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DPSIR framework and sustainable approaches of brine management from seawater desalination plants in Qatar

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ABSTRACT

Brine released from desalination plants is extremely high in salinity and contains various chemicals, which are harmful to the ecosystem. The disposal of brine has raised great concerns for the desalination industry around the world due to its detrimental impact on fauna and flora. This review complies with various zero liquid discharge technologies that have been proposed for successful brine disposal which aims to minimize the impact of brine discharge. Moreover, it highlights some of the detrimental impacts of brine discharge on marine fauna and Flora. It also discusses both thermal and membrane technologies for recovering freshwater, energy, and minerals from waste brine, in addition to the recent advances in a solar pond, membrane distillation, pressure retarded osmosis, etc. In Driver-Pressure-State-Impact-Response (DPSIR) framework was used in this review to analyze the water resource system in Qatar. This review also facilitates and provides a comprehensive approach in minimizing the potential impact of brine discharge which can be practiced and applied in countries where desalination plants are set up. This promotes cleaner production, sustainability, and recycling of waste that will help protect and preserve the country's natural water resources.

1. Introduction

Water is undoubtedly the driving force for living organisms to survive on the planet. The alarming rate at which the world population is increasing has led to an increase in water demand. The existing natural water resources continue to be polluted by industries and various other agricultural practices leading to an increase in water scarcity (Al-Absi et al., 2021). On the other hand, the world population is also expected to reach up to 9.4 billion - 10.2 billion by 2050. Furthermore, it is also anticipated that water stress or water shortage will be faced by more than 50% of the countries by 2025. Conservation of water, restoration of existing infrastructure, and restructuring disturbing system are some of the actions that are being taken to minimize water stress. These steps are expected to improve the availability of water but not increase its availability in seawater. Seawater comprises 96.54%, while only 2.53% of total available water comes under freshwater, in which, 1.76% of water is stored in the form of ice caps, glaciers, and permafrost, while 0.76% makes up the fresh groundwater, leaving only 0.01% of surface freshwater from which 0.007% is stored in the freshwater lake. Keeping this in mind, it is safe to say, the global shortage of freshwater is perhaps not only vital but also a serious threat for living organisms, that needs to be addressed (Jørgensen and Fath, 2014). Various countries have been invested to determine various alternatives for conventional water resources.

Desalination has become a reliable option to cater to water stress by supplying potable water in a region where fresh water supply is restricted. Amongst all the nations, the Gulf countries are susceptible to a greater water crisis. Qatar is in the Arabian Gulf and can be regarded as one of the arid countries across the globe with limited water supply, low rainfall throughout the year and groundwater being the only natural source of fresh water. Groundwater is primarily used for agricultural and industrial activities. The annual withdrawal of groundwater (estimated 22.2 Mm^3) is several times more than the natural recharge rate (estimated 58.1 Mm^3). This over-exploitation of groundwater has caused a decline in the aquifer level, which ultimately leads to seawater intrusion. Over-dependence on freshwater resources will lead to an alternative method to meet water demand and supply, with almost 97% of total water resources on Earth, naturally, the most commonly opted method by many societies is desalination. This is also reflected by the exponential increase in the number of desalination plants being constructed globally.

Besides, the continuous use of groundwater has resulted in soil salinity and desertification in many parts of the country. Qatar is highly

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Nomenclature/abbreviations

AGMD	Air gap membrane distillation
AEM	Anion exchange membrane
BW	Brackish water
BWD	Brackish water desalination
CEM	Cation exchange membrane
CF	Characterization factor
CTA	Cellulose triacetate
DAF	Dissolved air flotation
DCMD	Direct contact membrane distillation
EMWD	Eastern municipal water district
EC	Elctrcocoagulation
ED	Electrodialysis
EDM	Electrodialysis metathesis
EDR	Electrodialysis reversal
FO	Forward osmosis
IAF	Induced air flotation
LCIA	Life cycle impact assessment
MSF	Multi-stage flash
MD	Membrane distillation
MDC	Membrane distillation crystallization
MED	Multi-effect distillation
MSD	Multi-stage flash
MSW	Municipal solid waste
NR	Not reported
Q_b	Total brine produced
Q_f	Total saline feedwater
Q_p	Total produced freshwater
Q_f	Feedwater volume
RED	Reverse electrodialysis
RO	Reverse osmosis
RR	Recovery rate
SGMD	Sweeping gas membrane distillation
SWRO	Seawater reverse osmosis
SWD	Seawater discharge
TDS	Total dissolved solids
TOC	Total organic carbon
VC	Vapor pressure
VMD	Vacuum membrane distillation
WWRP	Wastewater treatment plant
ZLD	Zero-liquid discharge
ZDD	Zero desalination discharge

dependent on its desalinated water to meet the majority of its municipal and industrial water demand (Baalousha, 2016). This goes without saying, an over-dependence on desalinated water comes with its own risk, 25% of the world's oil supply passes through the Arabian Gulf every day which is vulnerable to oil spills, which may interrupt desalinated water. Moreover, the Arabian Gulf is at risk for increased salinity due to various discharges to the sea, which may eventually result in algal blooms. Desalination is widely optimized as a feasible option to address the water crisis since the 1950s. Desalination capacity has increased up to 100 M m^3/d produced by 16000 desalination plants globally, of which 30% is utilized by industries, while 60% accounts for domestic use.

1.1. *Desalination technologies*

Desalination is broadly differentiated either by the applied desalination technology or the source of the feedwater. The source of feedwater can either be seawater (SW), which records for 61%, or brackish water (BW), which accounts for 21% while or river water accounts for 61%, 21%, and less than 10% respectively. Generally, desalinated water technologies can be divided into three categories membrane process (63.7%), thermal process (34.2%), or other emerging technologies (Sanmartino et al., 2016). It is safe to say thermal and membrane processes are dominated by 97% of desalination capacity (Jones et al., 2019). Membrane technologies include reverse osmosis (RO), membrane distillation (MD), and nanofiltration (NF) while, thermal technologies include multistage flash (MSD) or multi-effect desalination (MED), which accounts for 18% and 7% of total global desalination capacity, respectively. While on the other hand emerging desalination technologies are new recently studied and advanced, they seem promising, however, have not been completely commercialized or performed in a larger scale membrane or thermal technologies. These new technologies either involve different skills or technologies that use thermal coupled with membrane desalination. Desalination is a process that removes excess salts from saline water. The basic mechanism in which desalination plants operate is that the water that enters (feed), separates, and forms two different streams, i.e. the freshwater stream (product) and brine (by-product stream. Fresh water is the water that qualifies the regulations for anthropoid use while brine water is characterized as a high saline concentrate and contaminated (Václavíková et al., 2017).

One of the most widely used technologies in desalination plants is reverse osmosis (RO), which allows the removal of various trace organic pollutants, total dissolved solids (TDS) from wastewater, making it possible to reuse it in various sectors including agriculture, municipalities, and industries (Rajwade et al., 2020). While RO offers great advantages for treating wastewater, it also produces a high volume of high saline concentrate; brine. About half the amount of feed is discharged back to the marine water in the form of brine which is extremely saline and includes several chemicals that are introduced during the desalination process. Brine cannot be directly disposed of in water bodies due to the high amount of contaminants. It is either released directly to the coastal line or away from the shore through a diffuser system (Missimer and Maliva, 2018). It is reported that the salinity of brine in the mixing zone of seawater reverse osmosis (SWRO) discharge was between 1% and 10% above the acceptable level and rarely more than 25% above the ambient levels (Petersen et al., 2018a,b). Therefore, researches have been carried out to investigate appropriate technologies that could deal with the byproducts of desalinated plants (Boo et al., 2016). It can be said, technologies that are developed by mankind, in general, do pose economic and/or environmental impacts. Similarly, desalination, which was designed to cater to water supply in water-stressed regions consequently resulting in social prosperity (Kress et al., 2020). However, the environmental impact due to desalination cannot be ignored. The brine discharge not only affects the marine and land but the emission of greenhouse gas results in air pollution (Panagopoulos et al., 2019).

2. Environmental concerns

One of the major environmental concerns of desalination plants from a quantitative and qualitative perspective is the release of brine water (Qasim et al., 2019). The majority of water streams with brine/product ratio for SWRO is 1.5–2 while for thermal distillation it can reach up to 10, which will massively impact the marine environment (Panagopoulos, 2019). Brine water can be harmful due to multiple reasons, including salinity, temperature, the presence of concentrated chemical substances, and the presence of heavy metals. The chemical properties of brine from various sources are mentioned in Table 1. Brine water acquired from seawater desalination is generally released back to the sea (Panagopoulos et al., 2019). If not disposed of properly, brine water from desalination plants has a strong potential to adversely affect the physicochemical and ecological qualities of the receiving water body

Table 1
Chemical properties of brine from different sources.

pH	TDS (mg/L)	COD (mg/L)	K^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	Reference
9.12	73,75	1554	781	1382	2974	23931	Mohammad et al. (2019)
9.9–10.1	NR	NR	11300	NR	48.6	67600	Kasedde et al. (2014)
7.9	55000.0 ± 2500	NR	NR	879 ± 53	1864 ± 56	15270 ± 460	Sola et al. (2019)
8.2	1410	–	32	14	17	6840	Pramanik et al. (2017)
7.5	54746.86	–	276.38	1086.37	1394.09	17495.27	Mabrook (1994)
8.34	57400	NR	491	521	1738	18434	Katal et al. (2020)

(Del-Bene et al., 1994). The rejected brine that is normally disposed of back to the sea can have a harmful effect on aquatic life. For the past several years, there has been a fear in the Mediterranean countries regarding *Posidonia* oceanica which is considered a very vital ecosystem and is regarded as a habitat of priority by the European Habitat Directive (Council). Besides, it has one of the most common seagrass species in the Mediterranean, which covers around 40,000 km^2 of the seafloor as well as forms large sea meadows from the surface to a depth of 40 m (Cebrian and Duarte, 2001). Unfortunately, due to the discharges of brine, this field has undergone deterioration in several coastal areas as they are very sensitive to brine water (Sureda et al., 2008).

The rejected brine water produced from thermal-based technologies is almost 2 times more than 22 $^\circ C$ while the rejected brine water produced from membrane-based technologies is around 22 $^\circ C$ (Missimer and Maliva, 2018). The rejected brine salinity is almost double the salinity of seawater (35 g/L). Even though brine water is diluted by adding various ratios of water coming out from other power plants, which causes brine water to reach a warm ambient temperature (25 $^\circ C$) and salinity to decrease (which is still 10% higher). Al-Shammari and Ali, 2018, indicated that even a small rise in the seawater salinity poses threat to marine life as it can negatively affect the osmotic balance of marine species. The high density of brine water, which causes the formation of a saline plume that follows the bathymetry of the seabed (Fernández-Torquemada et al., 2009).

3. Environmental impact of brine discharge

High density and salinity cause brine water to sink to the bottom, causing a harmful impact on benthic organisms. The value of salinity of brine varies with differences in the technologies applied, for instance, brine salinity ranges from 60 g/L TDS to 85 g/L TDS for membrane-based technologies such as SWRO while thermal-based technologies such as MSF and MED the salinity can range between 55 g/L TDS to 65 g/L. Garrote-Moreno et al. (2014) have highlighted in their study that the biological impact resulted from brine discharge is connected to the stress caused by osmotic pressure from excessive salt intake. Such disruption can consequently lead to cells being dehydrated, turgor pressure decrease, which may lead to the extinction of the species (Belkin et al., 2017). In a study, Jenkins et al. (2012) found some aquatic species are more sensitive to change in salinity while some species can be tolerant. Petersen et al. (2018) found that an increase in salinity of seawater adversely affected the physiology and visual appearance of the corals. Additionally, it can also lead to a reduction in turgor pressure which is commonly known as dehydration, which can lead species to extinction. The density of brine water is usually higher than saltwater, which will cause brine water to settle at the bottom-most layer and affecting marine biodiversity (Sola et al., 2019). The benthic zone of the water body is usually occupied by different biodiversity from different tropical levels, such as prokaryotes, which include bacteria and archaea, microalgae, meiofaunel, and macrofaunel organisms (Lubinevsky et al., 2017). Benthic invertebrates and seagrass have shown a negative effect by the presence of brine from desalination (Frank et al., 2017). However, studies also showed that the impact was observed several miles away from SWRO desalination plants discharge (Petersen et al., 2018a,b).

