]. The Specific Energy Consumption (SEC) for ED typically ranges from 20 to 40 $kWh/m^3$ [4]. Also, ionic currents are converted into electrical currents at the electrodes through electrochemical reactions. The specific nature of these reactions depends on the composition of the electrode rinse solution. In ED, these electrode reactions may also lead to gas evolution as a by-product [35,36].

Similar to other membrane-based technologies, ED is susceptible to membrane fouling and scaling, particularly on the concentrate side during continuous operation in a fixed flow direction [4]. To mitigate these issues, Electrodialysis Reversal (EDR) was developed as an alternative operational mode. In EDR, the polarity of the electrodes is periodically reversed, causing the concentrate and diluate streams to switch roles [17]. This reversal reduces the accumulation of precipitates on the membrane, extends the lifespan of both the membranes and electrodes, and aids in membrane self-cleaning [18].

#### 2.4.2 Capacitive Deionization (CDI)

Capacitive Deionization (CDI), like ED, is an electrically driven desalination process that relies on an electric field to induce ion migration toward oppositely charged electrodes [37]. In CDI, a voltage is applied across two porous carbon electrodes, while saline water flows between them through a spacer layer [38]. Upon application of the electric potential, ions in the feed transfer toward the oppositely charged electrodes. These ions are subsequently adsorbed onto the surface of the porous electrodes, thereby reducing the salt concentration of the treated effluent stream [39]. Once the carbon become fully saturated with ions, their ion storage capacity is restored by reversing the electrode polarity, which facilitates the release of the adsorbed ions into a separate stream, forming a concentrated brine.

The fundamental mechanism of CDI is governed by the development of Electrical Double Layers (EDL) on the electrodes' surface, similar to the behaviour observed in electrostatic supercapacitors [40], but CDI is specifically engineered for ion removal rather than energy storage. During operation, the ions extracted from the feedwater are stored in the EDLs of the porous electrodes. Once the system reaches its ion storage capacity or any other operational constraints are met, the applied voltage is reduced or reversed, prompting the desorption of the adsorbed ions back into the water. This generates a concentrated stream that is flushed as waste effluent [41]. The process thus has cyclic nature, alternating between charging (ion removal) and discharging (ion release) within the CDI cell [20]. CDI operates at relatively low voltages to avoid Faradaic reactions, which are undesired redox reactions at the electrode's surface [42]. Such low voltages, combined with operation at ambient pressure and the straightforward fouling control of electrodes, render CDI among the few low-energy water treatment technologies [37]. In fact, CDI is proved to demand less energy compared to conventional processes such as MSF and RO distillation, consuming <0.6 kWh/$m^3$ for brackish water desalination [43].

Although CDI was introduced nearly three decades ago [44] and is recognised for its high energy efficiency, it has not been widely adopted for treating high-salinity waters such as seawater [45]. This limitation primarily arises from the need for a discharging step. Without periodic regeneration, the carbon electrodes become saturated, causing the desalination performance to deteriorate significantly, often to the point of complete functional loss [41]. Additionally, the quantity of porous carbon is constrained by the size of the current collectors to which it is attached, making CDI both energy- and cost-intensive for high-salinity applications like seawater desalination [45].

A comprehensive review of CDI's development and operating principles was presented by Porada et al. [20], with several subsequent reviews exploring different aspects of CDI systems and their evolving applications [46,47]. In its conventional form, CDI relies exclusively on fixed solid film electrodes [48] housed within an electrical cell that manages feed flow in and out. However, the process has two critical drawbacks: the intermittent nature of freshwater production [49], and additional energy consumption due to ion transport across the ion-exchange membrane interface, once during adsorption and again during desorption. Furthermore, scaling up CDI systems for practical use requires the deployment of numerous cells, significantly increasing overall system cost [50]. To mitigate these challenges, various approaches were proposed including the incorporation of membranes into the CDI design.

### *2.4.3 Membrane Capacitive Deionization (MCDI)*

To improve desalination and energy efficiencies of the CDI, IEMs are added on the surface of the electrodes, which leads to a developed and widely explored new configuration: Membrane Capacitive Deionization (MCDI), which enhances the ion adsorption capacity and charge efficiency in comparison to conventional CDI by incorporating IEMs, which promote greater ion selectivity [51]. Despite these improvements, MCDI performance remains constrained by electrode saturation [50,52]. Consequently, MCDI is most suitable for treating water with low to moderate salinity levels, typically around 3-4 g/L [53]. Furthermore, the process cannot be operated continuously without periodic regeneration of the ion-saturated electrodes, limiting its scalability and operational simplicity [37]. To address these challenges, recent studies have proposed advanced CDI configurations focused on improving electrode design. Many of these efforts aim to eliminate the need for a separate ion release step, which is a key limitation of conventional sequential-mode operation [45]. One particularly promising strategy involves replacing the fixed electrodes with flowable ones.

### *2.4.4 Flow-Electrode Capacitive Deionization (FCDI)*

Flow-electrode Capacitive Deionization (FCDI) was pioneered in 2013 to overcome CDI's and MCDI's drawbacks [45]. Instead of having the conventional static electrodes, a pumpable carbon suspension flows between the current collector and the membranes in the FCDI cell [54]. By applying voltage potential across two channels containing flowable carbon slurries, ions migrate from the feed water into the slurries. In contrast to CDI and MCDI, this process does not require a separate discharge phase. After exiting the cell, the oppositely charged carbon slurries are mixed, resulting in ion desorption. The slurry is then separated from the concentrated brine, allowing it to be regenerated and reused. This setup enables continuous desalination, as fresh flow electrodes are consistently circulated through the system [54].

FCDI offers enhanced water recovery in comparison to conventional CDI, primarily because of the decoupling of the adsorption and desorption processes. In conventional CDI with static electrodes, the desorption phase necessitates diverting a portion of the feedwater to serve as a concentrate stream, thereby reducing overall water recovery. In contrast, FCDI continuously performs ion adsorption on the feed stream, while desorption occurs independently within the flow-electrode loop. This separation allows for minimal feedwater loss and significantly improves water utilisation. Studies have reported water recovery rates as high as 90% under optimised FCDI regeneration strategies [55]. Additionally, FCDI offers the advantage of a dynamically adjustable total adsorption capacity by modifying the carbon slurry concentration in the electrode compartments and adjusting the effective contact area. Therefore, the FCDI system can be tailored to effectively treat high-salinity feedwater streams [56].

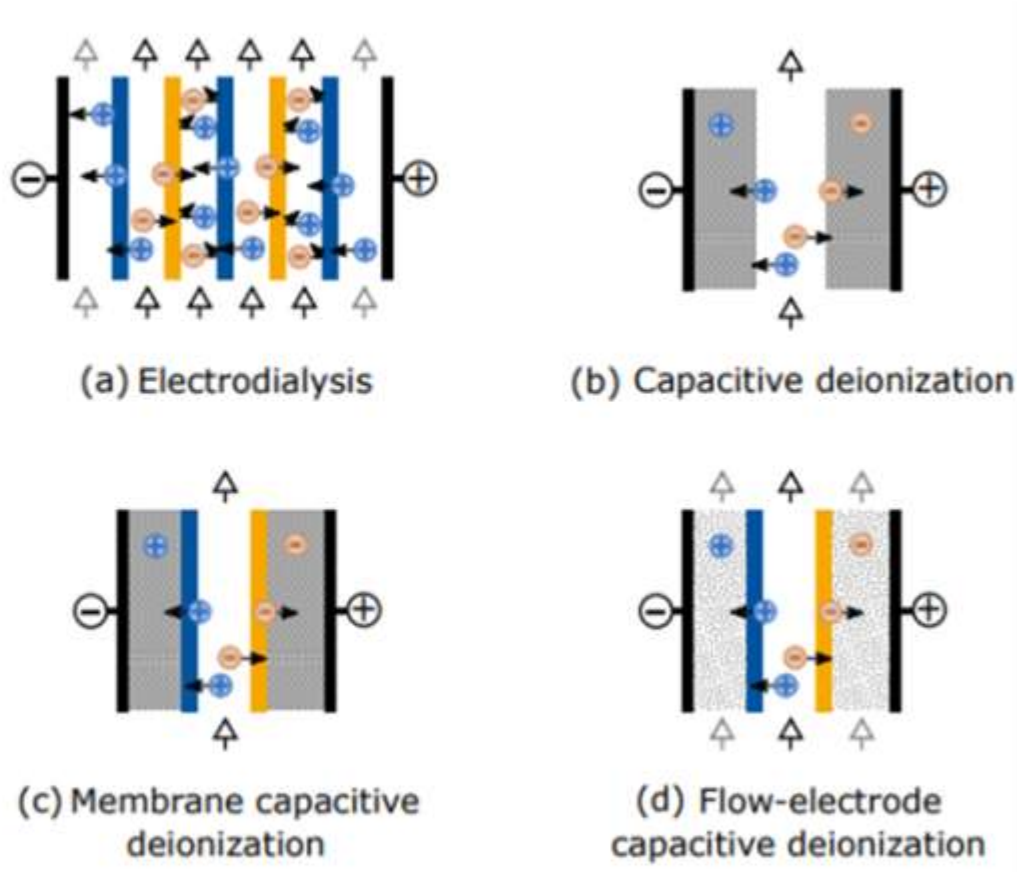


**Fig. 6:** Illustration of the working principles of major electrically driven desalination processes [25].

### *2.5 Summary of Desalination Technologies*

In summary, temperature-driven distillation processes rely on phase change to separate freshwater from saline solutions, typically by evaporating water and subsequently condensing the produced vapour. These include conventional large-scale methods such as MSF and MED, as well as more compact or specialised systems like TVC/MVC and MD. While each technique follows the same fundamental thermodynamic principle, they differ in terms of energy source, scale, and operational configuration.

Pressure-driven membrane processes have become the cornerstone of modern desalination, with reverse osmosis (RO) leading due to its maturity, high salt rejection, and energy efficiency. However, RO faces limitations, particularly in dealing with highly saline water and membrane fouling. Forward osmosis (FO) emerges as a low-energy alternative, offering reduced fouling and mechanical demands, though its viability is constrained by the need for draw solution regeneration. Nanofiltration (NF), sharing a similar mechanism to RO but with larger pore sizes, provides higher flux and selective separation, particularly for multivalent ions and small organics. These membrane technologies, each with unique strengths and constraints, represent key pathways toward sustainable and efficient desalination, especially when tailored to specific feedwater characteristics and recovery goals.

Ion-exchange and electrically driven processes present a diverse and innovative class of desalination technologies that rely on ion-selective materials and electric fields for salt removal. Ion-exchange resins and membranes enable selective ion substitution and transport, though their practical application is generally limited to low-salinity waters due to regeneration challenges and cost. ED and its reversal variant (EDR) have demonstrated effectiveness for brackish water treatment, offering modular design and relatively low energy consumption. CDI and its membrane-enhanced form (MCDI) represent next-generation technologies that leverage porous electrodes and electrostatic adsorption, providing energy-efficient desalination at low salinity ranges. However, both suffer from limitations related to ion saturation, regeneration cycles, and scalability. FCDI addresses these issues by employing flowable carbon slurry electrodes, enabling continuous operation and regeneration. This configuration enhances salt removal efficiency and supports higher water recovery.

## 3 Brine Discharge

Brine is widely recognised as the most critical by-product generated by desalination plants, posing significant environmental and operational challenges. In an effort to manage this waste stream, various disposal methods have traditionally been employed, often without prior treatment. As shown in Figure 7, the most common brine discharge strategies currently in use include surface water discharge, sewer discharge, deep well injection, evaporation ponds, and application for irrigation or land use [5].

