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Treatment and Disposal Methods of Concentrate Stream of Seawater Reverse Osmosis- A Review

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ABSTRACT

The exponentially multiplying population of the world demands increasing freshwater resources. Thelimited resources comprising less than 3% of the earth's water resources are getting polluted at an alarming rate. To deal with this situation, seawater reverse osmosis is being carried out at large scales across the globe. The concentrate generated in return is two times more concentrated in terms of total dissolved solids when compared to the feed. The adverse effects of the concentrate stream on the marine ecosystem and further pollution of water cause an immediate need to treat the concentrate. In this review, the harm caused by the direct discharge of concentrate stream has been discussed and therefore volume minimization using treatment methods has been addressed. The treatment methods are mainly classified into four types; membrane-based, thermal-based, electricity-based, and chemical-based methods. Integrated methods, which have been mainly tested on a pilot scale for zero liquid discharge, have also been discussed. The treatment methods that are probable for seawater concentrate treatment falling under the above categories for other concentrate sources have also been attended to. Finally, the disposal methods employed for the discharge of the leftover concentrate have been addressed. Thermal methods are well established but require a lot of energy compared to other methods whereas chemical methods can be economic due to the profit obtained from recovered chemicals, but they are mostly employed for pretreatment. Electricity-based and membrane-based methods are emerging technologies. It was also found that seawater reverse osmosis concentrate is usually discharged directly and therefore integrated methods based on zero liquid discharge are to be implemented. To compensate for the intensive research required for zero liquid discharge to become a reality, innovative and environmentally-friendly disposal methods are available to cut the resultant footprint.

INTRODUCTION

Reverse osmosis is a procedure that uses membrane technology to purify wastewater or water streams that are unfit for drinking or domestic use. It produces potable water that can be used as a substitute for natural freshwater resources. Reverse osmosis is the process in which water flows from a highly concentrated stream through a semi-permeable membrane to the fresh waterside giving out permeate stream and concentrate stream. The permeate stream is the water with the least quantities of total dissolved solids (Greenlee et al. 2009). Meanwhile, the concentrate stream has 1.5-2 times the dissolved solids as compared to the feed water (Younos 2005, Qasim et al. 2019). It has a smaller footprint, allowing the system to efficiently combine with other methods to enhance the overall recovery. Even then, researchers have looked into its high energy consumptions and carbon dioxide emissions (Heihsel et al. 2019). Countries in the Middle East did not rely on Reverse Osmosis (RO) earlier but with the rising prices of oil and fuel, they are increasingly switching to RO treatment (Tularam & Ilahee 2007).

NEED FOR REVERSE OSMOSIS

Nearly 3% of the Earth's water sources are fresh, divided unevenly across the countries. According to an estimate, over one billion people do not have fresh water sources in the world (Subramani & Jacangelo 2014). Freshwater resources available to us in nature are depleting day by day due to a drastic increase in population across the globe. The ever-increasing population demands higher quantities of freshwater resources to satisfy the daily needs of people. Countries such as the United States, Vietnam, Bangladesh, and India are encountering the problem of increasingly saline groundwater causing an increased demand for seawater treatment (Tularam & Ilahee 2007). The water stress index is the ratio of withdrawal of freshwater to the available freshwater resources. A value of 40% indicates water shortage, and water shortages may lead to increased prices, unavailability of freshwater to all spheres of the population (Fritzmann et al. 2007). As the water resources are getting depleted drastically due to this, various treatment methods have been employed for treating saline sources of water.

Amongst these, RO is found to be the most efficient method due to its lower energy requirements, higher recovery, and good quality of permeate obtained. The 330,000 $m^3.day^{-1}$ Sea Water Reverse Osmosis (SWRO) plant in Ashkelon, Israel, and the 136,000 $m^3.day^{-1}$ Tuas SWRO plant in Singapore are some of the high capacity RO plants (Pérez-González et al. 2012). Fujairah SWRO plant was also built in 2005 with a capacity of 170,500 $m^3.day^{-1}$ in the Middle Eastern region (Sanza et al. 2007). Apart from seawater, other sources of water are also treated by RO technology. International Desalination Association has classified brackish water as water containing TDS levels from 1000 $mg.L^{-1}$ to 10,000 $mg.L^{-1}$. Brackish water reverse osmosis can be carried out at a much lower energy consumption of 0.5-2.5 $kWh.m^{-3}$ compared to seawater reverse osmosis which has an energy consumption of 3-4 $kWh.m^{-3}$ (Xianhui et al. 2019). Thermal-based technologies are most commonly used in Middle Eastern countries because they have a surplus of fuel resources and its cheap price in comparison to other countries (Xu et al. 2013). But due to the large volumes of seawater available, the SWRO process should be made as efficient as probable to bring down the cost of energy consumption.