The concentration of some of the main salts (e.g. salts of Na or Ca) is comparatively high in brine water compared to seawater. High salinity coupled with the presence of chemicals may intensify the toxicity of brine discharge causing local eutrophication or turbidity (Portillo et al., 2014). This high content can give rise to various challenges when treating brine water. These include scaling, corrosion, high energy consumption, or fouling. There are various types of fouling that can be considered major problems that are faced by desalination plants, including chemical fouling, physical fouling, biological fouling, and organic fouling inorganic fouling (scaling). Scaling and fouling are two major common problems faced in desalination plants. Scaling occurs usually when divalent compounds or species change from soluble to insoluble form due to the change that occurs during the desalination process. These changes include the change in the chemistry of the solution as well as the various changes in the condition of the process. Suspended particles may precipitate and settle on the surface of the equipment or the separation device (such as membrane) which may cause hindrance in the desalination process by either decreasing the transfer of heat in the desalination plants or decreasing the mass transfer rate in plants that use membrane system. Additionally, the presence of heavy metal in brine is also another issue that is faced mostly by thermal-based technologies due to high temperature during the process which causes equipment to corrode. To combat corrosion, “corrosion inhibitors” are added to the feed to reduce the corrosion rate. The chemicals present in these inhibitors are considered toxic and thus can severely impact marine life (Sanni and Popoola, 2019). While in membrane-based technologies, heavy metal concentration is comparatively low since non-metallic materials (polymers) are used (Nagy, 2018). A single brine discharge from a desalination plant will not pose a severe threat to marine life (Panagopoulos et al., 2020). However, if multiple desalination plants are operating in the same location over a long period such discharge will over time have adverse and irreversible impacts (Van der Merwe et al., 2014).

Corals are also broadly affected by the exposure of brine from desalination plants (Petersen et al., 2018a,b). Corals are known to be a very productive ecosystem that consists of a variety of biodiversity and biomass (Lattemann and Höpner, 2008). Thus, the negative impact on corals may result in a cascade effect on numerous tropical levels. Corals are easily affected by a slight change in the environmental conditions, including an increase in water temperature (Marshall and Clode, 2004) or eutrophication (Koop et al., 2001) will cause certain stress on corals which can result in bleaching of corals (i.e. loss of *Symbiodinium* tissue from corals), which causes stress on corals and being subjected to mortality. Mabrook (1994) reported a loss of coral coverage in an area that was located in close proximity to a desalination plant in the Red sea. However, very little data to date is available that addresses the impact of SWRO desalination brine on the physiology of reef-building corals (Petersen et al., 2018a,b). This is particularly important for Qatar, as the coral reefs in Qatar are amongst the most biodiverse productive, and economically important coastal ecosystems in the region (Fanning et al., 2021). Furthermore, the coral reef in Qatar provides a massive biogenic structure and shelter of up to 290 t/Km^2 that acts as a vital nursery habitat for juveniles.

Surprisingly, since the 1980s, there have been a vast number of publications addressing the desalination process, including its economic benefits and its energy uses (Jones et al., 2019) yet between 1960 and

2017 less than 2000 publications were published addressing the same subject. Only 194 publications addressed the marine environmental impact.

3.1. Brine management

Desalination processes produce a vast amount of brine water. Various methods are present for its disposal which can be categorized as direct disposal, direct reuse, and brine minimization. However, none of these approaches can be used on a large scale for all desalination plants as various factors should be considered prior to choosing the most suitable brine disposal method. These factors include the capacity and quality of brine, the composition of brine, the geological location site of the brine, the available space in the receiving body, the possible acceptance of the option, capital, and operating cost. The traditional direct disposal includes surface water disposal, seawater discharge, deep well injection evaporation pond, and various land applications. Generally, brine disposal costs can vary from 5% to 33% of the entire cost of the process. Additionally, the cost to construct brine disposal depends on various factors including the volume and characteristic of the brine, pretreatment, and the level of pretreatment, disposal method, and disposal characteristic of the environment.

Raising major environmental concerns regarding desalination plants, therefore efficient brine management is important. For the longest time sodium chloride has been one of the major salt that is extracted from the sea. However, as science enhanced, people started exploring the possibility to mine other valuable metals such as bromide, gold, magnesium, cesium, lithium, etc. from seawater and brine. Zero liquid discharge and volume reduction are two approaches that are presently being optimized for managing brine water.

3.1.1. Zero liquid discharge (ZLD)

One of the major drawbacks of reverse osmosis is the high brine production, which can result in adverse environmental impact if not treated properly due to very high salinity and various contaminants (including organic and inorganic) (Subramani and Jacangelo, 2014). Generally, the direct discharge of RO desalination brine water from plants to the open sea has been contributing to an increase in the marine environment population (Azimibavil and Jafarian, 2021). Accordingly, zero-liquid discharge (ZLQ) (or near -ZLQ with feed recovery of 95–98%) (Nakoa et al., 2016) and zero desalination discharge (ZDD) have emerged as two new approaches proposed for managing brine discharge (Chung et al., 2017). ZLD generates solid saline products and preventing the production of liquid waste while ZDD on the other hand reintroduces the liquid waste and converts it to saline solid raw materials.

Due to an increase in awareness regarding the severe consequences of brine release from the plants to open bodies, the government and other organizations are trying to implement laws that are stricter which may not allow various conventional methods such as surface water discharge or sewer discharge. Therefore, such legislation has motivated various sectors to come up with designs that can improve the water quality by reducing the high level of brine discharge (to the lowest possible level). This purposed system is known as zero liquid discharge (ZLQ) or nearly ZLQ, which is still under investigation. This ideology of such a system is to reduce the maximum amount of rejected brine and increase the amount of fresh water at the same time (Panagopoulos et al., 2020). The system acclaims for 95%–99% of pure distillate and can be used for drinking purposes, irrigation, or process cooling water, while the solid residue that is obtained as a by-product can be either disposed of in a designated landfill or can be further processed into a useful material. The ZLQ system has various variations in its design, arrangements, and operation, thus having a uniform ZLQ system cannot be the definite solution for every desalination plant. However, there are three different stages in a standard ZLQ system has three different stages, namely preconcentration, evaporation, and crystallization. During the preconcentration stage, the recovery and volume of water are minimized through membrane-based technologies. This is a very vital stage as it drastically reduces the volume for the next stages. The next two stages are the most expensive part of the system which are operated using thermal-based technologies. In these stages, water minimization is further achieved to its maximum level and the solid residuals are also obtained (by-product).

There are various factors associated with the variation of the ZLQ plants such as the concentration of the brine, brine composition, the required purity of fresh water, and the final brine concentration required, the infrastructure of the country, and the budget available. This goes without saying if a desalination plant can be designed which provides high quality and pure water along with by-products that are economical and beneficial for various sectors at a sustainable operating cost and energy. Such discovery and implementation will indeed be a huge breakthrough in the desalination industry (Kasedde et al., 2014).

3.1.2. Brine pre-treatment

Brine pre-treatment is required for dewatering to avoid conditions that can jeopardize the performance of the downstream process. By performing various pretreatment, the fouling mechanism of dewatering processes can be avoided (Gullinkala et al., 2010). The pretreatment needed for brine water before the dewatering process depends on the quality and chemistry of the water. Chemical fouling, physical fouling, biological fouling, and organic fouling are the four common types of fouling that can affect the performance of brine dewatering. Chemical fouling is caused due to the scaling of the machine or the presence of inorganic precipitates on the wetted surface. Physical fouling results due to the accumulation of particle matter (Gullinkala et al., 2010). While biological fouling is the formation or growth of microorganisms. Organic material adsorption, such as protein or humic substance that rapidly deteriorates the performance of membrane productively is usually caused by organic fouling.

3.1.3. Disinfection

Microorganisms present in saline brine are able to survive in various extreme environments such as oxygen-deficient environment (anaerobic), nutrient-deficient environment (oligotrophic), high temperature (thermophilic), and in a saline environment (halophilic). Thus, disinfecting the saline brine is a fundamental step in the pretreatment process. One of the most common disinfecting techniques is chlorination. However, chlorination causes total dissolved solids (TDS) to increase in the saline water, which should be removed through dichlorination prior to any membrane treatment such as reverse osmosis. Polyamide membranes that are a commonly used type of RO membrane are sensitive to chlorine exposure, even at low concentrations while cellulose triacetate (CTA) has shown short resistance against chlorine concentration (up to 5 mg Cl_2/L) and long resistance for 0.2 mg Cl_2/L (Lior, 2013). While some membranes have reported chemical degradation due to dechlorination. However, chlorinated solvents are known to pose a severe threat to aquatic life, they are known to be toxic and mutagenic, while some studies have also shown chlorinated solvents as carcinogenic (Tobiszewski et al., 2012). Other alternative disinfecting strategies include ozone and ultraviolet disinfection. Ozonation has similar drawbacks as chlorination, besides, it has also been reported to show a greater risk of biofouling as a result of breaking down macro organic matter. Ultraviolet disinfection is another alternative that uses no chemicals to deactivate the microorganisms which can cause biofouling. However, the performance of UV is affected by a high concentration of humic substances present in water (Mezher et al., 2011).

3.1.4. Removal of suspended solids and oils - chemical treatment

Removing suspended solids, emulsified oil, and microorganisms is very critical as they can be one of the leading causes of the fouling mechanism of the dewatering process. Chemical coagulants are one of the conventional treatments that are used to destabilize colloids and promote floc formation. The addition of coagulants to the brine water can cause the solid matter to settle out of the solution. Salts of Iron, Iron (II) sulfate, aluminum, and sulfate, chloride, as well as lightweight cationic polymer, are some of the common coagulants used to remove suspended solids (Latorre, 2005). The coagulants added to the brine excites collides by neutralizing the negatively charged surface, which causes the colloidal and particulate matter to attach. Depending on the pH and the dosage, chemical coagulants are able to remove organic compounds, silica, and phosphorus. In ZLD however, chemical coagulation has not been integrated as part of the pretreatment, yet few studies have explored the potential of this technique for municipal brine water (Dow et al., 2016). Generally, iron or cationic polymers are preferred over other available coagulants such as aluminum as it can be one of the sources of fouling (Gacia et al., 2007). Liu et al. (2019), studied the removal of total organic carbon (TOC) from reverse osmosis concentrate (ROC) and found that $FeCl_3$ coagulant was much more effective to remove TOC than $AlCl_3$ coagulant. They also found the total removal efficiency of TOC was 59.3% while for color it was 83.0% by combining coagulation and ozonation. While 27.3% could be removed during coagulation only. In another study, by Ho et al. (2015) used poly aluminum chloride (PACl), aluminum chlorohydrate (ACH), and ferric chloride ($FeCl_3$) as coagulants to study their efficiency and found PACl and ACH achieved 31% and 27% removal of dissolved organic carbon (DOC) at 0.556 mM dosage, while $FeCl_3$ reported having 60% DOC removal. Additionally, $FeCl_3$ also reported the highest phosphate (>99%) and 14% silica removal at its ideal dosage and pH. Choi et al. (2018) studied the removal of calcium sulfate using two common chemical coagulants, $FeCl_3$, and $FeSO_4$. The amount of calcium rejected was 27.9% when $FeCl_3$, while the rejection percentage increased to 42.7% when $FeSO_4$ was added. Which indicated, that sulfate ion crystal was formed due to the presence of $FeSO_4$. Chemical coagulation can have an adverse effect on brine removal by increasing the concentration of ionic species promoting inorganic fouling in the dewatering process. It can also affect the quality of the brine if a high dosage of chemicals that are added. Coagulation alone is not enough and requires other pretreatment technology such as chemical precipitation for the removal of ions.

Electrocoagulation (EC) has been reported to achieve high hardness removal from various solutions including brine from the mining industry (Subramani and Jacangelo, 2014). The EC has a low sludge production, which makes it an attractive pre-treatment option. Complete familiarity with the EC mechanism has not yet been understood, however, the removal of hardness has been associated with the precipitation reaction in the cathode. Precipitation of calcium carbonate ($CaCO_3$) are some and $Mg(OH)_2$ are some of the common cathode reaction that occurs in alkaline condition (Melián-Martel et al., 2013) while few studies also highlight the possibility of hardness removal under acidic conditions and neutral condition (Zhao et al., 2014). The precipitation reaction of $MgOH_2$ and $CaCO_3$ is illustrated in the following reactions:

Principal cathodic reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Carbonate generation: $HCO_3^- + 2OH^- \rightarrow CO_3{}^{2-} + 2H_2O$

Possible precipitation reaction: $CO_3{}^{2-} + Ca^{2+} \rightarrow CaCO_3$

Induced air flotation (IAF) and Dissolved air flotation (DAF) are the other two common techniques employed for the elimination of minute suspended solids or oil droplets (Arena et al., 2017). Such particles either get stuck in the air bubbles that are rising either as foam or in the form of an impurities froth on the water surface which is easily removed. The main difference between both methods is how the air bubble is introduced into the brine. In IAF air sparer combing with motorized agitation is used, while DAF depends on depressurizing the supersaturated brine by high air pressure. Flotation is useful as it clarifies the water surface by removing different types of materials that are present in the water stream, such as colloids, protein, oil droplets, and algae. The addition of a cationic coagulant can be helpful in removing the small suspended solids. However, special attention should be taken when using air flotation techniques, therefore, introduce air into the brine solution can result in oxidation resulting in precipitation.