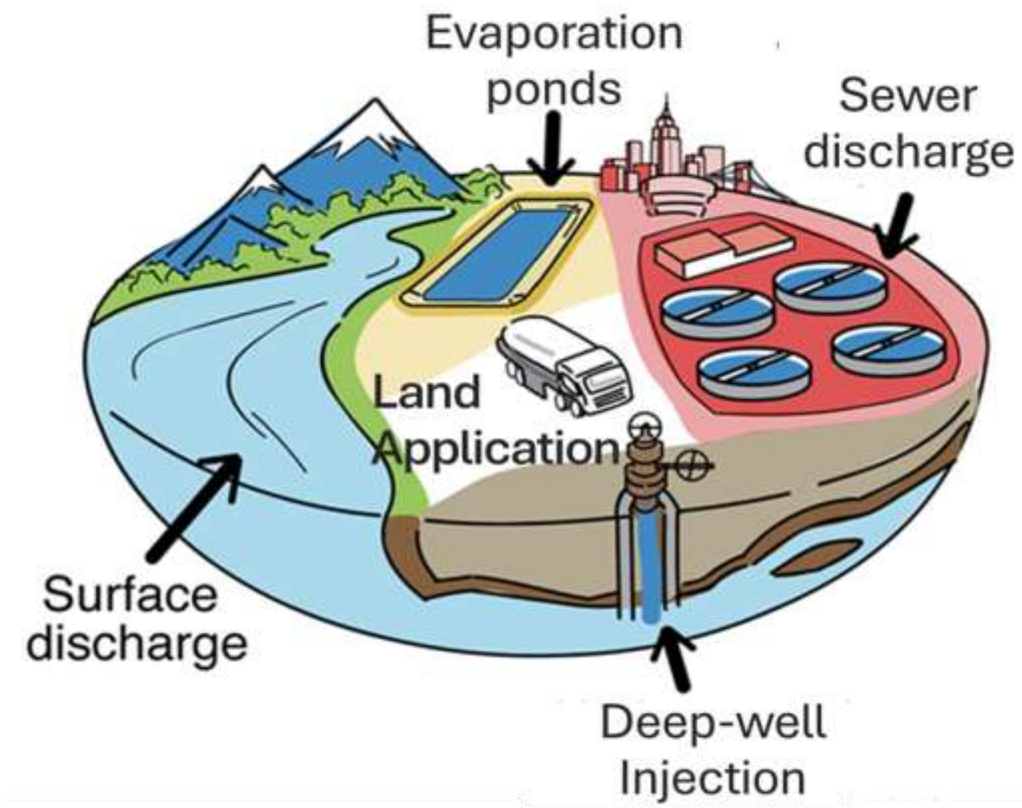


**Fig. 7:** Schematic showing the main brine discharge practices [57].

### 3.1 Surface Discharge

Surface water discharge is the most widely used method for brine disposal among large desalination facilities worldwide. In fact, it is used by more than 90% of large seawater desalination plants around the globe [14]. Notable examples include Spain, Singapore, Cyprus, Australia, and the Middle East [58]. This practice involves releasing the concentrated brine, along with other waste streams from the desalination plant, directly into open water bodies such as oceans, seas, or rivers, either near or offshore. Brine discharge can occur either directly on the surface or offshore through multiport diffusers installed on the seabed, known as submerged discharge [59]. The primary advantage of surface water discharge lies in its applicability across all plant sizes and its cost-effectiveness for medium to large brine flow rates. This makes it a widely adopted method for brine disposal, particularly in coastal desalination plants.

However, surface water discharge poses significant environmental risks. The elevated salinity levels of brine can exceed the tolerance thresholds of local aquatic ecosystems, leading to detrimental effects. Additionally, brine discharge may introduce harmful concentrations of other constituents, cause water discoloration, and reduce dissolved oxygen levels in the receiving body. These environmental concerns often result in complex and stringent permitting procedures, limiting this method's feasibility [58]. The suitability of surface water discharge depends heavily on brine composition and the resilience of the receiving environment. Brine is inherently harmful because of its high content of salt and other contaminants, but its impacts can be mitigated through pre-discharge measures. For example, dilution with ambient seawater can reduce salinity to safer levels before release. Such strategies may allow surface water discharge to remain a viable option, particularly for seawater desalination plants where natural dispersion is more achievable [60]. Nevertheless, even with mitigation efforts, the long-term ecological consequences necessitate careful evaluation. Regulatory frameworks and environmental monitoring remain critical to ensuring that this disposal method does not compromise marine ecosystems.

### 3.2 Sewer Discharge

Discharging brine into an existing sewage collection system, often referred to as sewer discharge, presents a cost-effective and low-energy disposal method, particularly when a wastewater collection system is already available near the desalination plant and the wastewater treatment plant (WWTP) can handle the brine volume [58], hence this disposal method is broadly used by small-scale brackish water desalination plants [14]. However, the feasibility of sewer discharge is significantly constrained by the WWTP's capacity to handle high concentrations without negatively affecting its biological treatment processes. Elevated salinity levels, particularly when influent exceeds 3,000 mg/L, can impair microbial activity essential to wastewater treatment. Given that seawater brine may contain TDS concentrations exceeding 55 g/L, the receiving WWTP must have at least 20 times the capacity of the incoming brine to keep the plant's feed salinity less than the critical threshold [14].

To protect treatment performance and safeguard infrastructure, pretreatment of brine is often mandated prior to discharge. This typically involves pH neutralisation and, in some cases, additional treatment to remove heavy metals or other contaminants commonly found in brine [14]. Discharge into municipal sewer systems is generally regulated under national or local industrial wastewater discharge standards enforced by the relevant environmental authorities [58]. Beyond operational challenges, co-disposal of brine with municipal wastewater may also pose environmental risks, particularly if elevated salinity persists in the final effluent. Such scenarios can lead to regulatory non-compliance and ecological harm upon discharge to receiving environments. Consequently, this disposal route is predominantly employed by brackish water desalination plants and is seldom considered viable for seawater desalination operations [60].

### 3.3 Deep-well injection

Deep-well injection is another brine discharge route that involves injecting the concentrated brine into a deep underground aquifer. This route is commonly employed by brackish water desalination plants of all sizes [14]. The discharge aquifer must be properly isolated from freshwater aquifers located over it. The system relies on multiple protective layers of casings with porous rock formations absorbing the brine while impermeable clay layers act as natural barriers against upward contamination. The depth of these injection wells is determined by the specific geological conditions of the site, but usually varies between 500 m and 1500 m. Crucially, the chosen receiving aquifer must possess sufficient storage capacity to accommodate the whole volume of brine produced across the lifespan of the plant, typically 25 to 30 years [14].

A related method is the use of shallow exfiltration beach well systems. These systems discharge brine into a relatively shallow, unconfined coastal aquifer. The brine then naturally migrates through the bottom sediments of the aquifer and ultimately conveys into the open ocean. Discharge beach wells are primarily utilized by small to medium-sized seawater desalination plants [58]. The primary environmental concern associated with deep well injection is the potential of polluting nearby freshwater aquifers that could serve as sources of drinking water. To mitigate this risk, thorough studies and comprehensive environmental overviews are mandatory before the construction of any injection well. It is critical to avoid areas with high seismic activity or sites near geological faults, as these conditions could compromise the well's integrity and risk leakage to the freshwater source. Other operational challenges such as plugging, contamination, and variation in brine flow rates and pressures must also be meticulously managed as they can impede injection efficiency and safety [58]. Given the stringent site requirements and the significant capital investment involved, deep well injection typically incurs higher capital costs compared to surface water discharge or sewage discharge. Therefore, this brine disposal method is generally considered only when other viable alternatives are not feasible [58].

## *3.4 Evaporation Ponds*

Evaporation ponds are a brine disposal method that employ shallow, lined earthen basins where brine undergoes gradual evaporation driven by direct solar radiation. As water evaporates, dissolved salts precipitate and crystallise, allowing for periodic harvesting and off-site disposal. This approach has been widely adopted in arid and semi-arid regions worldwide, capitalising on the availability of abundant solar energy [60]. Evaporation ponds offer several advantages, including their relative simplicity of implementation and operation, and their applicability for both inland and coastal use.

However, they come with significant limitations. A major disadvantage is the requirement for a high land footprint, which directly contributes to higher costs and limits their practical use primarily to smaller desalination plants [58]. Furthermore, their effectiveness is highly dependent on climate conditions. Solar evaporation is considered viable only in regions with warm, arid climates that exhibit high evaporation rates, low precipitation, and minimal humidity. Specifically, areas where the annual evaporation rate exceeds 1.0 m/year, rainfall remains below 0.3 m/year, or average humidity exceeding 60% are generally regarded as unsuitable for this method. Ideal sites also require flat terrain and low land costs. It's important to note that as the salinity in evaporation ponds increase, the rate of evaporation decreases. Therefore, minimising the volume of brine sent to the ponds can enhance overall efficiency and reduce land requirements [58].

A critical aspect of evaporation pond design and operation is the meticulous attention to environmental concerns, particularly regarding groundwater pollution. Environmental regulations typically mandate the construction of impervious liners to protect underlying aquifers. If the brine contains high levels of trace metals, a double-lined pond may be required to enhance protection. Without adequate lining, or if the liner is compromised, a portion of the brine can percolate into the underlying water aquifer, thereby degrading its water quality. Consequently, the selection of this method depends on several factors, including prevailing climatic conditions, the availability and cost of suitable land, and the quality of underlying groundwater aquifers [58].

## *3.5 Land Application*

Land application is a brine disposal approach that involves using brine for the irrigation of salt-tolerant vegetation, such as grasses and plants commonly found in parks, lawns, and golf courses, hence it is most appropriate for small volumes of brackish water brine [60]. The volume of brine that can be applied depends heavily on plant type, soil properties, and the characteristics of the brine itself. While most plants can endure concentrations less than 500 mg/L, only halophytic or highly salt-tolerant species can survive irrigation with brine containing TDS above 2,000 mg/L. As brine salinity increases, its use in land application becomes more limited, often requiring dilution with treated wastewater or other low-salinity water, such as that from shallow aquifers, to meet the acceptable thresholds for vegetation and soil health [14].

The practical implementation of land application at full scale is limited by several key factors, including local climate conditions, seasonal irrigation requirements, and other protection measures. Ideally, the disposal site would be at short distance with the desalination facility, incur minimal cost, and feature a warm, arid climate with relatively deep groundwater tables. In colder climates or during off-seasons for irrigation, temporary brine storage (for 2-6 months) or an alternative disposal method is typically necessary [58]. Optimal sites for land application are characterised by loamy or sandy soils with neutral to alkaline pH, which help limit trace metal leaching. A groundwater table depth of more than 2 meters is preferred. If groundwater lies closer to the surface (e.g., less than 3 meters), a subsurface drainage system is usually required [58]. One of the greatest environmental concerns with land application is the salinisation of shallow aquifers. Since groundwater in many regions has a lower salinity than the applied brine, both surface runoff and percolation can elevate the salinity of the aquifer. Exceptions include shallow or deep aquifers that are naturally protected from interaction with surface or near-surface flows [14].

### *3.6 Summary of Brine Discharge*

The preceding sections have detailed various conventional brine disposal methods, including surface water discharge, sewage discharge, deep well injection, evaporation ponds, and land application. Each method presents a unique set of advantages, limitations, and environmental implications, making the selection of an appropriate strategy a complex decision tailored to site-specific conditions and regulatory frameworks. A summary of the main disposal methods and their environmental challenges is presented in Table 1.

Surface water discharge involves releasing brine into large bodies of water such as seas or rivers, which can disrupt aquatic ecosystems due to elevated salinity and temperature changes. In sewer discharge, brine is sent to municipal wastewater treatment systems; however, its high salt content can impair biological treatment processes and affect plant performance. Deep-well injection, where brine is pumped into deep geological formations, poses risks of groundwater contamination and soil salinisation, particularly with large-scale use. Evaporation ponds, while passive and low-cost, may lead to groundwater pollution through seepage, especially if not properly lined. Finally, land application uses brine for irrigating salt-tolerant crops, but repeated or large-scale use can lead to soil degradation and salinisation over time

**Table 1:** Summary of the principles and environmental concerns of the main brine disposal methods.

| Brine Disposal Method | Mechanism | Key Environmental Concern |
|---|---|---|
| **Surface water discharge** | Brine is discharged into a water body such as oceans, seas, or rivers | Threatens aquatic ecosystems through salinity and temperature imbalances |
| **Sewer discharge** | Brine is directed to existing wastewater collection systems | Can overload wastewater treatment plants and disrupt biological processes |

| | | |
|---|---|---|
| **Deep-well injection** | Brine is pumped into deep underground rock formations | Risk of groundwater contamination and soil salinisation, especially at large volumes |
| **Evaporation ponds** | Brine is left to evaporate, leaving salt residues behind | Potential for seepage, which may pollute nearby aquifers |
| **Land application** | Brine is used to irrigate land or salt-tolerant crops | Long-term application can degrade soil and cause salinisation |

## 4 Brine Treatment

Traditionally, brine has been regarded as a waste product and managed through conventional disposal methods. However, recent perspectives have begun to recognise brine as a potential resource for both freshwater and valuable materials [10,11,66]. In addition to reducing environmental harm, emerging treatment strategies aim to harness this potential. Research in this area has increasingly focused on advanced concepts such as Zero Liquid Discharge (ZLD) and Minimal Liquid Discharge (MLD), which enable the recovery of water and salts from brine streams [6].