NEED TO TREAT THE CONCENTRATE

As mentioned before, RO gives out a concentrated stream that has 1.5-2 times more dissolved solids. Numerous problems are caused to the environment by this concentrated stream. The concentrate stream endangers the marine ecosystem in the area where it has been discharged. The areas receiving the concentrate undergo various degradations such as pH variations, eutrophication, and accumulation of heavy metals such as zinc, copper, iron, chromium, and nickel (Greenlee et al. 2009, Subramani & Jacangelo 2014, Rautenbach & Linn 1996, Chelme Ayala et al. 2009, Ng et al. 2008). Along with this, the concentrate stream upon disposal directly goes to the bottom of the sea due to the high concentration of total dissolved solids causing an increase in its density. The heavy metals present in these dissolved solids upon going to the bottom harm the aquatic animals and ecosystem including the coral reefs. Plenty of species such as the benthic community that inhabit the bottom of the sea disappear from the discharge zone (Li et al. 2019, Medeazza 2005, Mickley 2006, Missimer & Maliva 2018, Mondal et al. 2020, Panagopoulos et al. 2019). Due to all these adverse impacts, direct disposal of concentrate is restricted or banned by various organizations of different countries. To manage this problem, treatment of the concentrate must be done prior to discharge not just to prevent the adverse effects but also to minimize the volume of the concentrate. Treating the concentrate helps to provide an additional freshwater resource, minimizes the concentrate volume, and precipitates/extracts valuable chemicals (Li et al. 2012, Xu et al. 2009). The selection of the best treatment method for the reverse osmosis concentrate is mainly dependent on the characteristics of the concentrate, its density, and volume (Mickley 2006).

METHODS OF TREATMENT AND DISPOSAL

Certain methods like zero liquid discharge methods end up with complete elimination of concentrate stream. Zero liquid discharge is based on the principle of maximizing the recovery in the first RO process, thereby highly reducing concentrate volume (Ning & Troyer 2009). Methods such as thermal-based or membrane-based methods help reduce the volume but do not completely terminate the concentrate stream. The disposal of this concentrated stream can be done using various disposal techniques. Some of the disposal methods are surface discharge, deep well injection, evaporation ponds, etc. In some cases, dispersion models have been used to determine the point of discharge that causes the least impact on the environment but even this shows limited change or benefit. The cost of discharge is usually around 5-33% of the total cost of the process depending on concentrate characteristics, concentration, and volume. Direct disposal may lead to certain environmental issues such as an increase in salinity beyond threshold limits, the concentration of metals, the concentration of nutrients that harm the environment, elevated temperatures, etc. Therefore, thorough research must be carried out before the disposal of concentrate (Voutchkov 2011). In this review, the different treatment technologies of the concentrate for concentrate volume minimization along with integrated techniques, which try to achieve zero liquid discharge, have been discussed. Disposal methods employable after concentrate treatment also have been addressed. The various benefits of treatment methods such as the recovery of valuable salts decreased costs due to the profit gained, and benefits to the environment have been reviewed.

TREATMENT METHODS OF CONCENTRATE STREAM

The direct disposal of the concentrate generated by the seawater reverse osmosis process is not possible due to the high volume of concentrate generated in most cases. To deal with this problem, various treatment technologies have been developed and amended for the volume minimization of the concentrate stream. Intermediate treatment of the concentrate between RO stages spikes the efficiency of the system. These treatment methods can be broadly divided into thermal-based, membrane-based, electricity-based, and chemical-based methods. Integrated methods of treatment have also come into place.

THERMAL BASED METHODS

Thermal-based methods have been intensely researched and are well established industrially. The efficiency is high for thermal-based methods with the disadvantage being the high-energy requirement. Middle Eastern countries and countries with cheap fuel sources utilize thermal-based methods majorly in comparison with other treatment methods. The given Table 1 explains their properties.

MEMBRANE-BASED METHODS

Due to the depleting fuel resources around the world and the need to replace fuel-based technology with renewable technologies, thermal-based methods are not being used in most countries. Membrane-based methods have become quite popular due to the relatively less energy required and the high efficiency attained as discussed in Table 2.

A study of MD simulated an increase in the water recovery of a 40,000 $m^3.day^{-1}$ plant from 40-89%. The total brine volume after treatment with MD decreased by a factor of 5.5. When highly ideal conditions were used, the minimum spe-

Table 1: Thermal based methods.