Another type of technique that is also applied is the filtration of brine water either using media or membrane filtration. Media filtration includes media made of walnut shells, gravels, fiber balls, or anthracites. In media filtration, particles smaller than 0.1 μm can be adsorbed onto the surface of the media. While granular media filters are easier to work with, can be operated by gravity feed, however, continuous regeneration or replacement of media is required. While on the other hand, membrane filtration is considered an alternative to media filters.

3.2. Brine disposal

As discussed earlier, the desalination process produces a significant amount of rejected brine water which requires various disposal methods. Some of the common methods include surface water discharge, sewer discharge, deep well injection, evaporation pond, and land application (Panagopoulos, 2019). Various factors, including quantity, quality of the brine, the chemical characteristic of the brine, the geographical location of the dumping site, the availability of the land, authority permission, and the capital cost of the chosen facility should be considered when optimizing the most efficient disposal method for brine.

3.2.1. Direct disposal - surface water discharge

Seawater discharge (SWD) refers to directly discharge the rejected brine into the ocean, rivers, bay, lakes, or any other open acceptable water bodies. The cost of operating and constructing an SWD can vary from 0.05 US$/m^3 to 0.30 US$/m^3 (Ziolkowska and Reyes, 2017). The water is first transferred to a disposal site and from there it is discharged to a water body from an outfall structure. This method is implemented by more than 90% of the global seawater plants. This method can only be implemented if the constitution of brine is appropriate for the harmonization of the receiving water body. As discussed earlier, aquatic organisms face severe threats from the disposal of brine due to the presence of high saline content and pollutant. This can be minimized by diluting brine water with regular seawater or perhaps municipal wastewater (Arafat, 2017). However, to date, there has not been any comprehensive evaluation that can guarantee that aquatic life is not affected by the difference in temperature or salinity. The dissolved oxygen level in the marine environment can adversely be affected due to the increase in water, making it detrimental to aquatic life (Pramanik et al., 2017).

3.2.2. Sewer discharge

The sewer discharge method is usually adopted by small-scale brackish water reverse osmosis (BWRO) desalination plants due to the high level of total dissolved solids (TDS) content in the brine water which can pose a destructive impact on the wastewater treatment plant (WWTP). Brine discharge includes a specific nearby wastewater collection system. The reason why SW brine water cannot be used is that the TDS level can reach more than 55000 mg/L which will require the WWTP to have at least 20 times more capacity to treat the SW high TDS concentration before its disposal as high TDS may cause environmental and regulatory issues by the government. To further minimize the risk pH neutralization or other prerequisite treatment might be imposed because the brine may contain a high amount of metals. (Hobbs et al., 2016). Thus, to avoid such complications, this method is mostly used for BWRO desalination plants and may cost up to 0.66 US$/m^3 ().

3.2.3. Evaporation ponds

This type of disposal method includes shallow man-made lined basins where the brine is disposed of and gradually evaporates with the help of direct solar energy (Mickley, 2001). Once the water is evaporated, it leaves the salt crystals behind which are regularly collected and disposed to the allocated area. This method requires serious precautions while constructing the basins. Evaporation pond requires multiple ponds to make sure the brine disposal is not interrupted. To minimize environmental issues, this process requires to be built accordingly to a design and strictly be maintained and operated properly. The design should be carefully followed. The evaporation pond is very simple, requires low maintenance. Generally, it requires a resistant lining to protect the natural aquifers. If there is a risk that the brine will have high salinity and a high concentration of metals and heavy metals, then double or triple lined ponds must be constructed. This is very important as brine water may enter the aquifer and deteriorate the water quality. Prior to evaporation pond construction, various factors should be considered such as the climate of the area, the availability of the land, the quality of water show within the aquifer, and the legal requirement. Amongst all disposal methods, this is perhaps the most expensive method which may cost up to 10.05 US$/m^3.

These ponds can be conventional which is used for disposing of brine or they can be modified with advanced solar salinity gradient ponds that can use solar energy to generate electricity (Rostamzadeh et al., 2019). There are three zones in a typical solar pond, the upper zone is a convection zone in which the salinity level is low and the temperature is almost close to the surrounding, middle, which is a non-convection zone where the salinity and temperature keep increasing as the depth increases, and a lower convection zone which has the highest salinity and temperature (Mohamed and Bicer, 2019). Although these ponds are easy to develop and do not need much equipment and maintenance, the drawback of such ponds is high footprint and is only operational for low capacity. Besides, solar ponds are a viable option for those countries that are close to the equator and have large vacant lands. Power can be generated from the hot saltwater during the process, however, it should be taken into account that the solar energy conversation is less than 2% which makes it time-consuming and uneconomical. As the water increases the thermal capacity of the remaining water also increases, which makes this method slow.

3.2.4. *Deep well injection*

In this method, the brine water is disposed into a well-defined deep underground aquifer, which is properly isolated from the above water aquifer. One of the main environmental issues in this method is the possibility of polluting the nearby water aquifer which can potentially be used as a potable water source. Therefore, prior to its construction various testing are conducted such as deep drill testing, comprehensive hydrological studies of the area, pilot test, and environmental overview. Therefore, this method mostly opts when other disposal methods are not viable. This method is usually preferred for all size and BW desalination plants. In a typical deep-well injection aquifer, the brine water is injected into a well that involves a multi-layer of casting and filling. To prevent leaching, permeable rocks are used to contain the brine while clay and other substances that are importable are used to prevent water pollution.

3.2.5. *Land application*

The use of rejected brine water inland applications can be beneficial for the irrigation of grass fields, parks, golf courses, or other horticulture. This can be a good practice as brine water contains nutrients that are essential for the growth of vegetation. However, various factors should be considered before opting for this practice. Such as the

Table 2
A summary of current desalination direct brine disposal methods.

Disposal method	Primary operational method	Cost	Advantages	Disadvantages	References
Surface water discharge	**NR**	**NR**	• Cost-effective Operated by medium and large-scale plants	• Can have limited availability of dissolved oxygen in the receiving water bodies Cause an increase in water pH as well as eutrophication and toxicity	Ziolkowska and Reyes, 2017
	Brine water is directly discharged to the surface of water bodies	USD ($) 0.050–0.300/ m^3 of rejected brine	• Handles large water volume • High dilution rate • Natural process • Promotes degradation	• Can cause adverse effects to the marine water, if water is not treated appropriately. • Can cause thermal pollution	Soliman et al. (2021)
Sewage discharge	The brine is discharged to an existing sewage collecting system	USD ($)0.320–0.660/ m^3	• Cost-effective, as it uses an existing infrastructure • Easily implemented	• Can cause bacterial growth • Overload the existing capacity of the wastewater treatment plant	Ziolkowska and Reyes, 2017
	NR	NR	• Brine is diluted • Low capital and operational cost are required.	• Not commonly used for the seawater desalination plant	Roychoudhury and Petersen, 2014
Evaporation pond	Salt can be accumulated at the bottom, while the brine water is evaporated in the pond	USD ($) 3.280–10.040/m^3 of brine rejected	• A feasible option for inland plants in a dry region • Easy construct and maintenance • No apparent marine life threat	• Requires large area • Restricted to capacity • Climate dependent, suitable for dry arid countries • High construction and operational cost required • Risk of underlying soil and groundwater.	Roychoudhury and Petersen, 2014
Deep well injection	Brine water is introduced to a porous subsurface structure rock formation	USD ($) 0.320–2.650 of rejected brine	• Best suited for inland desalination plants • Does not affect marine life • No pretreatment is required prior to brine disposal • Oil wells that are not active or being used can be optimized, which reduces drilling cost	• Dependent on the suitability of isolated aquifer structure • Not appropriate for areas near geologic faults or areas that are susceptive to seismic activities • Regulatory compliance cost	Valipour et al. (2014)
Land application	Brine water is used for irrigating plants that are tolerant to high salt	USD ($) 0.740–1.950/ m^3 of rejected brine	• Does not affect marine life • Easy to implement • Easy to construct • reasonable for inland desalination plants with less brine water volume	• Depends on seasonal irrigation • Existing vegetation can be effected • Affect groundwater by increasing the pollution and groundwater salinity • Medium operational and capital cost required	Hobbs et al. (2016)

availability of the land, availability of water to dilute the brine water, the cost of diluting water, the setup of the irrigation system, filtration rate, the plants tolerant to the salinity level, and the possibility and consequences for the water to leach into groundwater. It should bear in mind that the water should not have a high level of nutrients and should meet the nutrient level set by the Food and Agriculture Organization (FAO) due to the severe implication of disposing brine on groundwater. The increase in salinity in soil can reduce the soil's permeability and crop yield. Table 2 gives an overview of existing desalination direct brine disposal methods.

3.3. *Brine minimization*

As discussed earlier, most of the desalination technologies are not able to achieve 100% water recovery, hence these plants produce a huge volume of brine water along with various other undesired substances. Brine water can be categorized into two distinct categories high saline brine and low saline brine water. High saline water is generally treated with thermal treatment while low saline treatment is treated using membrane technology, various pretreatment, and ion exchange technology.

3.3.1. *Evaporation pond-high saline*

Evaporation is used as one of the common techniques for treating high saline brine water in desalination plants either through mechanical or natural approaches (Giwa et al., 2016). Evaporation pond is known as shallow ponds where the brine water is disposed and then the water evaporates from rejected brine naturally by the sun. This approach is widely adapted in arid countries due to the availability of the land, high saline level, and hot climate. One of the major drawbacks of this method is a high ecological footprint and large land availability which could be used for other economically viable applications (Morillo et al., 2014). Thus, many countries have tried to minimize the use of evaporation ponds (Ahmed et al., 2001).

3.3.2. *Multi-effect distillation & flash distillation-high saline*

Multi-effect distillation (MED) and multistage flash distillation (MSF) are two of the common thermal-based desalination technologies that are widely used for brackish water (BW) and seawater (SW). However, with material upgrades, these technologies can also be used for treating brine water (Mezher et al., 2011). This method has up to the middle to high capacity. In MSF, the feed (brine water) enters and is preheated using the condensing vapor from the flash unit, and an external heating source (brine heater) is used to raise the temperature to 110 °C–120 °C. Once the brine feed reaches the desired temperature, it is transferred to a flash unit by a series of chambers through sequential low pressure and low temperature. Additionally, in the feed preheat exchanger, some of the feed is evaporated and condensed. The brine which is present as a concentrated solution exits from the final flash unit while water vapor is present in the form of condensed vapor.

In a typical MED chamber, external steam is used as a source to evaporate water from the high saline feed in the first effect. The steam that is generated as a result of pressurized steam, the condensed steam from the first effect returns to the boiler while the steam from the first chamber is used to evaporate water from the second effect. The steam that is condensed in each effect becomes the produced water from the process. This arrangement of steam generation and then forwarded in a consecutive chamber continues with each chamber having less pressure than the previous one. The process continues until there is no longer a sufficient temperature gradient to heat and evaporate the feed (brine water) (Panagopoulos et al., 2020).

There are currently various options available to manage brine water disposal to open water bodies, such as installing a vacuum system in which the following vessel will have low pressure to make sure the water quality is not bad or by adding the remaining water into the successive vessel. However, MSF is favored over MED. As mentioned earlier, MED can experience scaling on the heat transfer tube, it requires high capital cost for maintenance in contrast to MSF. This goes without saying various new development in MED technique has been applauded since it produces low CO_2 emission and has also reported having better thermal performance and higher recovery ratio in contrast with MSF (Cherif and Belhadj, 2018).

3.3.3. *Vibratory shear enhanced processing (VSEP) - low saline*

To choose the best available technology is to minimize the volume concentrated brine factors such as RO concentrate characteristic treated water quality, energy consumption, and cost should be considered (Giwa et al., 2017). Membrane distillation (MD), forward osmosis (FO), electrodialysis (ED), or MD coupled with crystallization (MDC), and eutectic freeze crystallization (EFC) are some of the emerging technologies that are developed to decrease the volume of brine concentrate to achieve ZLQ and also recover valuable compounds.

Vibratory shear enhanced processing (VSEP) is one of the promising technologies that are used to further improve membrane-based minimization strategies (Gugliuzza and Basile, 2013). This technology treats RO in a VSEP unit by utilizing configuration. RO is directly introduced to the system to enhance the overall recovery from brackish water origin. This technology operates on the principle/mechanism by establishing vibratory shear to produce oscillation (50 Hz) within the surface of the membrane. This is produced in a way that the shear is ten times greater than the typical cross-flow of the membrane. The vibration generates a high shear rate, emulsion particles, organic macromolecules, and crystals of salt that are removed from the membrane surface which subsequently reduces fouling and scaling (Yee et al., 2012). Due to which VSEP provides various advantages including a higher filtration rate, membrane scaling resistance, and reduction in footprints. However, important consideration must be taken prior to VSEP utilization, VSEP requires high energy consumption due to continuous oscillatory vibration through torsional spring. This method can generate high fluxes (50–100 $L/m^2 \cdot h$) in addition to improved total recovery which can be enhanced by 75%–93%.