ZLD refers to a treatment strategy that seeks to recover virtually all water from the brine, leaving behind only solid residues. This approach offers several advantages: it allows complete water reclamation for reuse, mitigates the environmental risks associated with hypersaline effluent disposal, and produces a reduced volume of solid waste that can either be landfilled in leach-proof facilities or further processed to extract valuable minerals, improving the system’s overall economic viability. The adoption of ZLD technologies is being driven by increasingly stringent environmental regulations worldwide [57]. However, due to the high energy consumption and capital costs of achieving complete water recovery, MLD is a less costly alternative. MLD targets water recovery rates of up to 95%, offering a balance between performance and economic feasibility [10].

Despite the variability in brine composition, most ZLD systems follow a generalised two-stage treatment framework. The first stage involves pre-concentration using membrane-based or thermal evaporation processes, which can typically recover 60-80% of the water. The second stage employs thermal technologies, including crystallisation, to evaporate the remaining liquid and separate dissolved salts as solid waste [58]. For an MLD/ZLD system to be viable, the selected combination of technologies should demonstrate high separation efficiency, low energy and operational costs, and minimal environmental footprint, particularly in terms of carbon footprint [5].

### *4.1 Thermal-based Concentration and Crystallization*

Thermal-based technologies for brine treatment and concentration fundamentally use the principles of evaporation and condensation to separate water from dissolved solids. This includes various distillation and crystallization technologies designed to reduce brine volume, produce high-quality permeate, and recover solid salts, particularly as part of ZLD systems.

Among these, Brine Concentrators (BC) and Brine Crystallisers (BCr) are the most established and commercially implemented solutions for treating high-salinity streams. They are typically deployed at the final stages of a desalination treatment train, after less energy-intensive technologies have maximised recovery. Other technologies include MSF, MED, vapor compression evaporators, and ohmic evaporator, while crystallization technologies include spray dryer, and wind-aided intensified evaporation [12,67,68,69].

#### 4.1.1 Established Technologies

Brine concentrators are designed to reduce the liquid volume of brine by recovering water through evaporation. They are commonly based on MVC for water evaporation. This single-effect evaporator process enables high recovery (90-98%) and can handle up to 250,000 mg/L, producing water below 10 mg/L [9].

BC represent the benchmark for ZLD technologies, having been used successfully in industrial applications for decades. They are typically employed after reverse osmosis (RO) and other membrane processes, ensuring that only the most concentrated brine is exposed to this high-energy step. Despite advances in energy recovery using heat exchangers, BC remain energy-intensive, consuming approximately 15.86-26 kWh/m$^3$ of treated feedwater [14]. Their capital costs are also significant, mainly due to the need for corrosion-resistant materials to withstand high salinity and boiling conditions [9].

Brine crystallizers take over where brine concentrators leave off, further reducing brine volume and precipitating salts in solid form. Similar to BCs, vapor compressors raise the temperature of water vapour and become the source of heat required for evaporation. The most widely used type is the forced-circulation crystallizer, which combines incoming feed with recirculated slurry to form a nearly saturated solution. This mixture is then heated via submerged heat exchangers under pressure to avoid boiling within the tubes, which minimizes scaling. Upon entering a crystallization vessel, the fluid is depressurized, causing rapid vaporization of water and precipitation of salts. The generated vapor is mechanically compressed and reused as a heat source, increasing energy efficiency [57].

These systems can handle feed salinities of up to 300,000 mg/L and typically achieve overall water recoveries up to 97%. However, such high performance is accompanied by significant energy demands, typically ranging from 52-70 kWh/m$^3$ [4]. This substantial energy requirement is largely unavoidable, as crystallisers are tasked with processing feed streams of extremely high salinity and viscosity, which inherently demand greater thermal input for effective treatment [9].

BCr units are particularly valued for their ability to generate solid salt products that can be valorised for industrial uses in agriculture, food processing, or manufacturing. Still, they remain among the most energy-demanding components of a ZLD system and are usually reserved for the final treatment stage [4].

#### 4.1.2 Other Thermal Technologies

While BC and BCr are central to industrial ZLD thermal systems, other distillation technologies also rely on evaporation and condensation.

Multi-Stage Flash (MSF): While its applications specifically within sequential ZLD systems have not been as extensively reported in literature compared to MVC brine concentrators [9], it is increasingly applied in broader MLD and ZLD approaches due to its ability to handle high-TDS brine (<180,000 mg/L) and produce high-quality water. MSF is known for being less prone to fouling, hence require minimum pre-treatment. Nevertheless, its main drawbacks are high capital costs [4] and significant energy requirements (12.5-24 kWh/m$^3$) [14].

Multi-Effect Distillation (MED): MED is another widely used thermal technology for treating high salinity brine (<180,000 mg/L), designed to lower water flow and pressure differences, resulting in lower pumping power and relatively low thermal energy consumption (7.7-21 kWh/m$^3$) [14]. Despite these advantages, MED still requires high electrical energy consumption and substantial capital investment [4].

Ohmic Evaporation: Ohmic evaporation utilizes alternating electric current to generate heat directly within the brine, causing evaporation. This method is effective for high-TDS brines (>80,000 mg/L), achieving water recoveries of 81-93.5% under optimal conditions [70]. Nonetheless, its economic viability for full-scale applications is limited due to the huge energy consumption (150-220 kWh/m$^3$) [5].

Wind-Aided Intensified Evaporation (WAIV): These systems enhance natural evaporation by using vertical surfaces and wind energy. They evaporate brine more efficiently than conventional ponds while requiring less land. A study showed that WAIV unit produced final brine with TDS higher than 300,000 mg/L. WAIV also offer low energy consumption (0.3-1 kWh/m$^3$) [14] and can potentially recover salts. However, risks of brine leaching and groundwater contamination exist [4].

Spray Dryer (SD): As an alternative to conventional crystallizers, spray dryers use centrifugal atomizers to disperse concentrated brine as fine droplets in a hot air stream, rapidly evaporating water and leaving behind powdered salt. Though effective in producing solid salt, the system is complex and may require additional energy inputs compared to crystallizers, reaching up to 52-64 kWh/m$^3$ [4].

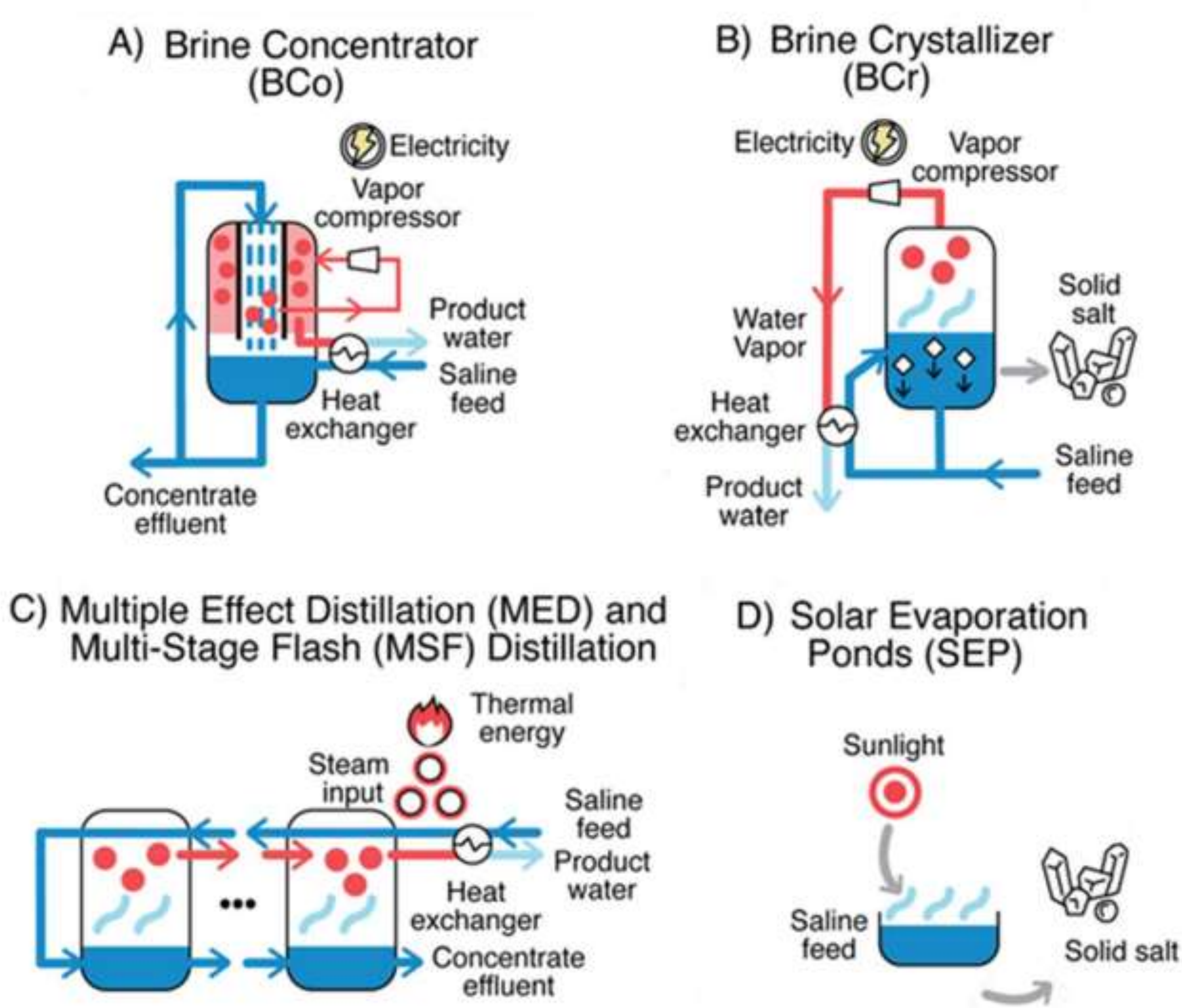


**Fig. 8:** Illustration of the major thermal-based concentration and crystallisation brine treatment technologies [53].

### 4.2 Membrane-based Concentration and Crystallization

While RO is a core technology in water desalination with relatively low energy requirement (2-6 kWh/m$^3$) [14], its application in ZLD systems faces two key limitations: membrane fouling/scaling and a limited upper salinity threshold [56,71]. Conventional RO systems are generally unable to treat streams with TDS exceeding 70,000 mg/L. This ceiling is considerably lower than what can be handled by brine concentrators, which can reach up to 250,000 mg/L. Therefore, RO in ZLD processes is often followed by brine concentrators or other volume-reduction steps [9].

In addition, as the feedwater becomes more concentrated than in typical seawater or brackish water RO operations, membrane fouling becomes more severe [72], reducing permeability and shortening membrane lifespan [56,73]. Therefore, extensive pretreatment is needed. Ultrafiltration membranes can be used for pre-treatment to help mitigate fouling. A variety of chemical and biological treatment processes can be employed to remove specific constituents from brine, including silica, organic compounds, trace heavy metals, and even precious metals [74,75]. These methods involve a wide range of technologies such as chemical softening, pH adjustment, precipitation, coagulation (both chemical and electrochemical), ion exchange, adsorption, and advanced oxidation processes [76,77,78]. Pretreatment of brine effluents increase operational complexity, cost, and generate additional chemical waste.