Sl. No.	Method	Properties	Advantages	Disadvantages	References
1.	Multiple Effect Evaporation (MEE)/ Vapor Compression (MVC)	In solution's vapor pressure is reduced within the system to make the solution boil at a lower temperature. The evaporator admits the concentrate feed into the tube side in series where it undergoes boiling. In MVC, the principle difference is that the vapor produced on evaporation is compressed using a compressor, for reuse as steam.	● They are the most cost-effective amongst the evaporation methods. ● Steam used for boiling condenses over the tube walls and is reused for heating. ● They have a simple geometry and are easy to operate, resulting in high efficiency. ● They do not depend on weather conditions.	Fossil fuel requirements and the high cost of energy sources are the main drawbacks.	(Morillo et al. 2014)
2.	Dewvaporation	The concentrate upon heating by hot air evaporates and condenses in the form of dew on one face of the heat transfer surface.	● Scaling can be avoided as evaporation occurs at the air-liquid interface. ● Dewvaporation using solar energy combined with a chimney attains not just freshwater but also generates power. ● At high heating power of 4.9 kW, 48 $g.min^{-1}$ of freshwater was seen to be the highest.	There is a higher footprint as the tower operates at atmospheric pressure. The energy requirements are considerably high making it suitable only for high scale plants. To produce 1000 gallons of pure water, 2.6 X 10^6 BTU of heat will be required. 32.14% was the highest thermal efficiency obtained for seawater desalination.	(Hamieh & Beckman 2006, Cao et al. 2020)
3.	Wind Aided Intensive Vaporization (WAIV)	Based on the principle of simultaneous humidification-dehumidification. In this method, intensely packed towers wetted with concentrate streams are evaporated using high-speed wind. These towers are vertical hydrophilic trays with the wind passing in a parallel direction. The heat flux at the wetted surface caused by the temperature difference between the warmer wind and cooler water surface causes evaporation.	● A demonstration in Australia showed that WAIV's efficiency was found to be 10 times higher than evaporation ponds. ● It doesn't cause salt drift. ● It has the lowest specific energy consumption of 1 $kWh.m^{-3.}$ ● Wind energy is the main source of energy. ● It has reduced land requirements.	This method may have a drop-off in efficiency. Industrial research is needed to keep a tab on the detection of groundwater pollution.	(Gilron et al. 2003, Panagopoulos et al. 2019)

Table 2: Membrane-based methods.

Sl. No.	Method	Properties	Advantages	Disadvantages	References
1.	Membrane Distillation (MD)	It operates on the same principle as distillation except that it uses a membrane to form support between the vapor-liquid interface. Only the volatile component of the solution passes through the hydrophobic membrane. The driving force is the vapor pressure gradient between heated feed and cooled water. The most suitable MD for desalination purposes is direct contact membrane distillation. Here, a hydrophobic membrane is placed between hot brackish water concentrate and cold pure water	● MD isn't energy-intensive, as it requires a temperature between 60-80^{o}C. ● The volume of the membrane with respect to the equipment provides a large contact area. ● It can be coupled with cheaper heat sources such as geothermal, solar, and waste energy. ● The water produced was purer when compared to that of the other membrane processes. ● MD membranes are resistant to oxidation in comparison with nanofiltration and RO membranes.	● The hindrance to this method is the conductive heat loss that occurs at the MD membrane, thereby increasing the energy costs. ● The research on this method should focus on the development of new membranes such that heat loss is less and scaling is eluded. ● The $CaCO_3$ and $CaSO_4$ cause scaling, which can be reversible by washing and chemical cleaning.	(Lawson 1997, Xianhui et al. 2019, Office 2003), Mericq et al. 2010)
2.	Forward Osmosis (FO)	A concentrated solution called draw solution, in this case, concentrate stream causes osmotic pressure differential and carries out dilution of the stream.	● FO has a lower energy requirement compared to RO ● It has a reduced specific energy consumption of 4.49 kWh.m^{-1} in comparison with a double RO system of 6.43 kWh.m^{-1}. ● No external pressure is required. ● Membrane fouling is also relatively low and easily reversible.	● Concentration polarization is high. ● Suitable draw solutions that provide a strong driving force are hard to find. ● To reduce the concentration polarization, hydraulic configurations need to be optimized. ● Scaling takes place in real systems due to the presence of organics.	(Zhang et al. 2011, McCutcheon & Elimelech 2006, Shaffer et al. 2012, Subramani & Jacangelo 2014, Kazner et al. 2014, Martinetti et al. 2009, Liyanaarachchi et al. 2020).
3.	Bipolar Membrane Electrodialysis (BMED)	Bipolar membrane electrodialysis is an electrodialysis process carried out with the help of bipolar membranes. This gives mixed acids and bases as the product. Mono polar cation and anion exchange membranes with alternating bipolar membranes are installed as a whole. The membranes split water into protons and hydroxides, Protons combine with anions to form acids meanwhile hydroxides combine with cations to form bases.	● It is a source of valuable metals. ● One of the recent studies shows BMED powered by photovoltaic energy overcame the energy consumption issue. ● Byproducts reduce the environmental impact of the process of treating seawater concentrate.	● There is limited stability of the ion exchange membranes. ● When the salt concentrations are very high, the separation of acids and bases is hindered as salts also permeate through the bipolar membrane and precipitate.	(Badruzzaman et al. 2009, Morillo et al. 2014, Jones et al. 2019, Strathmann 2010).