3.3.4. *Ion exchange resins - low saline*

The exchange of an anion or cation in a solution with a charged cross-linked polymer anion or cation is known as ion exchange. Ion exchange resins can be classified as one of the following types: a weak acid cation exchange resin, a strong acid cation exchange resin, a weak base anion exchange resin, or a strong base anion exchange resin (Arena et al., 2017). The main difference between these types is the functional group. Ion exchange resin is mostly studied for the removal of deviant ions.

3.3.5. *Membrane distillation - low saline*

Membrane distillation (MD) is a heat-driven membrane-based technology that uses vapor pressure as a driving force (Thomas et al., 2017). Vapor pressure is created due to the variation in temperature established between both sides of the membrane. Typically, the operation temperature lies between 30 °C - 80 °C (Dow et al., 2016). The hydrophobic microporous membrane is a key component that separates the vapor phase from the liquid phase by allowing the passage of water vapors and preventing the flow of liquid molecules. This mechanism enables the achievement of highly purified fresh water by preventing continuous interruption due to fouling (Jönsson et al., 1985). Polypropylene (PP), polyethylene (PE), and polytetrafluoroethylene (PTFE) are most often used as membrane materials with pore diameters between 0.1 and 0.5 μm (Abdel-Karim et al., 2019). There are four main parts of the MD system: air gap MD (AGMD), direct contact MD (DCMD), sweeping gas MD (SGMD), and vacuum MD (VMD). Fig. 1 illustrates a schematic diagram of all four configurations. In AGMD, an air-filled cavity is introduced between the membrane and the condensation surface in which the vapor should pass through the membrane thickness and across the air gap prior to reaching the cold surface avoiding the liquid contact with the membrane on both sides and avoiding wetting fouling by

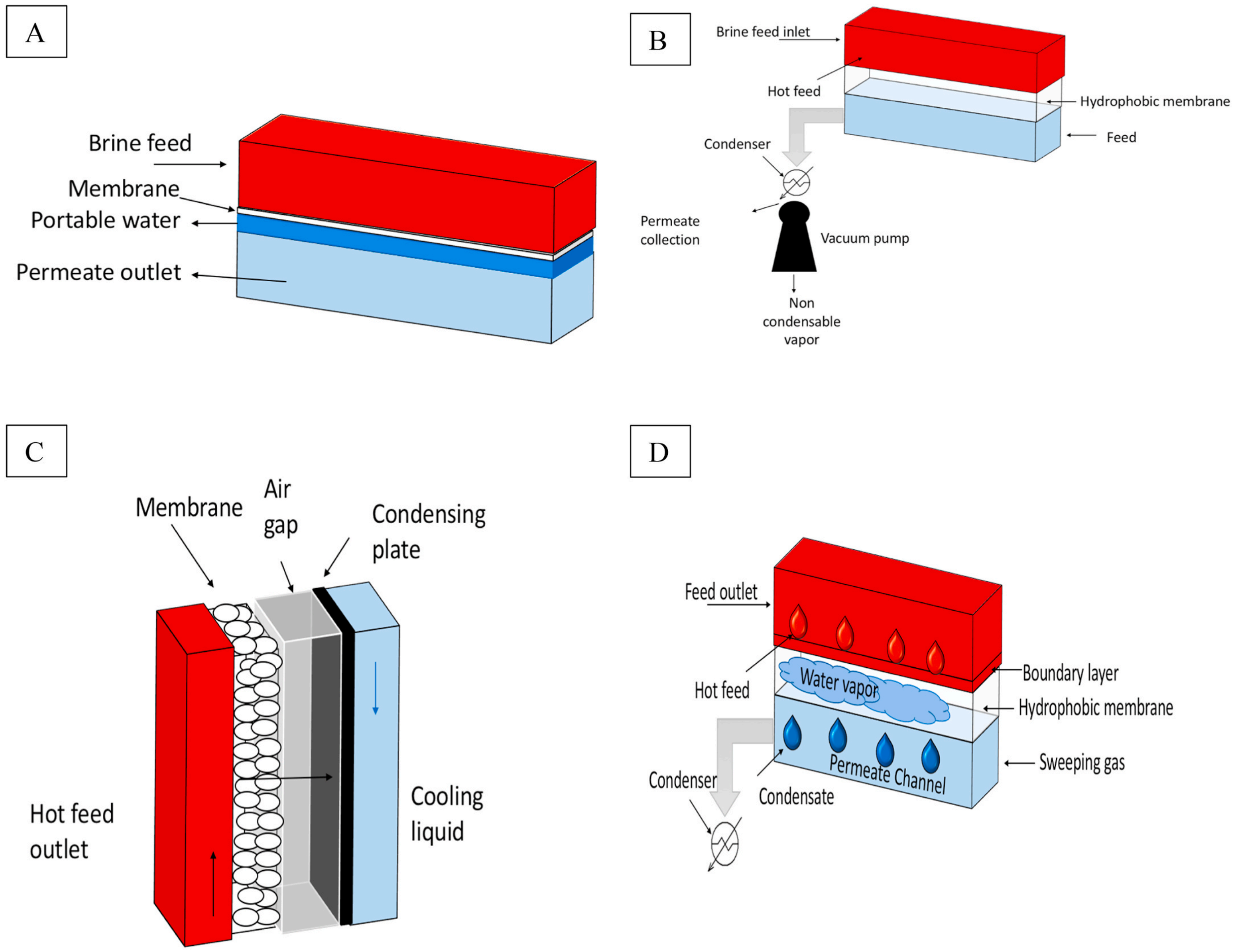

Fig. 1. (a) direct contact MD (DCMD), (b) Air gap MD (AGMD), (c) Vacuum MD (VMD) and 9D) sweeping gas MD (SGMD).

reversing. Schwantes et al., 2018, adapted AGMD to treat hypersaline brine (0.240 g NaCl/kg solution) and found that by using stagnant distillate in the air gap the wetting phenomenon was considerably reduced. Duong et al. (2015) achieved 95% recovery of produced water by combining RO with AGMD without any observable membrane scaling. Direct MD is the most common type used to manage brine water (Duyen et al., 2016). In a typical DCMD unit, the feed (brine) is first heated prior to membrane contact. The heated brine flows from one side of the membrane, and the vapor passes through the open pores of the membrane (Park et al., 2019). While from the other side the vapors are collected as cold distillate through condensation and the concentrated brine is collected from the hydrophobic membrane (Karam et al., 2017). However, chemically altered ceramic membranes recently are known to have high mechanical strength, thermal resistance, and prolong lifetime (Yang et al., 2017). Omniphobic membrane is another type of membrane that is currently being investigated. The omniphobic membrane prevents low or high surface-tension liquids (Lu et al., 2019). The notion of omniphobicity has caused attention which has enabled various studies to prepare omniphobic membrane for MD plants including Boo et al., 2016 who fabricated omniphobic polyvinylidene fluoride (PVDF) membrane, integrated an omniphobic substrate and an air hydrophilic, underwater superoleophobic skin layer (Huang et al., 2017). Woo et al. (2017) prepared a PVDF membrane by electrospinning and CF_4 plasma surface modification for AGMD. Zheng et al., 2018 spray-coated nano/microspheres onto a commercial PVDF porous substrate to obtain a PVDF membrane with a hierarchical structure. Lu et al., 2018 prepared a hollow-fiber membrane by silica nanoparticles deposition followed by a Teflon AF 2400 coating. Though this process is commonly utilized in seawater desalination plants, due to various advantages such as its ability to withstand high salinity, tendency to perform at mild temperature ($\cong 90^{\circ}C$) and requiring pressure more or less similar to atmospheric pressure, high salt rejection, low energy requirement as well as low grade such as solar energy, and small space requirement. VMD is another common type of MD used for seawater and brackish water desalination. VMD is thought of as an attractive and cost-effective membrane separation technology (Gacia et al., 2007). VMD comprises an evaporative process that operates under vacuum conditions, separating aqueous liquid feed from vapor permeates, the vapors are transported across the membrane under low pressure from the permeate side (Gugliuzza et al., 2013). VMD can deliver high salt rejection by operating at low hydrostatic pressure and temperature and not requiring a membrane with high mechanical properties. One of the benefits of using VMD is being able to convert an available source of energy such as solar energy into useful energy (Abdallah et al., 2013). Similarly, Lu et al. (2019) also achieved a 99.8% rejection rate. However, full-scale utilization of MD for brine water is not common due to various barriers that are yet to be overcome. MD is expected to treat extremely high saline brine water (up to 350,000 mg/L TDS) (Said et al., 2020).

SGMD can be thought of as a mix of AGMD and DCMD (Said et al., 2020). In SGMD, however, a flow of cold inert gas enters the permeate chamber and absorbs the vaporized solution before introducing it to the external condenser, where it is condensed back into a liquid with minimal heat loss and mass transfer resistance. This system achieves higher permeate flux, high evaporation efficiency, but it is the least researched configuration amongst the four mentioned earlier. Studies indicate that SGMD can provide a potentially economically feasible alternative to obtain purified water (Duyen et al., 2016), and permeate gas instead of stagnant gas. The permeate side is one of the major disadvantages of SGMD as it requires an external condenser for the condensation of permeated vapor (Abejón et al., 2019).

There have been several studies regarding the prospect of using the MD technique for treating concentrated brine (Bello et al., 2021). However, despite numerous advantages, the utilization of MD for RO brine must be carried out carefully as the contamination present in the feed may cause fouling (Sanmartino et al., 2016). There are a few known drawbacks of using MD technology including membrane wetting, fouling, and scaling. Calcium carbonate ($CaCO_3$) and calcium sulfate ($CaSO_4$) are considered the main culprit to first cause precipitation due to low solubility forming mixed crystals and settling on the membrane surface (Dow et al., 2016). Additionally, the formation of crystals results due to the concentration of brine reaching above the saturation point of salts (Curcio et al., 2010). These crystals can damage the membrane, breaking the membrane fibrils and allow brine liquid to pass through the membrane pores, known as wetting of membrane (Sanmartino et al., 2017). Therefore, it is important for the brine to go through pre-treatment prior to RO to avoid high energy and cost consumption (Chen et al., 2018). While membrane wetting is perhaps one of the major drawbacks of the MD system, which prevents the commercialization of this technique. Membrane wetting is caused due to the water leaking from the membrane pores as well as the dissolved solids present in the water affecting the capabilities of the system for salt or other unwanted contamination rejection. Additionally, the presence of active surface compounds such as oil, which absorb on to hydrophobic membrane and cause the membrane to be hydrophilic leading to the passage of liquid water (Wang et al., 2020). Membrane wetting is usually common during the treatment of complex feed with a high concentration of organic compounds such as industrial water or produced water (brine). When dealing with a complex such as wastewater from pharmaceutical semi-conductor industries and RO brine, wetting might occur due to the interaction of various complex compounds (Bogler et al., 2017). To overcome this phenomenon, many investigators have been conducted to develop wetting resistant MD membrane in various membrane materials such as omniphobic, superhydrophobic, or Janus membrane with hydrophilic and hydrophobic sides were prepared by coating the membrane with the re-entrant structure using nanofibers, nanoparticles, or polymers (Ghaleni et al., 2020). Overall, these membranes were able to reduce the wetting phenomenon for prepared wastewater as well as acquired wastewater from various plants. Table 3 summarizes the advantages and disadvantages of DCMD, AGMD, VMD, and SGMD.

Table 3
Summary of the advantages and disadvantages of DCMD, AGMD, VMD, and SGMD.

DCMD	AGMD
Advantages	**Advantage**
Simple design and operation	Seawater can be utilized as a cooling stream
Internal heat recovery	High thermal energy efficiency
High heat permeate flux	Possibility of heat recovery.
Disadvantage	**Disadvantage**
If the permeate is strong it can cause pollution	Low permeate flux due to resistance towards water vapor
Concentration polarization and high temperature	High footprint
Low heat energy efficiency	
VMD	**SGMD**
Advantage:	**Advantage**
Less heat loss	High recovery rate
Lower conduction	Low heat lost
Low concentration boundary	Low risk of wetting
Disadvantages:	**Disadvantages**
Membrane wetting	Recovery of heat energy is not challenging
Recovery of heat is difficult	Sweeping gas is complex
	A large condenser is required

3.3.6. *Reverse osmosis*

Pressure-driven reverse osmosis (RO) is one of the most popular membrane-based technologies for removing the salinity of brine water. From the opposite direction of the brine (feed), the hydraulic pressure is applied. This forces the solvent to pass through a semi-permeable membrane in a reverse direction to that of natural osmosis. The pressure that is applied should be high enough to overcome the osmotic pressure between the feed (brine) and the permeate liquid. This causes the feed (concentrated brine) to be retained on the side where pressure is exerted while the pure solvent (fresh water) passes through the other side of the membrane (Nagy, 2018). Fig. 2A illustrates a typical RO diagram. However, due to high maintenance and operation cost RO cannot be applied for feed that has high saline concentration (>65 g/L) as high salinity increases osmotic pressure caused by high salt concentration (above 80×10^5 Pa) while the TDS concentration to be up to 70,000 mg/L. In a study, Aines et al. (2011), mentioned that a typical RO technology can be used to treat brine with 85000 mg/L TDS with only 10% recovery of water. While Davenport et al. (2020) found specialized membranes and modules can handle higher pressure (82 bar) allowing the application of high-pressure RO for treating brine with TDS higher than 70,000 mg/L. Nevertheless, a disc tube (DT) module system is available that has proven a configuration of 82–150 bar, however, the average freshwater production is low (3 m^3/day) are some of the commercially available membranes that can handle such high pressure (Pall cooperation, 2019). The unit cost is estimated to be USD ($) 0.75/$m^3$ of freshwater produced while the energy consumption of the water fed to the process can range between 2 KWh/m^3 - 6 KWhe/m^3 or 1.5 KWh/m^3 - 2.5 KWhe/m^3 (Panagopoulos et al., 2019). While the electrical consumption can vary between 4 KWh/m^3 - 6 KWh/m^3 (Soliman et al., 2021).