To overcome the limitations of conventional RO in ZLD applications, advanced membrane-based solutions has been explored. These innovations either enhance the pressure-handling capabilities of RO or incorporate additional driving forces, such as osmotic or thermal gradients [30,79].

#### 4.2.1 Advanced RO Configurations

Some technologies are modifications of the conventional RO setup to advanced RO configurations capable of treating high-salinity streams pushing recovery limits while reducing energy demands and operational complexity.

High-Pressure Reverse Osmosis (HPRO): HPRO systems operate at pressures exceeding 100 bar, allowing treatment of brines with concentration values up to 130 g/L. They achieve water recovery rates of 40-70% with SEC ranging from 3-12 kWh/m$^3$. While HPRO entails higher capital and operational costs than conventional RO, these costs remain significantly lower than those associated with thermal evaporators. However, similar to conventional RO, HPRO is also susceptible to membrane scaling and fouling, necessitating robust pretreatment [4].

Osmotically Assisted Reverse Osmosis (OARO): OARO is a recent innovation designed to treat high-salinity waters (<140,000 mg/L) more efficiently than RO [49]. Like RO, it is a pressure-driven membrane process but introduces a saline sweep on the permeate side to lower the osmotic pressure differential across the membrane. This adjustment enables treatment of more concentrated brines at lower pressures [4]. OARO improves energy requirement (6-19 kWh/m$^3$) and water recovery (up to 72%) [14] while reducing the need for pressure-resistant materials [29,30], thereby minimising energy costs and membrane degradation [4].

#### 4.2.2 Other Membrane Technologies

Alternative membrane-based technologies are designed to offer promising routes for brine concentration and resource recovery.

Forward Osmosis (FO): FO uses osmotic pressure gradients to drive water transport across a semipermeable membrane. A recent pilot study used FO with ammonia/carbon-dioxide draw solution to concentrate to an average salinity of 180,000 mg/L. The reduced energy requirement for vaporising the volatile solute instead of water, combined with FO's modularity and adaptability, positions FO as a competitive alternative to MVC brine concentrators. Although the initial osmosis step occurs spontaneously with minimal auxiliary energy input, the regeneration of the diluted draw solution demands substantial thermal energy, which significantly contributes to the overall SEC, estimated at approximately 13 kWh/m$^3$ [14]. FO has yet to conclusively demonstrate better overall separation efficiency than directly desalinating saline feedwater [9].

Membrane Distillation (MD): MD is a temperature-driven membrane-based process that separates water vapour from saline feed via a temperature gradient through a membrane. It operates at comparatively low temperatures (typically 40-80°C) and low pressures. MD is not subject to theoretical limitations of feed salinity, hence is capable of treating high salinity brines reaching up to 350 g/L [14]. A water recovery of up to 39% with salt rejection exceeding 99% has been reported [4]. However, even with heat recovery, the energy demand is 39-67 kWh/m$^3$ [14]. Moreover, MD faces dual challenges from both membrane-based and evaporation-based technologies, including fouling, scaling, pore wetting, and the intrinsic energy cost of vaporisation [9].

Membrane Crystallisation (MCr): It is an advanced extension of MD, designed not only for water recovery but also for salt harvesting. In MCr, the feed solution is concentrated beyond its saturation point, allowing salt crystals to form. Unlike conventional crystallisers, MCr offers improved control over crystals purity and size distribution. MCr inherits the benefits of MD, while achieving further volume reduction and solid salt production [78,79], supporting ZLD objectives [4]. Nevertheless, the energy consumption is 39-73 kWh/m$^3$ [14], and it still has high capital and operating costs [4].

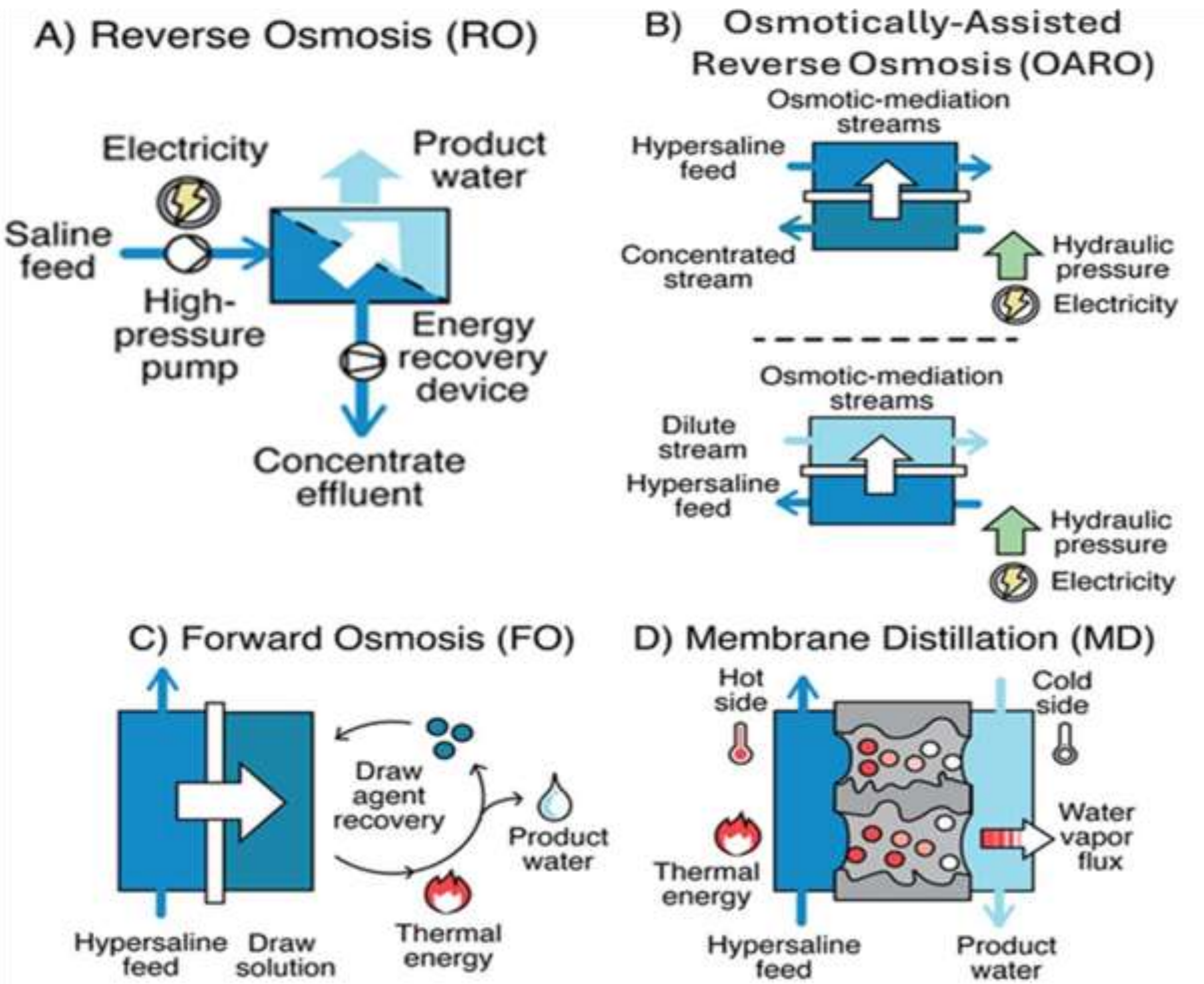


**Fig. 9:** Illustration of the major membrane-based concentration brine treatment technologies [53].

### *4.3 Electrical-based Concentration*

Electrically driven desalination processes rely on selectively moving ions by applying an electric potential, while keeping water largely confined to specific flow compartments. Among the most established electrically driven processes are ED and CDI and their variants [56,75,80,81].

#### *4.3.1 Electrodialysis Technologies*

ED is particularly attractive for brine concentration prior to final crystallisation due to its relatively lower energy demand relative to thermal concentration methods. However, ED is constrained by membrane scaling and fouling, especially in high-salinity or hardness-rich feeds. To reduces the build-up of scaling and fouling on the membranes, EDR operates on the same principal mechanism as ED but periodically reverses the polarity of the electrodes, thus extending system lifetime and improving stability [4].

Electrodialysis Metathesis (EDM) is a more recent advancement that integrates selective ion removal with a metathesis reaction, enabling the conversion of poorly soluble salts into more soluble forms. In EDM, four alternating IEMs create four compartments: two feed zones (one for brine and one for a substitution solution, typically NaCl) and two product zones where new soluble salts accumulate. For instance, calcium and sulphate in the brine may be replaced with sodium and chloride, forming sodium sulphate and calcium chloride, both of which are more soluble and easier to manage or recover. This ion substitution aids in scaling control and opens new avenues for selective salt recovery. However, it can only concentrate high-salinity brine to around 150,000 mg/L, consuming 5.1 $kWh/m^3$ [14]. Although EDM has shown promise in pilot setups, it remains underdeveloped, with limitations related to salt precipitation, low permeate flux , membrane scaling, and energy efficiency still under investigation [4].

In terms of energy efficiency, ED and EDR typically consume 7-15 $kWh/m^3$ of feedwater when concentrating brines to high salinity levels, which is lower than MVC. Several pilot studies have successfully integrated ED/EDR into ZLD configurations. In one system, RO was used for primary desalination, followed by EDR to concentrate the brine to up to 200,000 mg/L [14] before feeding it to a crystalliser. Another study applied EDR to treat saline aquifer water, effectively reducing hardness and scaling potential, thereby enabling higher RO recovery without chemical dosing. However, the salinity of ED/EDR effluents typically remains above 10,000 mg/L, making it unsuitable as a standalone ZLD solution. To achieve true ZLD, ED/EDR must be coupled with further downstream concentration steps such as brine crystallisation [9].

While ED-based systems offer notable benefits, their performance declines in hypersaline conditions. As salinity increases, the ion exchange membranes struggle to maintain high current efficiency due to co-ion leakage. Additionally, electro-osmotic drag and osmotic water transport can reduce net product water volume. The electrical resistance across the membranes also rises with salinity, further increasing energy consumption. Although multi-stage designs can partially mitigate these limitations, a conductivity-selectivity trade-off continues to hinder performance optimisation. High-resistance membranes are often more selective, but also more energy-intensive [57].

#### *4.3.2 Capacitive Deionisation Technologies*

In CDI, applying voltage difference drives ions to migrate towards the electrode of opposite charge, where they are electrostatically adsorbed at the electrode and electrolyte interface [82]. The primary challenges identified in applying CDI to brine treatment are the high salinity and the high potential for fouling. The typical limit for conventional CDI treatment is 10 g/L consuming 0.4-8 $kWh/m^3$ [5]. Higher salinity can lead to increased energy consumption and reduced efficiency in salt removal, however, using the membrane (MCDI) and flow-electrode (FCDI) variants, can enhance performance compared to classic CDI [56].

MCDI offers several advantages over conventional CDI, including higher ion adsorption capacity, improved energy efficiency, and less fouling tendency, all of which are advantages for brine concentration applications [56]. MCDI systems consume 0.4 to 6 kWh/m$^3$, depending on the configuration employed [5,83].

Nevertheless, CDI and MCDI utilise stationary carbon-based electrodes, which restrict their overall ion adsorption capacity in a single cycle, making them less suitable for high-salinity brine treatment. As a result, these technologies are typically operated in a discontinuous mode involving repetitive charge-discharge cycles [82]. Although MCDI has reached a level of development suitable for industrial-scale applications [56], both CDI and MCDI are generally confined to brackish water treatment. This is because higher salinity feeds rapidly saturate the electrodes, necessitating very frequent regeneration cycles [82].

In FCDI systems, the stationary electrodes used in CDI are replaced by pumpable carbon slurry electrodes, which allow the adsorption and desorption steps to occur independently. These flow electrodes can be regenerated through mixing or within a dedicated module or chamber, facilitating fully continuous desalination operation. Water recoveries of up to 90% [56] consuming 0.1-2.67 kWh/m$^3$ [84] were reported using different regeneration schemes in the FCDI process, where the ion storage capacity in the carbon suspensions is continuously restored while producing a diluate and concentrate stream [82].

Additionally, FCDI offers several advantages over traditional electrodialysis ED. First of all, FCDI has dual mechanism for ion removal, combining capacitive trapping and electrodialytic migration, allowing for more efficient ion removal [85]. Furthermore, the flowing electrode design minimizes electrode fouling, which is a common issue in ED systems. FCDI also relies more on electrosorption (non-Faradaic process), avoiding the need for high-voltage-driven oxidation-reduction reactions required in ED. This leads to less energy loss and minimises undesired chemical reactions. Both experimental and theoretical studies indicate FCDI outperforms ED in small-scale stacks (1-5 pairs), highlighting its potential for scalability [86].

In contrast to conventional fixed-electrode CDI systems, the FCDI system is capable of treating high-salinity feedwaters [87], making it a promising candidate for brine treatment applications. This improved performance is due to its high salt adsorption capacity, effective desalination efficiency, and ability to operate in a fully continuous mode [82]. A key advantage of FCDI lies in its dynamic adsorption capacity, which can be tailored by adjusting the carbon electrode density and the contact area within the cell, hence enabling targeted removal of salts from high-TDS streams [56]. Near-complete salt removal was achieved in one study by increasing the carbon content in the flow-electrode slurry to 11.1 wt% [88], while another investigation demonstrated successful brine concentration exceeding 290 g/L [82].

FCDI stands out as a promising option for brine treatment, even when compared with well-established thermal- and membrane-based technologies. At moderate salinity levels (around 60,000 mg/L), its energy consumption is competitive with that of BC. While at higher salinities, FCDI’s energy requirements barely approach those of MVC. In comparison with membrane processes, FCDI proves competitive, particularly when its total effective membrane area is optimally configured [89]. Also, FCDI operates based on the capacitive adsorption of ions onto electrodes under low voltage conditions without, unlike ED, involving electrochemical reactions at the electrode surfaces. As a result, issues such as gas evolution and the need for acid addition within the electrode are effectively avoided. Additionally, the absence of Faradaic reactions also makes FCDI particularly suitable for treating solutions containing chemically sensitive compounds, which could otherwise degrade under the high voltages and reactive by-products of processes like ED [90,91,92].

### *4.4 Emerging Brine Treatment Technologies*

Current desalination technologies face notable limitations related to technical efficiency and economic feasibility, particularly in the treatment and concentration of hypersaline brine. These limitations have driven the development of innovative and emerging technologies.

Humidification-Dehumidification (HDH): A thermally driven desalination process that mimics the natural water cycle by evaporating saline water into a carrier gas (usually air) at moderate temperatures (50-90°C), followed by condensation in a cooler chamber to collect fresh water. It has high tolerance to scaling and corrosion, as evaporation occurs away from equipment surfaces. HDH has demonstrated treatment of brines up to 345,000 mg/L, but energy consumption remains very high (>210 kWh/$m^3$). The need to heat and cool large volumes of carrier gas imposes additional thermal load and reduces energy efficiency. Moreover, HDH systems are bulky due to the heat and mass transfer resistances linked with non-condensable gases [57].

Solvent Extraction Desalination (SED): SED is a liquid-liquid separation method that uses hydrophilic solvents to extract water from saline streams without vaporisation. The water is absorbed into an immiscible solvent and then released by adjusting temperature, yielding desalinated water while the salt remains in the raffinate. SED operates below 80°C, making it compatible with low-grade heat and less prone to corrosion than conventional distillation. It has been demonstrated for hypersaline brines up to 247 g/L with >50% recovery and salt rejection up to 98.4% at 39-77 kWh/$m^3$. Its non-evaporative, membrane-less nature allows SED to avoid scaling and interface fouling. However, solvent loss, toxicity concerns, and the need for post-treatment are key limitations, and performance with real-world brines containing complex contaminants remains a challenge for commercial adoption [57].

Supercritical Water Desalination (SCWD): SCWD leverages the unique properties of water beyond its critical point (647 K, 221 bar), where it behaves as a nonpolar solvent and causes dissolved salts to precipitate. This process enables complete salt removal and inherently achieves ZLD. SCWD can treat feedwaters of any salinity and composition, including hypersaline brines, and avoids scaling by precipitating salts in the bulk fluid rather than on surfaces. However, the high temperature and pressure requirements result in very high energy consumption (around 125 kWh/$m^3$) and necessitate use of advanced, corrosion-resistant materials. Although effective in laboratory and pilot studies, SCWD has not yet been implemented industrially due to prohibitive energy costs and durability issues under harsh operating conditions [57].

Freeze Desalination/Crystallization (FD/FCr): FD is a low-temperature alternative that involves cooling saline water to form ice, which excludes salts during crystallisation. The ice is separated and melted to obtain fresh water and salts simultaneously. This method can significantly reduce energy consumption by up to 60% less than conventional evaporation, at 43.8-68.5 kWh/$m^3$. However, some salt typically remains trapped within or on the surface of the ice, necessitating additional purification steps. FD can theoretically treat high-TDS feeds but tends to achieve lower salt rejection (<50% at 250,000 mg/L) compared to thermal distillation. The process is less energy-efficient, slower, and its mechanical complexity has limited its mainstream use. Nonetheless, FD is gaining renewed interest due to its low scaling tendency and potential for coupling with renewable cooling sources [57].

Clathrate Hydrate Desalination (CHD): CHD operates by mixing saline water with clathrate-forming gases at low temperatures and high pressures to form crystalline hydrates that exclude dissolved salts. These hydrates are separated from the brine and melted to release fresh water and the original gas. Like freeze desalination, CHD suffers from salt adherence to the hydrate surface, requiring posttreatment to improve product water quality. It is electrically driven and has been experimentally studied with various working gases but remains unproven beyond the lab scale. Energy demands for seawater CHD are high (roughly 65 kWh/$m^3$ at 40% recovery), and even higher for hypersaline brines due to greater inhibition of hydrate formation. Although CHD can handle a wide salinity range and suppress fouling mechanisms, it faces major limitations, including extremely slow hydrate formation kinetics, gas recovery complexity, and poor salt rejection, making it less promising than even freeze desalination for practical ZLD applications [57].

Solar Thermal Desalination (STD): Such as solar stills, passively harness solar energy to evaporate water in a simple enclosure, achieving freshwater production rates of 4-6 L/$m^2$/day. Its simplicity, low equipment cost, and compatibility with remote locations make it attractive, especially in areas with abundant solar irradiance and inexpensive land. As an evaporative process, this technology is theoretically unlimited by salinity and can handle hypersaline streams. Recent improvements in absorber design have enhanced sunlight-to-heat conversion up to

99.8%, but heat losses and salt accumulation on evaporators remain critical challenges. However, without latent heat recovery, the energy requirement remains high (around 667 kWh/$m^3$), and water output is constrained by solar intensity, necessitating large land areas [57].

Other novel technologies targeting ZLD: membrane-promoted crystallization, low-salt-rejection RO, selective ED, bipolar membrane ED, and microbial CDI [93,94,95].

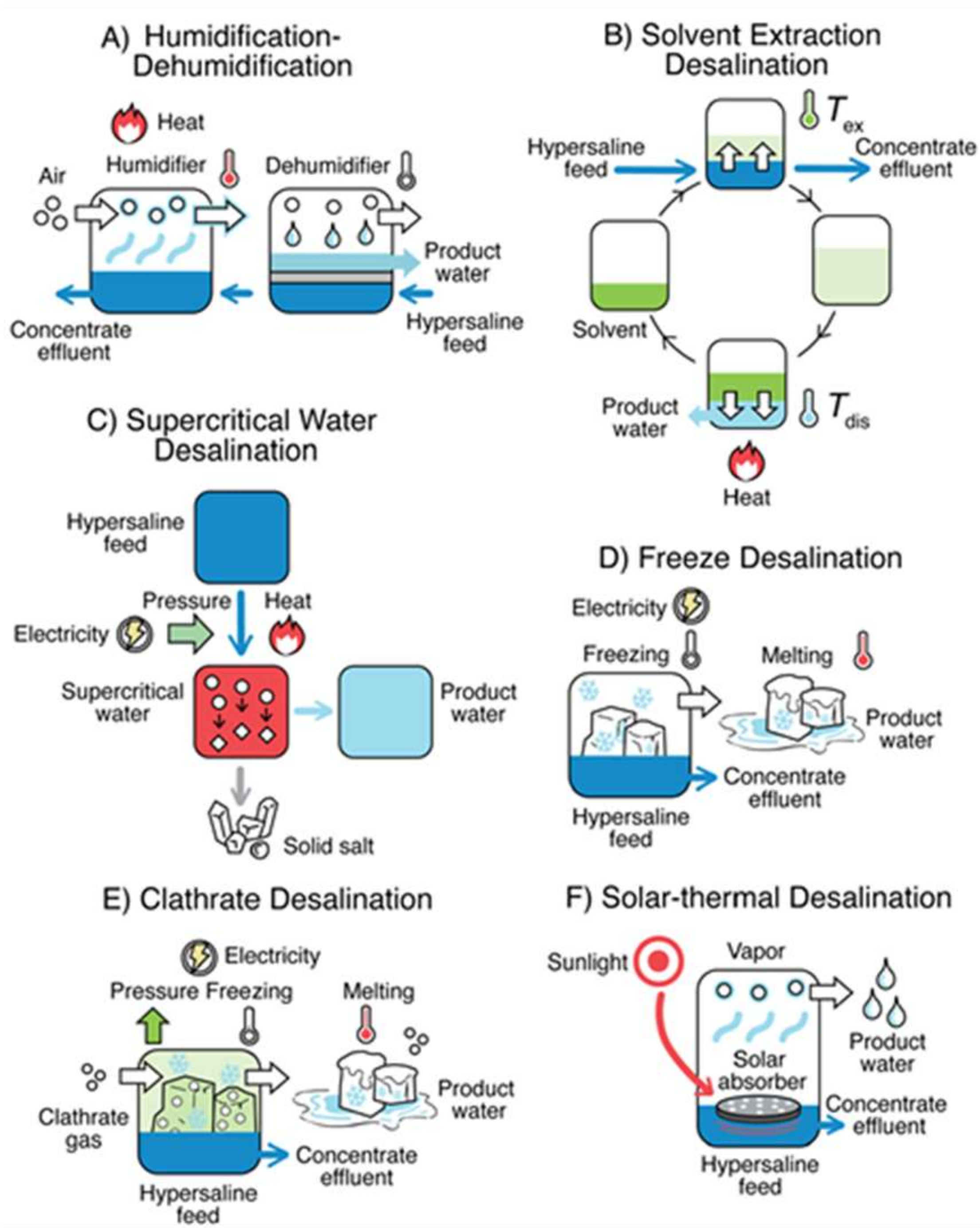


**Fig. 10:** Illustration of emerging concentration and crystallisation brine treatment technologies [53].

### 4.5 Comparative Analysis and Conclusion

The goal of ZLD in brine management is to eliminate liquid waste while enabling the recovery of both water and valuable salt. Initial ZLD systems primarily relied on thermal technologies such as single-effect evaporators, particularly BC followed by BCr. However, these systems are associated with high capital costs and significant energy consumption compared to the multi-stage MED and MSF [57]. Evaporation ponds can serve as an alternative to brine crystallizers. However, their main drawback is that water evaporated is not recovered, hence not contributing to increasing the water recovery [9].

Collectively, membrane technologies offer promising routes to enhance water recovery and minimise liquid discharge in high-salinity applications. HPRO and OARO extend the salinity threshold of conventional RO systems, while emerging methods like FO, MD, and MCr address the energy and fouling limitations through innovative driving forces and configurations. Despite their potential, most still require significant optimisation or integration with thermal steps to achieve full ZLD.

On the other hand, electrically driven desalination processes are well-suited for selective ion removal, hardness control, and intermediate brine concentration, particularly when integrated with RO. ED technologies has limitations in membrane performance at high salinity. Continued development of more selective, low-resistance IEMs and cost-effective system designs is essential for brine treatment schemes. Regarding CDI technologies, several advantages make FCDI a promising alternative for high salinity brine concentration compared to other electrically driven processes.