3.3.7. *Forward osmosis*

Forward osmosis (FO) technology uses an osmotic pressure gradient rather than applied pressure (Ahmed et al., 2019). To create an osmotic pressure gradient through the semi-permeable membrane, a high-concentration feed is used. This causes the transfer of water molecules from a region of low concentrated brine to a region with high concentrated brine. The fresh water is separated from the drawn solution. A typical schematic diagram of FO is illustrated in Fig. 2B. The drawn solution which is also known as regeneration, principle role is to establish osmotic pressure thus the concentration of a drawn solution affects FO efficiency. Additionally, this process is also energy efficient as it does not require an exterior source for applied pressure. Ideally, to make RO sustainable, the drawn solution should be inexpensive and readily available in the market yet provide high water flux with low fouling, reverse solute diffusion, low or none toxicity, and easy recovery/regeneration (Zhao et al., 2014). Organic solutes have been researched using a variety of possible drawn solutions and recovery methods including thermal separation, membrane separation, precipitation, or combination process. (Ali et al., 2018) and inorganic salt (Bacaksiz et al., 2021), nanoparticle-based (Ng and Shahzad, 2018). However, each drawn solution have their own pros and cons thus, a particularly drawn solution cannot be nominated as an ideal solution. However, reverse salt flux, internal concentration polarization (ICP) in the FO membrane are some of the major disadvantages of these technologies. However few recent studies have proposed methods that can help overcome such issues. By specifically modifying the membrane and

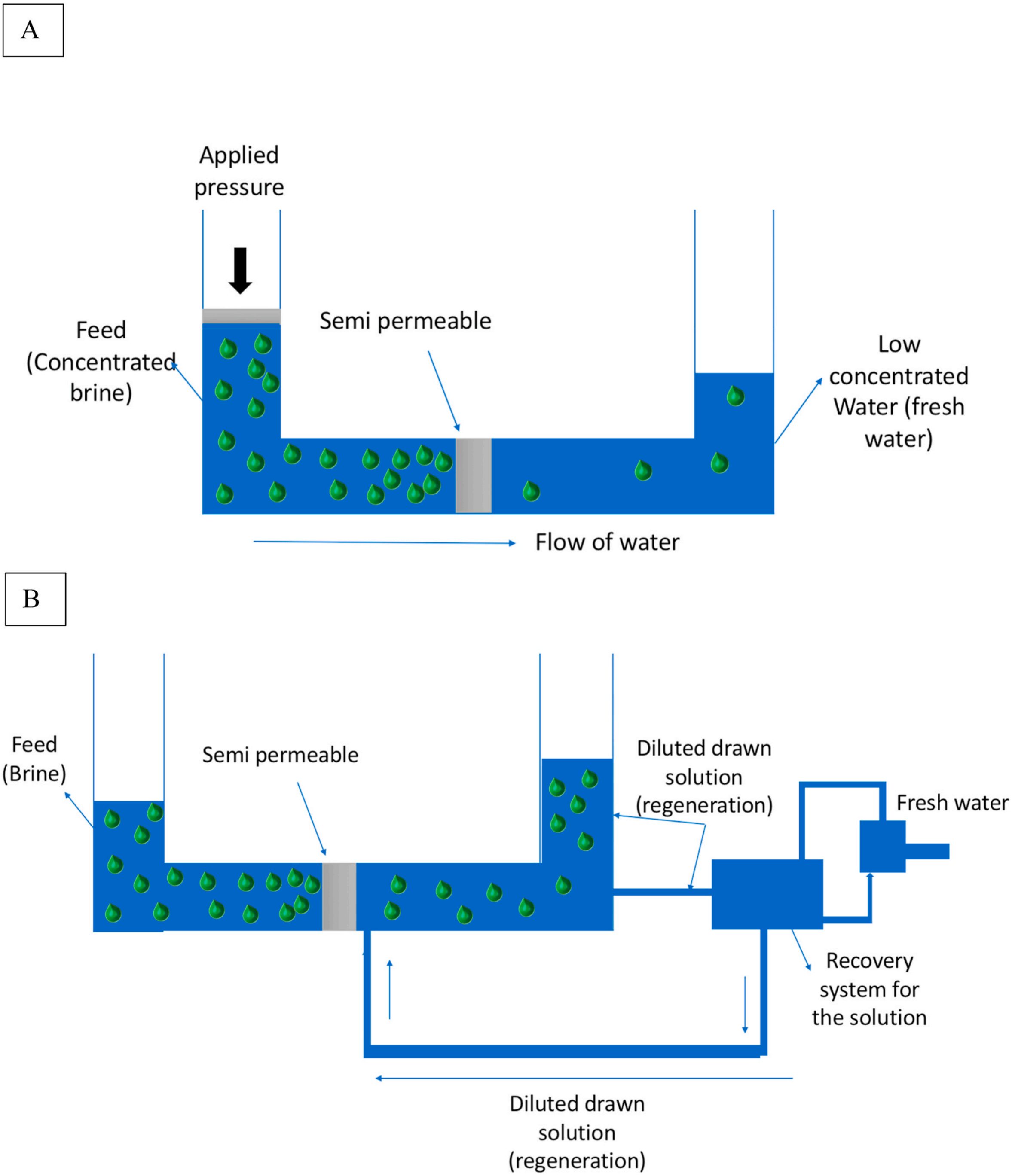

Fig. 2. A typical schematic diagram of (A) reverse osmosis and (B) forward osmosis.

preparing a novel membrane. One of the most popular ways to change a membrane is to apply a surface coating to the active membrane (which is normally a thin film composite membrane) to overcome fouling, increase surface hydrophilicity which reduces ICP, and increases water flux). The two proposed materials i.e. polydopamine and nanoparticle consisting of graphene oxide nanosheet are two have been used and were able to give promising results have been obtained. While membranes that consist of carbon nanotubes integrated into the active layer or using interfacial polymerization with graphene quantum dots to engineer membranes are some of the purposed ways to prepare novel membranes (Guo et al., 2018).

There are only a few units that are available using FO technology for high TDS brine. Fluid Technology Solutions Inc. designed a membrane for brine feed with TDS as high as 65,000 mg/L, while Oasys Waters Inc. developed a hybrid thermal-based FO system (pilot scale) to treat brine with TDS higher than 70000 mg/L. The test result reported 60% water recovery.

3.3.8. *Membrane crystallization*

Membrane distillation crystallization (MDC) is a hybrid technology between crystallization and MD and is expected to recover useful salts. Additionally, high water recovery is also possible due to MDC capacity to treat high concentrated solutions unlike other pressure-driven membrane processes that are currently useable, which reduces the volume of SWRO brine water being disposed of. In this process, the brine first becomes supersaturated and forms crystals which are then collected via an external crystallizer. Pure water and a concentrated solution are produced due to the vapor phase from the liquid phase due to the membrane employed. The crystals that are from membrane crystallization, can be altered and produce a specific crystal superstructure. In a typical MDC, supersaturation can be achieved due to the low temperature maintained (Choi et al., 2019).

3.3.9. Electrodialysis

However, ionic transport for electrodialysis depends on the ionic species concentration and the properties of the material for membrane for ion exchange such as resistance. This process requires less cleaning and regeneration of chemicals as it is not driven by water pressure which minimizes the formation of a fouling layer (Ismail et al., 2019). However, during electrodialysis, suspended solids can deposit on the membrane or the surface due to the positive and negative charges (Rijnaarts et al., 2019). This drawback is usually avoided by performing reverse electrodialysis (every 30 min), which causes the electrical polarity to reverse resulting in the removal of the particles that are deposited on the membrane or the surface. Electrodialysis can also be performed using high salinity water and still produce a high RR. However, high saline feed requires high energy consumption. Furthermore, the mention cation causes the membrane to degrade over time which will affect the

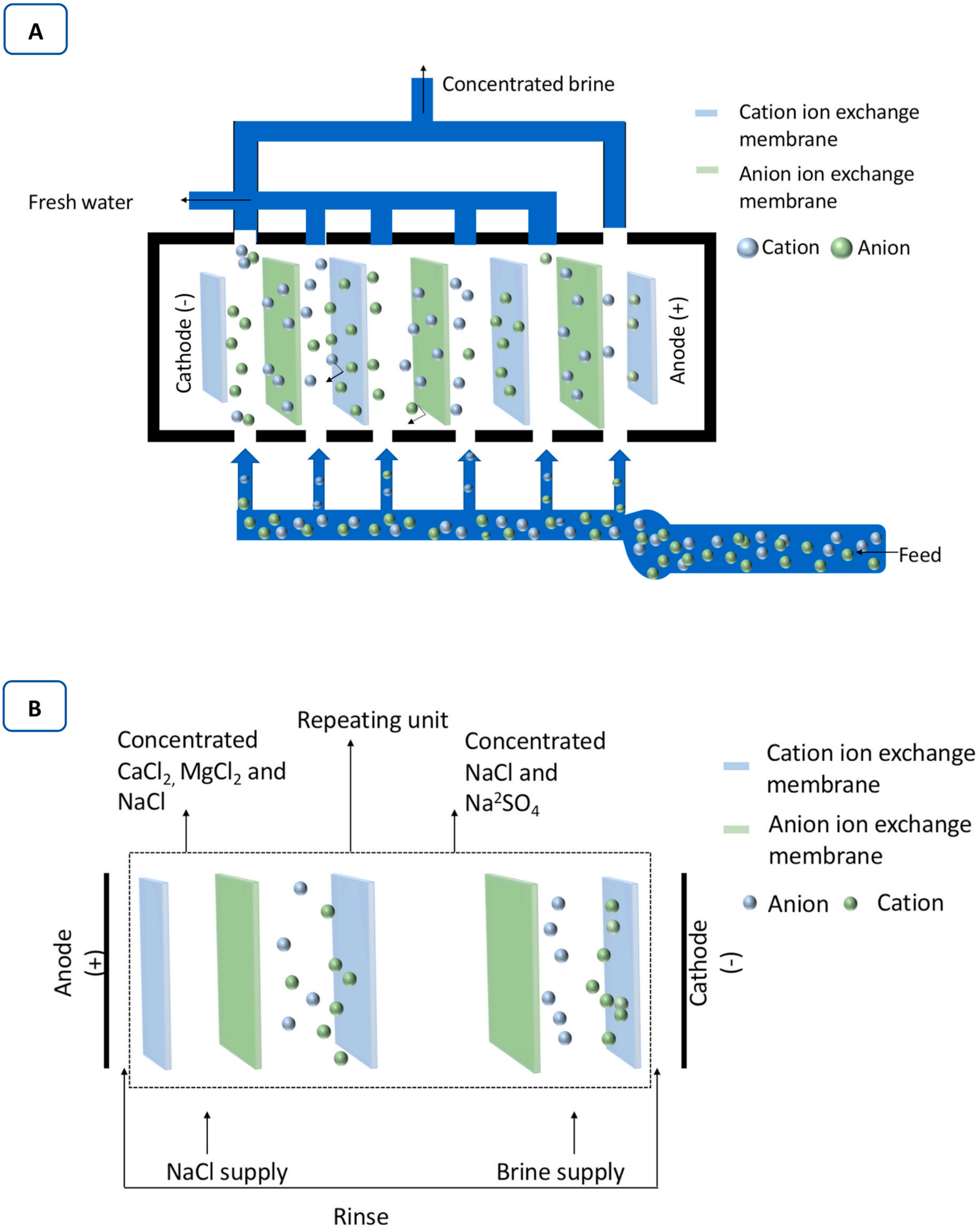

Fig. 3. A. Electrodialysis and B. Electrodialysis metathesis.

desalination efficiency over time. Studies have also reported the splitting of water into H^+ and OH^- when it reached a certain amount of density limit which also lowers the overall efficiency.