The brine treatment technologies discussed in this section can be alternatively grouped as concentrating, evaporating, or crystalising technologies, as summarised in Table 2.

**Table 2:** Summary of brine treatment technologies.

| | **Technology** | **Driving Force/Separator** | **TDS (mg/L)** | **SEC (kWh/m$^3$)** |
|---|---|---|---|---|
| **Pre-concentration** | RO | Pressure - Membrane | 70,000 | 2-6 |
| | HPRO | Pressure - Membrane | 130,000 | 3-12 |
| | OARO | Pressure/Osmotic pressure | 140,000 | 6-19 |
| | FO | Osmotic pressure - Membrane | 180,000 | 0.8-13 |
| | MD | Thermal - Membrane | 350,000 | 39-67 |
| | ED/EDR | Electrical - IEM | 200,000 | 7-15 |
| | EDM | Electrical - IEM | 150,000 | 0.6-5.1 |
| | CDI | Electrical | 10,000 | 0.4-8 |
| | MCDI | Electrical - IEM | 10,000 | 0.4-6 |
| | FCDI | Electrical | 291,000 | 0.1-2.67 |
| | SED | Liquid-liquid separation | 247,000 | 39-77 |
| | SCWD | Critical conditions | - | 125 |
| **Evaporation** | BC | Thermal | 250,000 | 15.86-26 |
| | MSF | Thermal | 180,000 | 12.5-24 |

| | | | | |
|---|---|---|---|---|
| | MED | Thermal | 180,000 | 7.7-21 |
| | OE | Electrical Heat | 80,000 | 218 |
| | HDH | Thermal | 345,000 | 210 |
| | STD | Thermal - Solar | - | 667 |
| **Crystallization** | BCr | Thermal | 300,000 | 52-70 |
| | WAIV | Thermal - Wind | 300,000 | 0.3-1 |
| | SD | Thermal - Atomizer | 180,000 | 52-64 |
| | MCr | Thermal - Membrane | 350,000 | 39-73 |
| | FCr | Thermal - Freezing | 250,000 | 43.8-68.5 |
| | CHD | Hydrate formation | - | 65 |

Although BC and BCr are the main commercial technologies used in ZLD systems and can achieve water recovery rates of over 99%, their extremely high capital and operating costs have prompted interest in alternative solutions. Technologies like MSF and MED offer lower energy consumption. However, they remain prone to significant scaling issues in heat exchangers, even with adequate pretreatment. SD stand apart from other crystallization technologies as they are uniquely capable of producing solid end-products with favourable quality standards. In contrast to SD, FD/FCr do not require strict feed composition conditions and can yield high-purity salts, often exceeding 90% purity. However, the capital investment required for these systems remains significant. Another alternative is the WAIV system, which offers a simplified approach to crystallization. WAIV serves as a more advanced version of traditional evaporation ponds, with the advantages of a smaller land footprint. Similar to SDs, WAIV systems rely on atmospheric evaporation and therefore do not enable water recovery.

In terms of energy demand, thermal-based systems used for evaporation consume between 7.7 and 26 kWh/m$^3$, while those used for crystallization require significantly more energy, ranging from 43.8 to 70 kWh/m$^3$. This increase is inherent to the nature of the more saline and viscous feed solution treated during crystallization.

Although RO is the most widely implemented desalination method, its utility in brine treatment is constrained by its salinity constraints (limited to <70 g/L) and modest water recovery rates (typically <50%). As a result, RO is typically employed as a primary desalination step, followed by more robust technologies within ZLD frameworks. HPRO can manage slightly more concentrated brines than RO, yet its performance remains comparably limited. OARO has emerged as a more advanced technique, offering higher recovery rates at elevated feed salinities. FO is considered a cost-effective option for treating highly saline streams (up to 180 g/L) but its broader adoption is hindered by the lack of universally suitable draw solutions and ongoing membrane limitations. MD and MCr are particularly promising for extreme salinities, tolerating up to 350 g/L; nonetheless, membrane durability and fouling continue to pose major challenges.

Membrane-based technologies generally exhibit lower SEC than thermal processes, primarily because they avoid the need for phase change, and thereby reduce energy losses during evaporating and condensing water. As summarised in the table, the SEC for most membrane-based systems is 0.8 to 19 kWh/m$^3$. An exception to this is MD and MCr, which, though membrane-based, are thermally driven and thus demand considerably more energy, reaching between 39 and 73 kWh/m$^3$.

Electrodialysis-based technologies, while generally less energy-efficient than pressure- or osmosis-driven membrane processes, offer unique advantages in treating brines with high silica content, as silica is uncharged and unaffected by ion-selective membranes. Among these technologies, EDM shows particular promise by selectively removing problematic salts from RO brine, thereby enhancing overall recovery rates without requiring multiple stags of ED or EDR, which would increase the cost.

Capacitive deionisation technologies are emerging electrically driven technologies for salt removal that offer low energy consumption, particularly at low to moderate salinities. However, their applicability is still limited at high salinity levels. FCDI, on the other hand, represents a significant advancement: it can treat brine up to exceptionally high salinities (290 g/L) with notably low SEC, consuming only 0.1-2.67 kWh/m$^3$.

Figure 11 is a visualisation of the data summarised in Table 2. At first glance, FCDI and WAIV technologies are the only ones capable of treating high-salinity brines with low energy consumption, however, FCDI has the added benefit of retrieving the water content in brine, which is instead lost to evaporation in WAIV. This unique capability makes FCDI a highly attractive candidate for integration into ZLD systems, especially when energy efficiency and high-recovery desalination are key priorities.

In summary, while a wide range of desalination and brine treatment technologies exist, only a few offer a viable combination of high salinity tolerance, energy efficiency, and potential for water recovery. Thermal, membrane-based, and electrically driven processes each present unique strengths, yet most remain constrained by high operational costs, energy demands, or limited recovery when applied independently.

These limitations have prompted increasing interest in hybrid configurations, particularly those built around RO, to extend recovery rates while balancing cost and energy input. In the following section, recent advances in RO-based systems targeting ZLD are reviewed, with a focus on emerging configurations that incorporate novel post-treatment technologies or alternative driving forces to overcome the shortcomings of conventional methods.

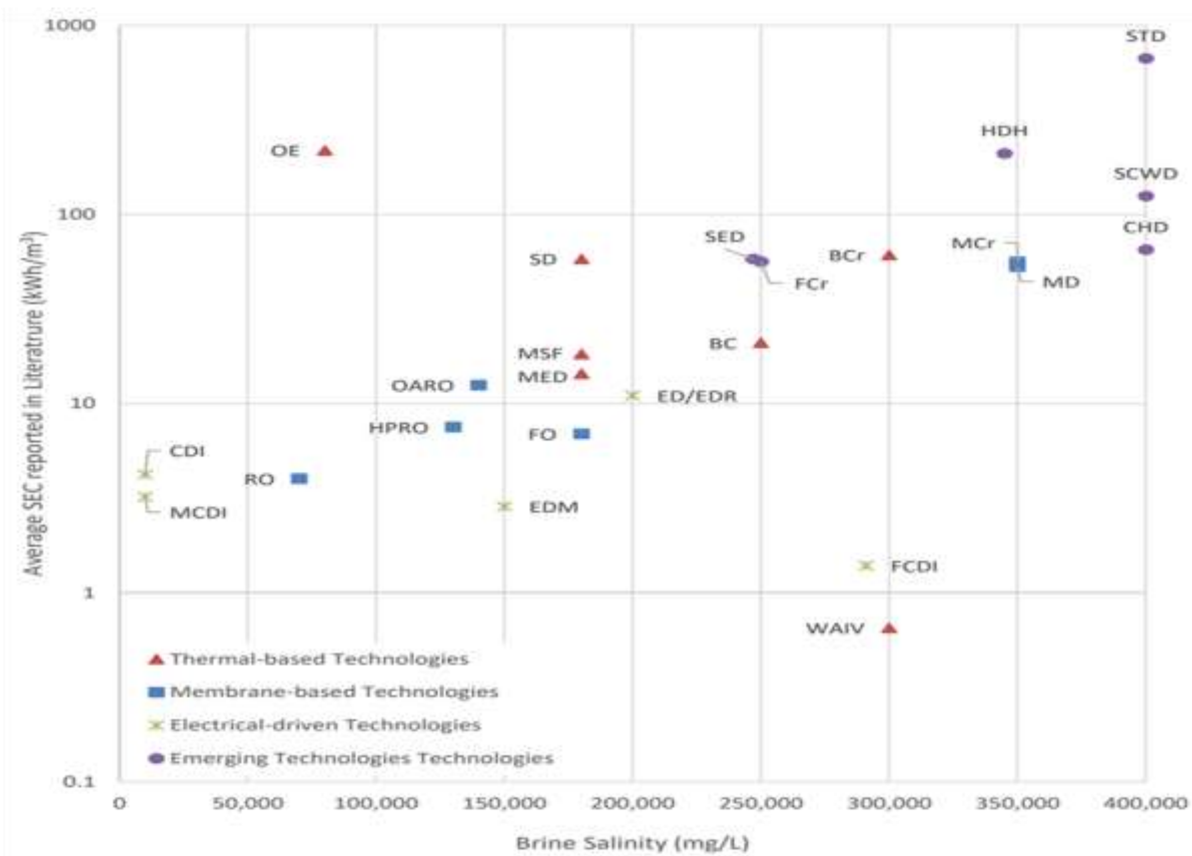


**Fig. 11:** Energy-salinity map of brine concentration and crystallisation technologies.

## 5 Advanced RO-Based Configurations for ZLD

Several studies reported in literature attempted to reach high recovery rates targeting ZLD through RO-only or RO-hybrid configurations with new and unconventional brine concentration technologies either pressure-driven, thermal, or chemical-based post-treatment methods. While many show promise in extending water recovery, most present significant limitations in terms of energy use, system complexity, or cost.

### 5.1 Tandem RO and Chemically Enhanced RO Configurations

While Tandem RO systems can achieve recovery rates up to 97-99%, divalent salts and colloidal fouling limit RO recovery rates, hence these systems require intermediate precipitative treatments to remove foulants [96]. Nevertheless, these systems incur high costs in high-pressure operation and long-term maintenance considerations such as membrane replacement, antiscalant dosing, and pretreatment requirements.

Other studies proposed mitigated the previous work's limitations by adding intermediate chemical demineralization [97] or lime-soda pretreatment [98] between the RO stages. Theses system could achieve up to 95% recovery, but they are highly chemically intensive. Additionally, the system is operationally complex as it requires strict pH control and faces persistent scaling risks. Furthermore, it generates large volumes of chemical sludge that adds to the operational costs.

### 5.2 Semi-Batch and Novel RO Configurations

Another approach is The Hybrid Semi-Batch Reverse Osmosis (HSBRO) system. Based on simulation studies [99], the system is predicted to reach up to 94-95% recovery from feed waters with salinity below 6000 mg/L. However, the HSBRO design remains unvalidated in experimental or pilot-scale settings, and its performance under real-world, high-salinity conditions is still unknown.

Other novel RO configurations such as Low Salt Rejection RO (LSRRO), OARO, and Cascading Osmotically Mediated RO (COMRO) have been developed to push recovery rates up to 75% and concentrate to crystallizer-feed requirements [100]. However, these systems are energy-intensive and complex, requiring multi-stage designs with precise control. Additionally, LCOW estimates for these systems were high mainly from energy and membrane replacements.

### 5.3 RO with Thermal or Crystallisation-Based Post-Treatment

Some dual-RO systems followed by crystallisers and evaporation ponds [101] can achieve full ZLD with significant cost and energy reductions compared to thermal methods. However, they are primarily applicable to moderate-salinity brines, and face challenges when treating high-TDS or silica-rich streams.

RO-WAIV-MCr [102] while capable of reducing brine volume significantly (99.25-99.73%), still depends on windy climates for effective evaporation which limits their universal applicability. Additionally, this system does not recover the evaporated water, marking it a low water recovery system.

A novel approach using RO-FCr reported recovery rates that could reach 88.8-93% for seawater and RO brine streams, based on thermodynamic modelling [103]. However, the system required extremely high energy demand (approximately 54 kWh/$m^3$) substantially exceeding even thermal ZLD benchmarks. Additionally, FCr requires complex freezing/thawing cycles which hinders the continuity of the process.