Jiang et al. (2014) used different membranes for reclaiming freshwater and salt from synthetic RO brine using a three-stage ED (107 g/L TDS). Results showed that the feed (brine) concentration could be up to 271.3 g/L TDS and 67.7% of water can be recovered. However, the purity of fresh water obtained was very low (2.7 g/L TDS), similar to brackish water. While on the other hand, McGovern et al. (2014) treated NaCl brine (195 g/L) using a 10-stage ED system and obtained high-purity freshwater (0.24 g/L TDS). Similarly, Yan et al. (2018) reported success by concentrated bine from 3.6 g/L to 20.6 g/L TDS while Zhang et al. (2017) achieved 82% water recovery using SWRO brine (45, 000 mg/L TDS).

Reverse electrodialysis (RED) is similar to ED however, the DC voltage is revered 3–4 times per hour and delivers around 97% water recovery. This technique operated by using the difference in the salt concentration between solutions to generate an energy of salinity gradient. Similar to ED, RED also comprises CEM and AEM that are alternatively stacked together.

Various studies have mentioned organic fouling due to the high concentration of sparingly soluble ions such as Ca^{2+}, Mg^{2+}, $HCO_3{}^-$, $SO_4{}^{2-}$ (Asraf-Snir et al., 2016). This pre-treatment is often required to minimize scaling problems. Additionally, a modified ED canned electrodialysis metathesis (EDM) has also been purposed to improve the performance of ED (Václavíková et al., 2017). EDM has a unique ability to concentrate and recombine ions simultaneously. Besides, it also converts various sparingly soluble/insoluble salts into high soluble salts (Chen et al., 2018). In a typical EDM, there are four compartments for a solution and four EM membranes. The solution compartment is divided into one for NaCl solution, one for the dilute, and 2 for the concentrate as illustrated in Fig. 3. While the four membranes of EDM consist of one standard CEM and ARM, and one monovalent selective CEM and AEM. Such a system allows the transport of ions from two different feeds into two streams of salt, i.e. interchange of cations and anions (Jaroszek and Dydo, 2018). Chen et al. (2019) mentioned in their study that, TDS value progressively improved from 0 to 200 g/L in 72 h using EDM, and the scaling phenomenon was successfully avoided.

3.3.10. *Adsorption*

Another widely used technique in wastewater treatment to remove organic compounds, heavy metals, and other pollutants is adsorption (Al-Ghouti and Da'ana, 2020). Due to low adsorption capacity and selectivity, it is complicated to recover minerals from high concentrated effluent (Echevarríaac et al., 2020). However, some lab-scale results indicate a high concentration of minerals can be recovered from adsorption. However, a successful adsorbent should have high adsorption capacity as well as be highly selective towards the desired minerals. This is a very crucial part, as a highly concentrated solution is laden with minerals in high concentration. Rejected brine is a good source of uranium, along with other metals. Wiechert et al. (2018) used amidoxime functionalized adsorbent to recover uranium from brine water. 3.95 mg/g of uranium mass was adsorbed on the adsorbent that competes with each other for adsorption. Activated carbon (AC) is one of the most common adsorbents used due to its high surface area and various physical properties such as porosity and high surface area. However, AC adsorbent is constantly regenerated due to its limited adsorbent capacity which makes AC expensive. AC has been optimized in various initial studies to remove organic compounds from brine water.

3.4. *Recovery*

Over the years, desalination plants and their procedures have been modified to obtain a better quality of the disposed of brine water. Brine water can be classified as a resourceful by-product rather than a waste. There are many useful components present in rejected brine water, which can be used in various industrial sectors. Recent studies have mentioned the recovery of valuable salts and chemicals including sodium (Na), calcium (Ca), magnesium (Mg), lithium (Li) (Calvo, 2019), and sodium sulfate (Choi et al., 2020). However, scaling up the extraction process requires higher capital and improvement. However, such treatment requires high costs and advancement in extraction technology. Thus, there is a need to further improve the management of rejected brine to use it to its great potential in terms of its utilization rather than being restricted to its disposal. Chemical treatment has proved to be one of the vital techniques to recover salts from RO brine using different reagents such as sodium carbonate (Na_2CO_3) (Sorour et al., 2015), sodium hydroxide (Casas et al., 2014), and calcium hydroxide (Curcio et al., 2010). Table 4 shows various metal recovery technologies from brine. Fig. 4 illustrates the development timeline of resource recovery from brine and seawater (Mavukkandy et al., 2019).

4. Energy consumption by ZLQ technologies

Successful brine management keeps energy consumption in mind when planning treatment plants. High energy consumption by desalination plants has always been a major issue ever since it is implemented on an industrial level. As science and the concept of sustainability have gained awareness it has called for various life cycle assessments, which has encouraged stakeholders to seek better alternatives without compromising efficiency. To evaluate the feasibility of the ZLQ plant, various aspects should be considered including the economic aspect, operation and running cost, construction cost, and environmental impacts. Energy requirement which is part of the operation costs varies from one plant to another mainly due to the capacity and the technology applied. Generally, for the plants that apply RO technology, the total cost is reduced due to the development of the membrane and its energy recovery system (Mezher et al., 2011). While MVC for instance requires electricity as the only energy source. On the other hand, desalination plants that use TVC, MED, or MSF require two forms of energy, electric

Table 4
Metal recovery from brine in various studies.

Technology	Recovery material	Efficiency	Study
Combination of nanofiltration (NF), membrane distillation (MD), and precipitation	Lithium (Li)	42% Studies indicated that MS can enhance Li recovery with a concentration of 2.5 for raw brine and 5 for NF-treated brine.	Pramanik et al. (2020)
Photocatalysis method	Uranium (U)	72 μg from 250 mL real saline lake brine	Wang et al. (2020)
Integrated MD-SWRO with an adsorbent of potassium copper hexacyanoferrate in MD feed tank	Rubidium (Rb^+)	96.6%	Luo et al. (2019)
Addition of alkali (NaOH) to the brine	MgO		Dong et al. (2018)
Reverse electrodialysis	Energy	The power density was reduced up to 43% due to the presence of organic matter in the RED stack. On the other hand, the presence of inorganic matter only reduced (up to) 7% of the	Kingsbury et al. (2017)
fractional-submerged membrane distillation crystallizer (F-SMDC)	sodium sulfate (Na_2SO_4)	Na_2SO_4 crystals were successfully removed (72% and 223.73 g) from simulated SWRO brine using laboratory-scale F-SMDC	Choi et al. (2020)

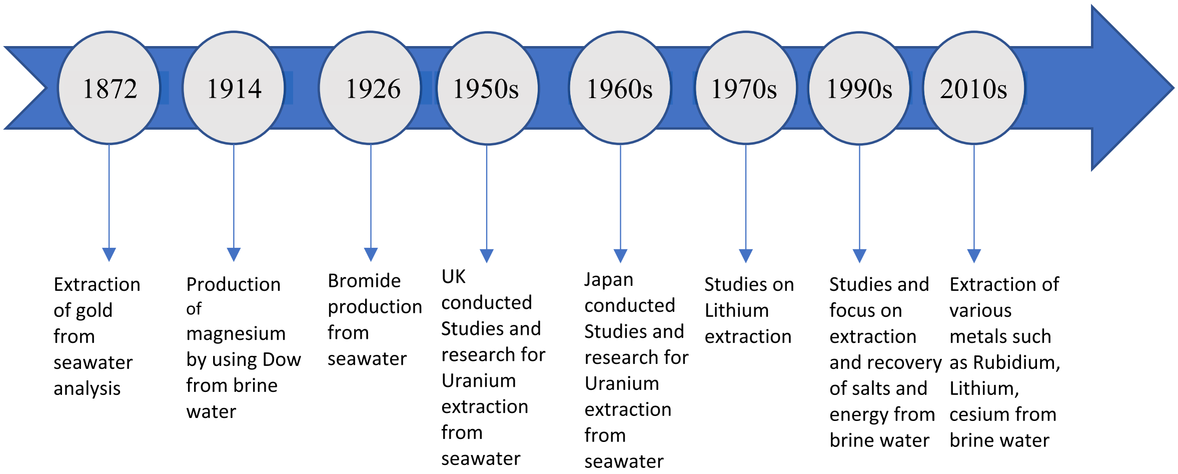

Fig. 4. Brief timeline illustrating the development of resource recovery from brine and seawater (Mavukkandy et al., 2019).

energy and thermal energy with low temperature. However, in all technologies, fossil fuels are used as a source to fulfill the required energy consumption. This section reviews the energy demand of various ZLQ treatments. Fig. 5 shows a comparison of energy requirements for various ZLQ treatments.

The energy required to run a typical MSF technology is determined by a variety of factors including the number of stages, the material used during the construction, the maximum level of temperature for the heating source, the design of the heat exchanger the heat sink, and salt concentration in the brine. One of the ways to reduce the cost of MSF is by increasing the number of stages (Semiat, 2008). On the other hand, MED also has similar energy requirements including a running pump, with low temperature. RO only requires energy to operate the pump as a source of energy. The feedwater salinity and the recovery rate determines the amount of energy consumed (Chehayeb and Nayar, 2018). ED is also similar to RO when it comes to energy requirements. To operate the pump as an energy source, ED, requires either alternating current or direct current (Al- Karaghouli & Kazmerski, 2013). The salinity level in the feed determines the electricity consumption. Lastly, TVC and MVC processes both require electricity and low temperature.

Thus it can be said, distillation processes including MED, MSF, and VC energy consumption are not affected by high salinity however, membrane-based processes such as ED or RO are sensitive to salt concentration. It can be noticed within the seawater desalination methods, RO requires less energy (around 4 kWh/m^3 - 6 kWh/m^3) while MSF would require 19.58 $kWh_e\ m^3$ - 27.25 $kWh_e\ m^3$ and MED will require 14.45 kWh/m^3 - 21.35 $kW\ h/m^3$ (Karaghouli & Kazmerski, 2013). This may be attributed to ongoing advancements in RO technology, which have resulted in lower energy usage as well as high demand for energy to vaporize water. Table 5 illustrates a brief comparison between brine from thermal treatment and membrane-based thermal technologies.

5. Cleaner production and sustainability

Desalination plants have both drawbacks and advantages. The availability of fresh water in various forms is considered a positive impact while the energy consumption and the environmental impact is considered a negative impact (Alnaimat et al., 2021). Depending on the size and the frequency of the operation, the CO_2 emission ranges from 7 kg/m^3 to 15 kg/m^3. Generally, the bigger the desalination plants the higher the energy consumption, consequently larger the carbon footprint. The energy required to operate desalination plants is typically derived from the combustion of fossil fuels that are depleting at an alarming rate and are not environmentally friendly due to the release of various greenhouse gases. By incorporating various renewable resources energy (RE) and transforming it into desired energy forms, the sustainability of desalination plants can be improved. There are many ways how renewable resources can be used in desalination plants, it can either be directly employed such as solar energy, or can be converted into the desired type of energy prior to its use in the desalination plants such as photovoltaic powered (PV-RO). Solar desalination plants system were successfully and efficiently constructed using various innovative materials (Ihsanullah, 2020). Wind, ocean, geothermal, and biomass are some of the renewable resources that can be used as potential resources. Using ocean thermocline energy, by using the difference in temperature between cold water in deep-sea and hot water on the surface thermal energy can be required for MED systems (Ng & Shahzad, 2918). Additionally, by recovering the energy loss and waste energy desalination use can be optimized (Tan et al., 2020). Various energy recovery techniques have also been proposed that can provide sustainability and economic advantages. By using the wastewater stream that comes from the desalination plant to dilute the feed for the RO process can result in a significant reduction in energy consumption (Wei et al., 2020). In recent studies, a novel membrane has been applied for MD treatment, which uses green technology and is also economically viable (Das et al., 2019). A hybrid desalination system can also provide a sustainable option and help to reduce environmental impact. A study by Lu et al. (2019) demonstrated the successful utilization of solar energy as a source to operate hybrid freeze desalination and membrane distillation crystallization using ZLQ desalination. To reduce high energy consumption in MD, various low-grade waste heat energy has been applied as a driving force. Fig. 6 summarizes some of the environmental benefits of using greener sustainable approaches for desalination plants.