### 5.4 RO-Membrane Hybrid Systems

RO-NF hybrid has been studied to pre-concentrate RO brine, however, the main focus was on mitigating the fouling of RO membranes at high recovery rather than complete ZLD demonstration. NF systems suffer from scaling and fouling that resist chemical cleaning, and no solutions were proposed by the authors [104].

Other studies focused on comparing RO-hybrids focusing on brine post-treatment. A study presented techno-economic assessment performed at pilot scale of four different systems that consist of MD, NF, ultrafiltration, and chemical deposition [105]. Maximum recovery of approximately 85% was by the RO-MD with antiscalant, which still do not reach even MLD requirements (95%).

Another membrane-based hybrid approach was proposed by integrating NF and MD into a single treatment train with RO. In this system, NF was employed as a pretreatment step to reduce membrane fouling, while MD was used to concentrate the brine streams from both NF and RO stages. The integrated configuration achieved a water recovery of 76.2% with a reported water production cost of \$0.92/m$^3$, which is competitive with conventional seawater RO benchmarks [106]. However, the system falls short of MLD or ZLD thresholds.

### *5.5 RO-Electrically Driven Hybrid Systems*

Other novel RO hybrid systems reported in literature include RO-EDR which could reach 91.6% overall water recovery [107], and RO-EDR-WAIV which achieved 97-98% water recovery [108]. However, both systems suffer from scaling risks and suspended solids risk fouling, requiring brine pre-treatment. Furthermore, EDR system's efficiency drops with high salinity.

The integration of FCDI with RO for ZLD remains unexplored in the current literature. To date, only one study has attempted this integration [109], however, it neither targeted ZLD nor compared the energy or economic performance with conventional brine treatment methods.

### *5.6 Summary of RO-Based ZLD Systems*

While several RO-based configurations have been developed to push recovery rates closer to ZLD, most remain hindered by high energy demands, chemical intensity, or system complexity. Few technologies have demonstrated consistent performance beyond 90-95% recovery under practical conditions, and many are yet to be validated at scale. Moreover, the lack of integration between RO and emerging technologies highlights a significant research gap.

## 6 Conclusion

Desalination has become a cornerstone in addressing global water scarcity, with Reverse Osmosis (RO) emerging as the dominant technology due to its scalability and energy efficiency. However, the challenge of brine management remains a critical barrier to sustainability, especially in the context of Zero Liquid Discharge (ZLD). While numerous disposal and concentration strategies have been developed, including thermal, electrical, and hybrid processes, many remain limited by high energy demands, operational complexity, or environmental trade-offs.

Recent innovations in RO-based systems demonstrate promising potential for achieving high water recovery. Nevertheless, most systems fall short of full ZLD, particularly under real-world, high-salinity conditions. The integration of novel technologies with RO remains largely unexplored in the literature, representing a promising area for future research.

To advance towards practical and sustainable ZLD implementation, future efforts should focus on developing energy-efficient, modular, and economically viable hybrid systems capable of handling diverse brine streams. Research must also address operational reliability, fouling control, and material durability under harsh conditions. Bridging the gap between lab-scale innovation and full-scale deployment will be crucial to realising circular water systems and minimising the environmental footprint of desalination.

## References

[1] Panagopoulos A, Haralambous KJ (2020) Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) strategies for wastewater management and resource recovery – Analysis, challenges and prospects. J Environ Chem Eng 8:104418

[2] Shabib A, Tatan B, Elbaz Y, Aly Hassan A, Hamouda MA, Maraqa MA (2025) Advancements in reverse osmosis desalination: Technology, environment, economy, and bibliometric insights. Desalination 598:118413

[3] Moon J, Son S, Kim J, Park K (2025) Critical challenges in high-salinity seawater reverse osmosis systems: Technical, energy, and environmental reviews. Desalination 607:118811

[4] Cipolletta G, Lancioni N, Akyol Ç, Eusebi AL, Fatone F (2021) Brine treatment technologies towards minimum/zero liquid discharge and resource recovery: State of the art and techno-economic assessment. J Environ Manage 300:113681

[5] Panagopoulos A (2022) Brine management (saline water & wastewater effluents): Sustainable utilization and resource recovery strategy through Minimal and Zero Liquid Discharge (MLD & ZLD) desalination systems. Chemical Engineering and Processing - Process Intensification 176:108944

[6] Yaqub M, Nguyen MN, Lee W (2022) Treating reverse osmosis concentrate to address scaling and fouling problems in zero-liquid discharge systems: A scientometric review of global trends. Sci Total Environ 844:157081

[7] Panagopoulos A (2021) Water-energy nexus: desalination technologies and renewable energy sources. Environ Sci Pollut Res 28:21009–21022

[8] Panagopoulos A, Haralambous KJ (2020) Environmental impacts of desalination and brine treatment - Challenges and mitigation measures. Mar Pollut Bull 161:111773

[9] Tong T, Elimelech M (2016) The Global Rise of Zero Liquid Discharge for Wastewater Management: Drivers, Technologies, and Future Directions. Environ Sci Technol 50:6846–6855

[10] Panagopoulos A (2021) Techno-economic assessment of minimal liquid discharge (MLD) treatment systems for saline wastewater (brine) management and treatment. Process Saf Environ Prot 146:656–669

[11] Panagopoulos A (2021) Energetic, economic and environmental assessment of zero liquid discharge (ZLD) brackish water and seawater desalination systems. Energy Convers Manag 235:113957

[12] Panagopoulos A (2022) Techno-economic assessment of zero liquid discharge (ZLD) systems for sustainable treatment, minimization and valorization of seawater brine. J Environ Manage 306:114488

[13] Khan Q, Maraqa MA, Mohamed AMO (2021) Inland desalination: techniques, brine management, and environmental concerns. Pollut Assess Sustain Pract Appl Sci Eng 871–918

[14] Panagopoulos A, Haralambous KJ, Loizidou M (2019) Desalination brine disposal methods and treatment technologies - A review. Sci Total Environ 693:133545

[15] Jones E, Qadir M, van Vliet MTH, Smakhtin V, Kang S mu (2019) The state of desalination and brine production: A global outlook. Sci Total Environ 657:1343–1356

[16] Jha SK, Ghosh A (2025) Towards sustainable water resources: A critical review of evaluating traditional and solar-based desalination technologies and innovations. Desalination Water Treat 322:101246

[17] Belessiotis V, Kalogirou S, Delyannis E (2016) Desalination Methods and Technologies—Water and Energy. Thermal Solar Desalination 1–19

[18] Al-Karaghouli A, Kazmerski LL (2013) Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. Renew Sustain Energy Rev 24:343–356

[19] Elimelech M, Phillip WA (2011) The future of seawater desalination: Energy, technology, and the environment. Science 333:712–717

[20] Porada S, Zhao R, Van Der Wal A, Presser V, Biesheuvel PM (2013) Review on the science and technology of water desalination by capacitive deionization. Prog Mater Sci 58:1388–1442

[21] Thiel GP, Tow EW, Banchik LD, Chung HW, Lienhard V JH (2015) Energy consumption in desalinating produced water from shale oil and gas extraction. Desalination 366:94–112

[22] Amy G, Ghaffour N, Li Z, Francis L, Linares RV, Missimer T, Lattemann S (2017) Membrane-based seawater desalination: Present and future prospects. Desalination 401:16–21

[23] Zheng H (2017) General Problems in Seawater Desalination. Solar Energy Desalination Technology 1–46

[24] Drioli E, Ali A, Macedonio F (2015) Membrane distillation: Recent developments and perspectives. Desalination 356:56–84

[25] Rommerskirchen AKE, Franzreb M, Wessling M (2020) Continuous flow-electrode capacitive deionization. https://doi.org/10.18154/RWTH-2021-02093

[26] (2022) FilmTecTM Batch vs Continuous Process Technical Manual Excerpt.

[27] Schunke AJ, Hernandez Herrera GA, Padhye L, Berry TA (2020) Energy Recovery in SWRO Desalination: Current Status and New Possibilities. Front Sustain Cities 2:513595

[28] Lin S, Elimelech M (2015) Staged reverse osmosis operation: Configurations, energy efficiency, and application potential. Desalination 366:9–14

[29] Peters CD, Hankins NP (2019) Osmotically assisted reverse osmosis (OARO): Five approaches to dewatering saline brines using pressure-driven membrane processes. Desalination 458:1–13

[30] Bartholomew TV, Mey L, Arena JT, Siefert NS, Mauter MS (2017) Osmotically assisted reverse osmosis for high salinity brine treatment. Desalination 421:3–11

[31] Mohammad AW, Teow YH, Ang WL, Chung YT, Oatley-Radcliffe DL, Hilal N (2015) Nanofiltration membranes review: Recent advances and future prospects. Desalination 356:226–254

[32] Strathmann H (2004) Ion-exchange membrane processes. Membr Sci Technol 9:89–146

[33] Goh PS, Ismail AF (2018) Flat-Sheet Membrane for Power Generation and Desalination Based on Salinity Gradient. Membr-Based Salinity Gradient Process Water Treat Power Gen 155–174

[34] Balster J, Stamatialis DF, Wessling M (2010) Membrane with integrated spacer. J Memb Sci 360:185–189

[35] Campione A, Gurreri L, Ciofalo M, Micale G, Tamburini A, Cipollina A (2018) Electrodialysis for water desalination: A critical assessment of recent developments on process fundamentals, models and applications. Desalination 434:121–160

[36] Strathmann H (2010) Electrodialysis, a mature technology with a multitude of new applications. Desalination 264:268–288

[37] Shin YU, Lim J, Boo C, Hong S (2021) Improving the feasibility and applicability of flow-electrode capacitive deionization (FCDI): Review of process optimization and energy efficiency. Desalination 502:114930

[38] Zhao R, Biesheuvel PM, Van Der Wal A (2012) Energy consumption and constant current operation in membrane capacitive deionization. Energy Environ Sci 5:9520–9527

[39] Presser V, Dennison CR, Campos J, Knehr KW, Kumbur EC, Gogotsi Y (2012) The electrochemical flow capacitor: A new concept for rapid energy storage and recovery. Adv Energy Mater 2:895–902

[40] Biener J, Stadermann M, Suss M, Worsley MA, Biener MM, Rose KA, Baumann TF (2011) Advanced carbon aerogels for energy applications. Energy Environ Sci 4:656–667

[41] Biesheuvel PM, Zhao R, Porada S, van der Wal A (2011) Theory of membrane capacitive deionization including the effect of the electrode pore space. J Colloid Interface Sci 360:239–248

[42] Choi J, Dorji P, Shon HK, Hong S (2019) Applications of capacitive deionization: Desalination, softening, selective removal, and energy efficiency. Desalination 449:118–130

[43] Welgemoed TJ, Schutte CF (2005) Capacitive Deionization TechnologyTM: An alternative desalination solution. Desalination 183:327–340

[44] Farmer JC, Richardson JH, Fix DV (1996) Desalination with Carbon Aerogel Electrodes. 298:

[45] Jeon S Il, Park HR, Yeo JG, Yang S, Cho CH, Han MH, Kim DK (2013) Desalination via a new membrane capacitive deionization process utilizing flow-electrodes. Energy Environ Sci 6:1471–1475

[46] AlMarzooqi FA, Al Ghaferi AA, Saadat I, Hilal N (2014) Application of Capacitive Deionisation in water desalination: A review. Desalination 342:3–15

[47] Zhang C, Ma J, He D, Waite TD (2018) Capacitive Membrane Stripping for Ammonia Recovery (CapAmm) from Dilute Wastewaters. Environ Sci Technol Lett 5:43–49

[48] Porada S, Weingarth D, Hamelers HVM, Bryjak M, Presser V, Biesheuvel PM (2014) Carbon flow electrodes for continuous operation of capacitive deionization and capacitive mixing energy generation. J Mater Chem A 2:9313–9321

[49] Kim C, Srimuk P, Lee J, Aslan M, Presser V (2018) Semi-continuous capacitive deionization using multi-channel flow stream and ion exchange membranes. Desalination 425:104–110

[50] Yu F, Yang Z, Cheng Y, Xing S, Wang Y, Ma J (2022) A comprehensive review on flow-electrode capacitive deionization: Design, active material and environmental application. Sep Purif Technol 281:119870

[51] Suss ME, Porada S, Sun X, Biesheuvel PM, Yoon J, Presser V (2015) Water desalination via capacitive deionization: what is it and what can we expect from it? Energy Environ Sci 8:2296–2319

[52] Alaei Shahmirzadi MA, Hosseini SS, Luo J, Ortiz I (2018) Significance, evolution and recent advances in adsorption technology, materials and processes for desalination, water softening and salt removal. J Environ Manage 215:324–344

[53] Oren Y (2008) Capacitive deionization (CDI) for desalination and water treatment - past, present and future (a review). Desalination 228:10–29

[54] Dykstra JE (2018) Desalination with porous electrodes: Mechanisms of ion transport and adsorption. https://doi.org/10.18174/443551

[55] Rommerskirchen A, Gendel Y, Wessling M (2015) Single module flow-electrode capacitive deionization for continuous water desalination. Electrochem Commun 60:34–37

[56] Liu E, Lee LY, Ong SL, Ng HY (2020) Treatment of industrial brine using capacitive deionization (CDI) towards zero liquid discharge – challenges and optimization. Water Res 183:116059

[57] Shah KM, Billinge IH, Chen X, Fan H, Huang Y, Winton RK, Yip NY (2022) Drivers, challenges, and emerging technologies for desalination of high-salinity brines: A critical review. Desalination 538:115827

[58] Charisiadis C (2018) Brine Zero Liquid Discharge (ZLD) Fundamentals and Design.