6. Driving force Pressure State Impact Response (DPSIR)

Originally DPSIR was formed as a Pressure-State-Response (PSR) which evolved to Driving force Pressure State Impact Response (DPSIR) by the organization of economic and cooperation development (OECD). DPSIR is a theoretical framework that is used to analyze the cause-effect relationship that exists between society and the environment to help make decisions to cater to various environmental issues (Spanò et al., 2017). DPSIR framework is an important tool in management as it integrates knowledge and understanding from various diverse disciplines and helps provide an alternative decision by considering various perspectives. This framework acts as a bridge between the scientific community and linking science policy and environmental management (Lewison et al., 2016). The driving force (D) such as anthropogenic activities, applies pressure (P) on the environment such as land occupation which causes disruption or a change in the state (S) of the ecosystem. These changes as a result cause an impact (I) on the living organisms, human health, and the environment, which may consequently cause a

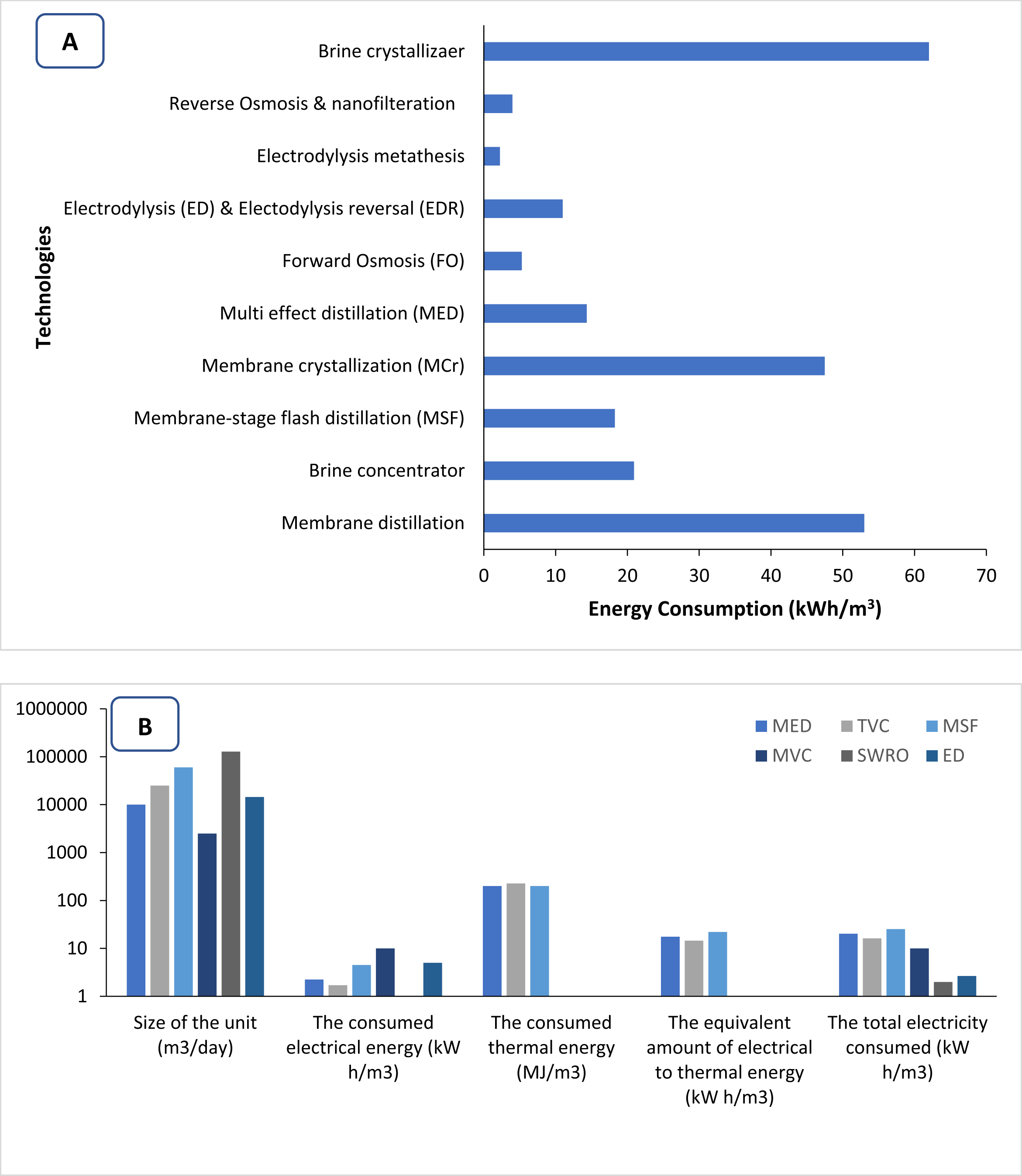

Fig. 5. The energy consumption of desalination and brine treatment technologies (A) and comparison of energy consumption by various plants (B) (Modified from Al-Karaghouli and Kazmerski, 2013).

Table 5
Illustrates a comparison between brine from thermal treatment (MSF or MED) and membrane-based (RO) desalination plants (Islam et al., 2018).

Brine type	TDS (Mg/L)	Scaling	Corrosion	Thermal discharge	Quality of water	Temperature (°C)	Chemicals employed
Thermal Brine	<10	3	4	4	3	<70	Warm acid, which can contain various corrosion inhibitors to clean the heat exchange surface to remove the alkaline scales.
RO brine	<500	3	3	4	4	<50	Strong acidic solutions (pH 2–3) are used the remove various metal oxides or scales. While strong basic solutions (pH 11–12) are added to clean the membrane. In addition, some detergents and oxidants may also be added. oxidizing biocides or non-oxidizing biocides are added to disinfect RO membranes

Index value 0: none, 1: low, 2: medium, 3: high, and 4: extreme.

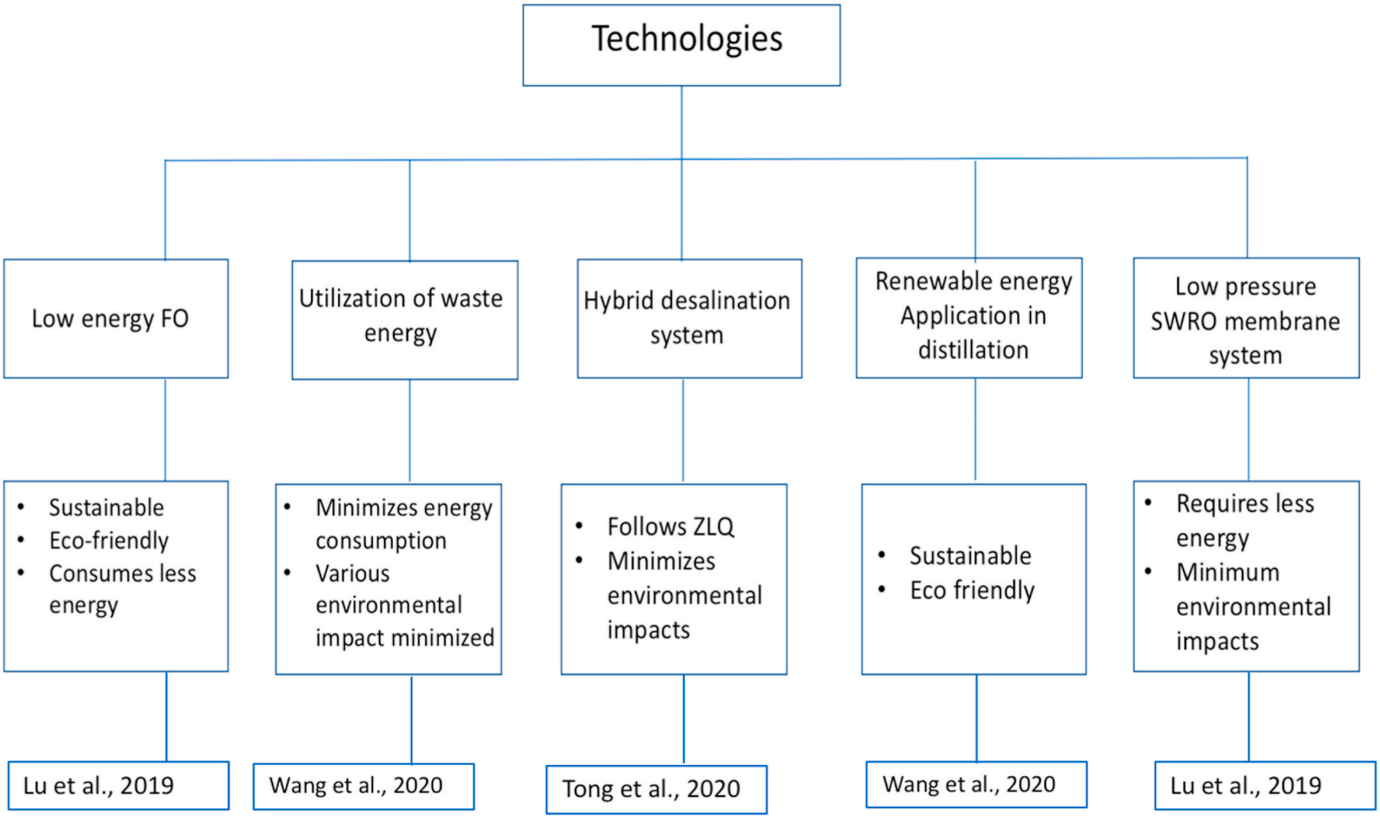

Fig. 6. Benefits of using various potential greener sustainable desalination technologies (Lu et al., 2019; Wang et al., 2020; Tong et al., 2020).

social response (R). DPSIR has been adopted in various studies for assessing alternative options. For Instance, DPSIR was used to reduce nitrogen in agriculture and protect water bodies at the European level (Fassio et al., 2005). Furthermore, to investigate the effect of climate change on the ecosystem (Omann et al., 2009). Recently Environmental Protection Agency (EPA) discussed the societal implication, cultural, industrial, commercial aspects of environmental and human health by incorporating the DPSIR framework (Yee et al., 2012). The current study aims to evaluate Qatar's brine water disposal system and aim to propose effective management options that can help mitigate the brine disposal issue by reducing the environmental impact.

6.1. *Driver*

6.1.1. *Population growth*

The water demand in the country is proportionally increased with an increase in the population. In the last two decades, Qatar's population has dramatically increased as seen in Fig. 5. Since 2005, Qatar's population has almost tripled. Such an increase, will significantly increase the water demand and reduce per capita water availability. Thus the increase in population can be said to be one of the main driving forces for the production and consumption of water. Additionally, in response to population and economic growth, agricultural activities have also increased to meet the consumers' agricultural demand this has further escalated the situation. Furthermore, the depleting natural water resource and groundwater level, coupled with an increase in population growth are one of the major drivers of the sector in the gulf region.

6.1.2. *GDP*

GDP is commonly used to measure a country's activity. An increase in GDP strengthens the country's economy and consequently improves the standard of living for the inhabitants of the country. Additionally, an increase in GDP increases the inflation rate, leading to an increase in the cost of consuming resources. From Fig. 7, it is evident Qatar has witnessed a sharp increase in the economic sector which has also caused water demand to be increased.

6.1.3. *Water security issue*

Unsustainable water consumption can be regarded as one of the major reasons for the increase in water demand by consumers. Several reasons have played a major role including the dramatic increase in industrialization. According to the report of The Qatar National Development Strategy, waste consumption is likely to increase by 5.4% annually for Qataris while 7% for non-Qatari residents by 2020. Additionally, statistics show that the net water loss decreased from 87 million m^3 to 32 million m^{3}per year in a period from 2008 to 2015 (Planning and Statistics Authority, 2017). During the same period, the country also witnessed one of the highest growth rates in various sectors. In the agricultural sector, the total treated wastewater used increased from 12.7% in 2006 to 22% in 2016 (Planning and Statistics Authority, 2017). However, the water productivity since 1990 remained the same, 1 L of water roughly contributes to QR 0.002 of GDP in agriculture.

Generally, the activities from building and construction, mining, manufacturing, and electricity and water activates are grouped under the industrial sector for the sake of data availability. While the total water consumption in the industrial sector increased from 2.5 million m^3 in 2002 to 11.62 million m^3 in 2016 (Planning and Statistics Authority, 2017). Besides, the GDP of the industrial sector increased from QR 184, 975 million to QR 236 196 million in 2014. This basically demonstrates that 0.042 L of water was required to produce QR 1 of industrial GDP in 2010, whereas 0.044 L was needed to produce the same GDP in 2014. Nevertheless, the commercial sector witnessed the highest increase in water consumption between 2002 and 2014 from 18 million m^3 per year to 74.97 million m^3 per year. About one liter of water was required to produce QR 0.87 of commercial GDP in 2002 while in 2014, 1 L of water produced QR 1.22 GDP. While the consumption of water in the

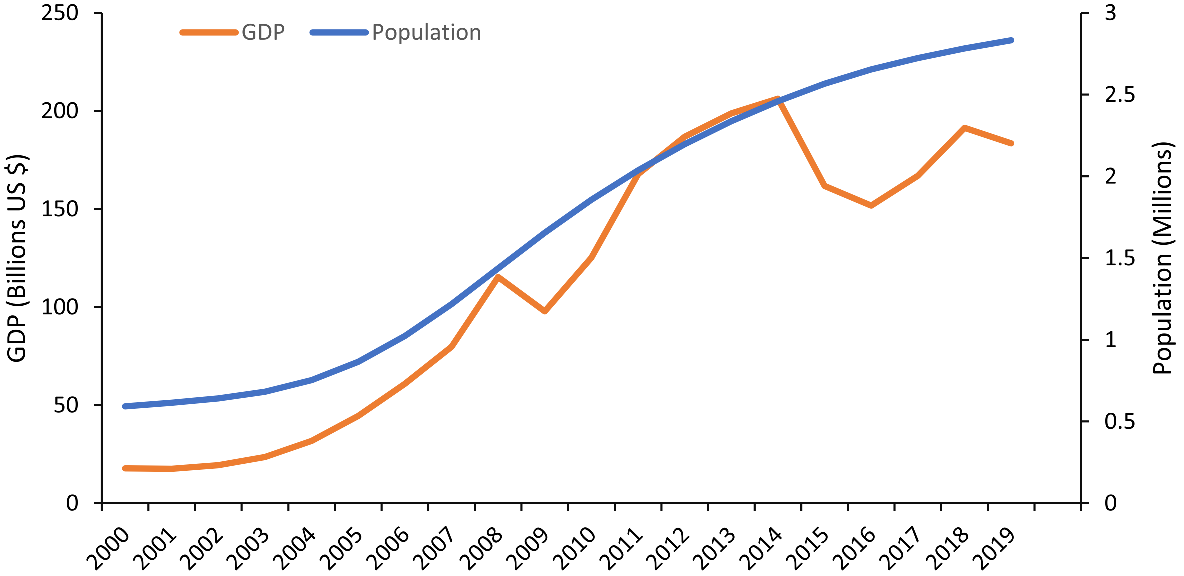

Fig. 7. Population and GDP growth in Qatar (2000–2019).

government sector increase from 18 million m^3 per year to 80 million m^3 per year in 2014.

The water loss could occur from multiple sources such as transportation of drinking water, septic tank, or wastewater sewers as well as while distributing treated sewage effluent (TSE). According to the classification of the International Water Association (IWA), there are two major types of loss apparent loss and real loss. Apparent loss may include unauthorized consumption of water as well as all types of inaccuracies associated with water meter (producing meter and consuming meter) while the real loss may account for physical water loss from the pressurized system up to the consumer metering. These also account for leaks, bursts, or overflows.

Desalination plants are the main contributor to brine discharge to the open water bodies. Thus the increase in population, agricultural activities, economic growth, and other factors have indeed increased the number of desalination plants in the country which has ultimately has increased the brine discharge. Statistical data depicts an alarming increase in water demands in the country, from 138 Million Imperial Gallons per Day (MIGD) in 2007 to 197 MIGD in 2008 and 420 MIGD in 2019. Additionally, the water demand is expected to reach up to 487 MIGD by 2022 (Kahramaa, 2015). To meet the water demand, Qatar has assigned the two biggest seawater desalination plants in Qatar and the region using RO totaling 450,000 m^3/day. Lastly, the capacity of portable desalinated water in Qatar was 476 MIGD in 2019, which is expected to reach up to 536 MIGD by 2021 and additionally 636 MIGD with the additional production capacity in Umm Al Houl while in 2023 is expected to reach 636 MIGD with the help of another new desalination plant to be completed in Facility E. Fig. 8 shows the increase in desalinated water production in Qatar (2007–2018) (Kahramaa, 2018).

6.2. *Pressure*

A continued effort in diversifying the government source of income from hydrocarbon industries to other sectors has led to an increase in constructing industries, plants, etc., which ultimately leads to more water demand. While the increase in water demand has also ventured the country to establish more desalination plants across the country. Qatar depends heavily on desalination plants to provide water for the

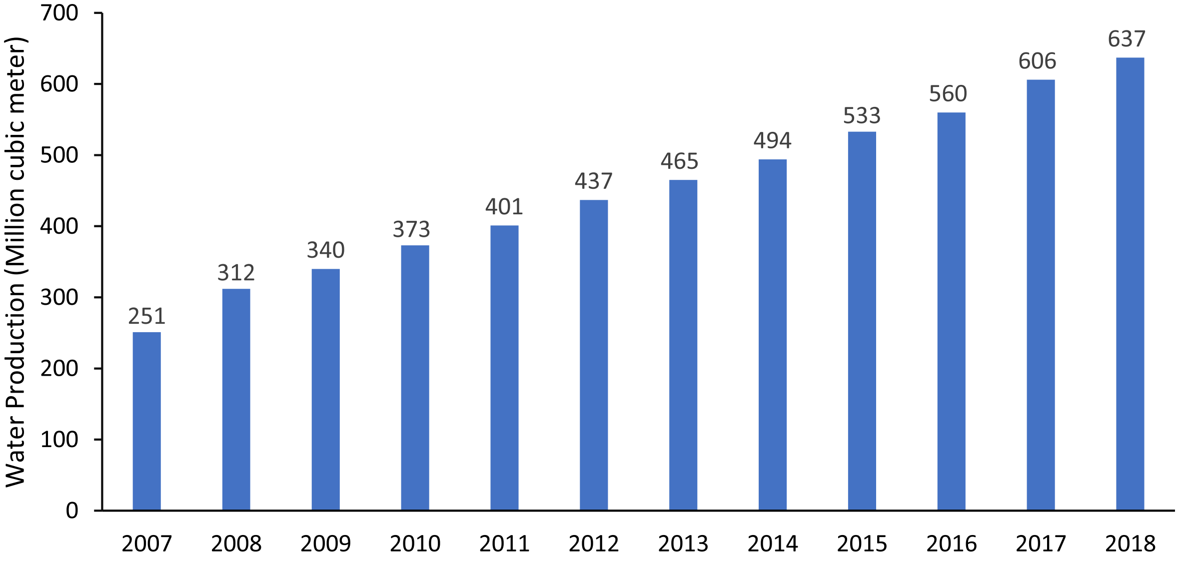

Fig. 8. Increase in desalinated water production in Qatar (2007–2018) (Kahramaa, 2018).

country. By installing more plants, the country's water requirement can be met. However, an increased number of desalination plants will also give rise to various negative impacts. Such as desalination plants require large land space, therefore various areas that will require to be cleared will cause loss of habitats. Furthermore, an increase in waste and wastewater production will require effective waste management to minimize environmental impact and protect many different ecosystems. The additional increase in brine production will also be challenging for disposing of since the availability of land might be occupied due to the construction of huge desalination plants as well as utilized for the disposal of other waste such as municipal solid waste (MSW).

6.3. *Status*

There has been an increase in brine discharge (drivers) due to an overuse of desalination plants. Thus, when brine discharge enters the water bodies it contains chemicals, coagulants, aggregate, and anti-scalants, these compounds may not necessarily be toxic, but, they may change the composition of the water and deteriorate the quality of seawater which may also have a direct impact on the function of microbial community and marine as well as the interactions of the coastal ecosystem (Lattemann and Höpner, 2008). It is also important to mention, the brine, which is introduced back to the water bodies, over time will impact the desalination plants and cause various wear and tears as discussed earlier. Brine impact on organisms is more or less the same around the globe, various literature has highlighted the negative impact on marine life by analyzing various seawater where brine is disposed of. Studying the coastal sediments is very fundamental as it plays an important role in the ecological and biochemical cycle of organic matter and inorganic nutrient recycling (Lukkari et al., 2009). Benthic habitat is home to various organisms from different tropical levels including macrofauna and macrofauna organisms and benthic prokaryotes and microalgae (Lubinevsky et al., 2017). Likewise, various benthic organisms including seagrasses and invertebrates have been negatively affected by brine discharge. Various studies reported in various reported that brine impacts can be observed seveal miles away from SWRO desalination facilities disposal point. Gacia et al. (2007) reported *Posidonia oceanica* near brine discharge showed significant difference from those that were investigated in other areas which indicated hypersaline water negatively impacted the species. While Riera et al., 2012 concluded ecological patterns of microbenthic fauna were significantly affected within the same spatial range (0–30 m). Petersen et al., 2018 found brine discharge can negatively impact the scleractinian hard corals holobiont (Corals and associated Symbiodinium and microbial community). While the abyssal heterotrophic bacteria are also negatively influenced by brine disposal, these impacts were observed to be site-specific. Additionally, brine disposal can also decrease the number of high tropic organisms such as bacterivores (nematodes and foraminifers) which can ultimately reduce the abundance of heterotrophic bacteria. Additionally, Darwish et al. (2015) also stressed that Qatar's over-reliance on groundwater has resulted in the over-exploitation of groundwater resources which has further worsen the water status.

6.4. *Impact*

Thus, one of the major impacts that will occur is perhaps due to the brine disposal back to the seawater which will change the water composition. This will lead to several impacts on humans as well as the ecosystem. For instance, an increase in salinity or other nutrients will result in the loss of marine organisms including Fiona and flora. The loss of fish will affect the ecosystem and also reduce the availability of fish supply to the consumers which will consequently impact the fisherman business. Qatar is enriched with coral reefs, as discussed earlier, increase salinity drastically impacts the corals by initially causing bleaching. Additionally swimming and diving activities will also be affected. One of the fundamental parts of the country's culture, fishing will also be affected. Another impact the can be associated with an increase in desalination plants is perhaps the loss of lands and an increase in pollution.

Riera et al. (2011) observed a significant decrease in the abundance of meiofauna in very close proximity (0 m) to a brine discharge point while at 10s of meters the meiofauna population increased. However, the difference in meiofaunal abundance in different locations also caused a change in the structures of the meiofaunal assemblage. Additionally, the increasing salinity and chemical concentration has been recorded to impact the marine organisms including bacteria (Drami et al., 2011), benthic heterotrophic (Frank et al., 2017), phytoplankton (Belkin et al., 2018), fishes (Iso et al., 1994), and others. Cambridge et al. (2019) tested the effect of brine on seagrass (*P.australis*) and found in 100% brine the growth was severely inhibited, additionally, brine increased the speed of stress symptoms on adults plants, however, seedlings were able to withstand brine for a longer period of time.

6.5. *Response*

It is crucial to important to invest heavily in raising public awareness amongst the citizen so that they can be aware of the major consequences. In light of such a strategy, the country has established "Tarsheed" in 2012, which aims to conserve electricity and water without compromising the necessity of the consumers (Local or non-local). Tarsheed also makes sure that its objectives are being met by conducting seminars and workshops in schools, parks, and other public places to ensure the public is getting maximum exposure to the campaign. The country has also made sure that the effectiveness of the awareness is also being practiced. Besides, the vision 2030 the country is also in line with sustainable development and practices. Additionally, Qatar has invested heavily in advanced technologies to produce high-quality treated wastewater, however, there is only limited demand due to various social and cultural factors (Dare et al., 2017). Thus, workshops or awareness campaigns should be set up in which the country could be informed about the safety and cleanliness of water which makes it safe to be used in various sectors. An in-depth understanding of the threats the country faces regarding the growing brine discharge should be prepared. Various samples from different disposal points should be collected, and the impact it has on marine life should be recorded, additionally, it should also be known how further from the point of disposal is marine life affect.

The country can also adopt various ZLQ technologies as discussed in the review paper that will minimize the harmful impact on the environment in addition it will also help achieve vision 2030 regarding sustainability. For instance, by using brine energy to produce powder by lowering salinity. This can be achieved by various salinity power production technologies. One of the promising technologies, which is believed to give high energy density is pressure retarded osmosis (PRO) (Chung et al., 2017). Furthermore, the country can invest in strategies that will help dispose of brine in a way that minimizes the threat. Additionally, another response the country could develop is perhaps installing plants that can recover salts from brine which can be beneficial for the economy. Sezer et al., 2017 showed the salt consumption in Qatar and found that the country imported 24.5 M USD worth of salt in 2010. It is also suggested that the country has 12,580.7 km^2 of available arable and undeveloped land, which could be used to construct an evaporation pond. This will be economically feasible for the country as it can turn waste discharged into salt production.

7. Conclusion

Brine management is perhaps one of the critical problems faced by the desalination industry. In this review, some of the common technologies used in desalination plants both membrane and thermal-based were critically assessed and their environmental impacts were evaluated. From this study, it is apparent that effective brine management must include the utilization of an appropriate technology that incorporates zero technology to reduce brine volume to its acceptable level while also recovering various valuable resources. Additionally, this review also highlighted that brine should not be considered waste but rather a resource that inhabits various useful matter including various types of salts and elements that can be of great economic value. Almost all technologies that were discussed in the review comprehensively have the ability to recover resources from brine water in a sustainable manner these resources have both high or low economic. For very concentrated brine, MD, or an MD hybrid was seen to show the highest potential to be efficient however, this process will have certain limitations such as membrane fouling or membrane scaling which needs to be mitigated. While adsorption can be used to extract valuable metals such as rubidium and uranium, this process requires minimal energy however, the drawback of using adsorbent can be the completion between other ions which may lower the efficiency of this process. This indeed calls for a more in-depth study that focuses on brine management and efficiency. DPSIR was conducted and found effective to analyze the overall scenario of the brine water and water resources system of Qatar. These several formulations of water using tariff structure, ZLQ brine discharge, and high-quality wastewater treatment are proposed under the "response" term.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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