[59] Abessi O (2018) Brine Disposal and Management—Planning, Design, and Implementation. Sustainable Desalination Handbook: Plant Selection, Design and Implementation 259–303

[60] Soliman MN, Guen FZ, Ahmed SA, Saleem H, Khalil MJ, Zaidi SJ (2021) Energy consumption and environmental impact assessment of desalination plants and brine disposal strategies. Process Saf Environ Prot 147:589–608

[61] Missimer TM, Maliva RG (2018) Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. Desalination 434:198–215

[62] Tang SCN, Birnhack L, Cohen Y, Lahav O (2018) Selective separation of divalent ions from seawater using an integrated ion-exchange/nanofiltration approach. Chem Eng Process Process Intensif 126:8–15

[63] Dahmardeh H, Akhlaghi Amiri HA, Nowee SM (2019) Evaluation of mechanical vapor recompression crystallization process for treatment of high salinity wastewater. Chem Eng Process Process Intensif 145:107682

[64] Panagopoulos A (2021) Beneficiation of saline effluents from seawater desalination plants: Fostering the zero liquid discharge (ZLD) approach-A techno-economic evaluation. https://doi.org/10.1016/j.jece.2021.105338

[65] Herrera V (2019) Reconciling global aspirations and local realities: Challenges facing the Sustainable Development Goals for water and sanitation. World Dev 118:106–117

[66] Havelka J, Fárová H, Jiříček T, Kotala T, Kroupa J (2019) Electrodialysis-based zero liquid discharge in industrial wastewater treatment. Water Sci Technol 79:1580–1586

[67] Dutta S, Moses JA, Anandharamakrishnan C (2018) Modern frontiers and applications of spray-freeze-drying in design of food and biological supplements. J Food Process Eng 41:e12881

[68] Das TK (2020) Industrial Environmental Management: Engineering, Science, and Policy. Industrial Environmental Management: Engineering, Science, and Policy 1–538

[69] Wu J, Wang J, Liu Y, Rao U (2021) Sustainable Desalination and Water Reuse. https://doi.org/10.1007/978-3-031-79508-4

[70] Assiry AM (2011) Application of ohmic heating technique to approach near-ZLD during the evaporation process of seawater. Desalination 280:217–223

[71] Morillo J, Usero J, Rosado D, El Bakouri H, Riaza A, Bernaola FJ (2014) Comparative study of brine management technologies for desalination plants. Desalination 336:32–49

[72] Guo W, Ngo HH, Li J (2012) A mini-review on membrane fouling. Bioresour Technol 122:27–34

[73] Gabelich CJ, Rahardianto A, Northrup CR, Yun TI, Cohen Y (2011) Process evaluation of intermediate chemical demineralization for water recovery enhancement in production-scale brackish water desalting. Desalination 272:36–45

[74] Ronquim FM, Sakamoto HM, Mierzwa JC, Kulay L, Seckler MM (2020) Eco-efficiency analysis of desalination by precipitation integrated with reverse osmosis for zero liquid discharge in oil refineries. J Clean Prod 250:119547

[75] Yang Y, Sun Y, Song X, Yu J (2021) Separation of mono- and di-valent ions from seawater reverse osmosis brine using selective electrodialysis. Environ Sci Pollut Res 28:18754–18767

[76] Hamdona SK, El-Aassar AHM, Ahmed AEMM, Nasra AES, Morsy A (2021) Enhancing anti-scaling resistances of aromatic polyamide reverse osmosis membranes using a new natural materials inhibitor. Chem Eng Process Process Intensif 164:108404

[77] Imdad S, Dohare RK (2022) A Critical Review On Heavy Metals Removal Using Ionic Liquid Membranes From The Industrial Wastewater. Chem Eng Process Process Intensif 173:108812

[78] Moreira VR, Lebron YAR, Amaral MCS (2021) Mining from wastewater: Perspectives and current practices of non-dispersive solvent extraction for metallic compounds valorization. Chem Eng J 425:130711

[79] Ruiz Salmón I, Luis P (2018) Membrane crystallization via membrane distillation. Chem Eng Process Process Intensif 123:258–271

[80] Camacho LM, Fox JA, Ajedegba JO (2017) Optimization of electrodialysis metathesis (EDM) desalination using factorial design methodology. Desalination 403:136–143

[81] Zhao D, Lee LY, Ong SL, Chowdhury P, Siah KB, Ng HY (2019) Electrodialysis reversal for industrial reverse osmosis brine treatment. Sep Purif Technol 213:339–347

[82] Rommerskirchen A, Linnartz CJ, Egidi F, Kendir S, Wessling M (2020) Flow-electrode capacitive deionization enables continuous and energy-efficient brine concentration. Desalination 490:114453

[83] Oh C, Lee B, An J, Yeon S, Je Oh H (2024) Performance optimization of a pilot-scale membrane capacitive deionization (MCDI) system operating with circulation process. Sep Purif Technol 343:126937

[84] Zhang C, Ma J, Wu L, Sun J, Wang L, Li T, Waite TD (2021) Flow Electrode Capacitive Deionization (FCDI): Recent Developments, Environmental Applications, and Future Perspectives. Environ Sci Technol 55:4243–4267

[85] Gu H, Hou C, Mao Y, Wu D (2025) Navigating the Dual Pathways of Ion Removal in Flow-Electrode Capacitive Deionization: Capacitive Trapping vs. Electrodialytic Migration. https://doi.org/10.2139/SSRN.5217000

[86] Yang F, He Y, Rosentsvit L, Suss ME, Zhang X, Gao T, Liang P (2021) Flow-electrode capacitive deionization: A review and new perspectives. Water Res 200:117222

[87] Cheng Y, Shi J, Zhang Q, Fang C, Chen J, Li F (2022) Recent Progresses in Adsorption Mechanism, Architectures, Electrode Materials and Applications for Advanced Electrosorption System: A Review. Polymers 14:2985

[88] Yang SC, Kim H, Jeon S il, Choi J, Yeo J gu, Park H ran, Jin J, Kim DK (2017) Analysis of the desalting performance of flow-electrode capacitive deionization under short-circuited closed cycle operation. Desalination 424:110–121

[89] Lim J, Lee S, Lee H, Hong S (2024) Energetic Comparison of Flow-Electrode Capacitive Deionization and Membrane Technology: Assessment on Applicability in Desalination Fields. Environ Sci Technol 58:6181–6191

[90] Chai S, Xi J, Chen L, He W, Shen J, Gong H (2022) Selective Ion Removal by Capacitive Deionization (CDI)-Based Technologies. Processes 10:1075

[91] Adewole JK, Al Maawali HM, Jafary T, Firouzi A, Oladipo H (2022) A review of seawater desalination with membrane distillation: material development and energy requirements. Water Supply 22:8500–8526

[92] Johnson DJ, Hilal N (2021) Can graphene and graphene oxide materials revolutionise desalination processes? Desalination 500:114852

[93] Kim N, Lee EA, Su X, Kim C (2021) Parametric investigation of the desalination performance in multichannel membrane capacitive deionization (MC-MCDI). Desalination 503:114950

[94] Wang Z, Feng D, Chen Y, He D, Elimelech M (2021) Comparison of Energy Consumption of Osmotically Assisted Reverse Osmosis and Low-Salt-Rejection Reverse Osmosis for Brine Management. Environ Sci Technol 55:10714–10723

[95] Stoll ZA, Forrestal C, Ren ZJ, Xu P (2015) Shale gas produced water treatment using innovative microbial capacitive desalination cell. J Hazard Mater 283:847–855

[96] Ning RY, Troyer TL (2009) Tandom reverse osmosis process for zero-liquid discharge. Desalination 237:238–242

[97] Gabelich CJ, Williams MD, Rahardianto A, Franklin JC, Cohen Y (2007) High-recovery reverse osmosis desalination using intermediate chemical demineralization. J Memb Sci 301:131–141

[98] Mohammadesmaeili F, Badr MK, Abbaszadegan M, Fox P (2010) Mineral recovery from inland reverse osmosis concentrate using isothermal evaporation. Water Res 44:6021–6030

[99] Hosseinipour E, Karimi S, Barbe S, Park K, Davies PA (2022) Hybrid semi-batch/batch reverse osmosis (HSBRO) for use in zero liquid discharge (ZLD) applications. Desalination 544:116126

[100] Atia AA, Yip NY, Fthenakis V (2021) Pathways for minimal and zero liquid discharge with enhanced reverse osmosis technologies: Module-scale modeling and techno-economic assessment. Desalination 509:115069

[101] Bond P, Veerapaneni S (2008) Zeroing in on ZLD Technologies for Inland Desalination. J Am Water Works Assoc 100:76–89

[102] Macedonio F, Katzir L, Geisma N, Simone S, Drioli E, Gilron J (2011) Wind-Aided Intensified eVaporation (WAIV) and Membrane Crystallizer (MCr) integrated brackish water desalination process: Advantages and drawbacks. Desalination 273:127–135

[103] Nemmour A, Zhang H, El Kadi K, Janajreh I (2024) Thermodynamic modeling of eutectic freezing for enhanced seawater desalination and reverse osmosis brine treatment. J Water Process Eng 68:106483

[104] Song W, Lee LY, Liu E, Shi X, Ong SL, Ng HY (2020) Spatial variation of fouling behavior in high recovery nanofiltration for industrial reverse osmosis brine treatment towards zero liquid discharge. J Memb Sci 609:118185

[105] Bindels M, Carvalho J, Gonzalez CB, Brand N, Nelemans B (2020) Techno-economic assessment of seawater reverse osmosis (SWRO) brine treatment with air gap membrane distillation (AGMD). Desalination 489:114532

[106] El-Zanati E, El-Khatib KM (2007) Integrated membrane –based desalination system. Desalination 205:15–25

[107] Turek M, Was J, Dydo P (2009) Brackish water desalination in RO–single pass EDR system. Desalination Water Treat 7:263–266

[108] Oren Y, Korngold E, Daltrophe N, Messalem R, Volkman Y, Aronov L, Weismann M, Bouriakov N, Glueckstern P, Gilron J (2010) Pilot studies on high recovery BWRO-EDR for near zero liquid discharge approach. Desalination 261:321–330

[109] Chung HJ, Kim J, Kim DI, Gwak G, Hong S (2020) Feasibility study of reverse osmosis–flow capacitive deionization (RO-FCDI) for energy-efficient desalination using seawater as the flow-electrode aqueous electrolyte. Desalination 479:114326