cific energy consumption of 7.7 kWh.m^{-3} was obtained with feed and distillate temperatures of 60^{o}C and 20^{o}C (Deshmukh et al. 2018). Similarly, to understand the efficiency of FO, it was used to concentrate brine from TDS 70,000 mg.L^{-1} to 225,000 mg.L^{-1}. 60% of water recovery was obtained using FO (Subramani & Jacangelo 2014). In the case of BMED, upon carrying out Life Cycle Impact Assessment with climate change as the factor, it was seen that the resultant water had TDS similar to seawater and hence direct discharge is quite possible (Herrero-Gonzalez et al. 2020).

ELECTRICITY BASED METHODS

Electricity-based methods are quite efficient for desalination. They also achieve recovery of valuable products from the seawater concentrates such as precious metals and other

Table 3: Electricity based methods.

Sl. No.	Method	Properties	Advantages	Disadvantages	References
1.	Electrodialysis (ED)	There is a cathode and an anode between which a series of alternating cation and anion-selective semi-permeable membranes are present. The cations pass through the cation-selective membrane and get attracted to the anode, which is negatively charged. Similarly, the anions pass through the anion-selective membrane and get attracted to the cathode, which is positively charged.	● It is well established. ● Hollow membrane fibers between the ion exchange membranes decrease the concentration polarization. ● It can operate with residual chlorine up to 1 mg.L^{-1}, controlling fouling. ● The salt concentration is increased from 0.2-2% to 12-20% with 1-7 kWh.m-^{3} energy requirement.	● It has a high cost of generation. ● It is only used for low concentrations of salts. ● Fouling occurs by the presence of colloidal materials and organics. ● It may have a high energy consumption if low selective membranes are employed. ● Industrially, batch ED processes are carried out but continuous supply is mostly required and needs to be further explored.	(Korngold et al. 2005, Xu et al. 2013)
2.	Electrodialysis Metathesis (EDM)	This method is also based on electrodialysis in which repeating units of the following are present; NaCl solution compartment, dilute compartment, cation exchange membrane, anion exchange membrane, two concentrate compartments, monovalent selective anion, and cation exchange membrane. This configuration separates the feed into two streams of highly soluble salts; sodium with anions and chloride with cations.	● This method is excellent at concentrating ions and recombining them simultaneously. ● In a recent project, EDM was used to concentrate the seawater brine and further sodium and chlorine were produced making it economically efficient.	● This method doesn't help remove organics from the water. ● High voltages give high specific energy consumption, which in the above-mentioned study reached up to 1.77 kWh.kg^{-1} TDS for a voltage of 8V.	(Bond & Veerapaneni 2011, Chen et al. 2019)

economic salts. The disadvantage of this method is quite obvious, namely, its high-energy requirements to fulfill the electricity demand. The following Table 3 below describes the different aspects of the methods.

In a recent study where seawater desalination was carried out in a two-stage ED plant, energy consumption was found to be around 3.6kWh.m^{-3} where the concentration decreased to 11.4mM, which is according to the standards prescribed (Doornbusch et al. 2019). Whereas, Electro Dialysis Metathesis (EDM) is not commonly used and so far, has only been used at lab scale and not industrially. Electrodialysis metathesis helped increase water recovery to 99% with BWRO feed and can be used as a secondary treatment.

CHEMICAL-BASED PROCESSES

Chemical-based processes mentioned in Table 4 mainly focus on the recovery of chemical products from the concentrate stream of SWRO. This is because it increases the environmental benefits by reducing the volume of the discharge while increasing the economic benefits by producing valuable chemicals simultaneously. Various chemical-based methods have been employed for treatment. Although, some may increase costs due to the added cost of chemicals whereas others generate profit when byproduct chemicals are of value to other industries.

As mentioned, the by-products formed to make this category economic most of the time. SAL-PROC processes have been tested for installations with a capacity of up to 822-7991 m^{3}.day^{-1}. The recovery rates in the four plants in Oman were found to be 70% on average (Schantz et al. 2018). A recent study used to treat 17.5 t.h^{-1} seawater concentrate; the Chlor-alkali process was the last treatment step to produce chlorine and alkali. 208.4 kg.h^{-1} of NaOH was obtained including the caustic soda required in the process (Du et al. 2018). When chemical softening was accompanied by a secondary step of RO, 95% overall water recovery was obtained. In another study, flocculants were also used to enhance precipitation and remove hardness by floc formation (Ordóñez et al. 2012).

INTEGRATED PROCESSES

Integrated processes are the combination of different processes into a flow where the final product is seen to have enhanced recovery as compared to single methods. Certain integrated processes such as a combination of RO with a membrane reactor have achieved up to 88.94% recovery but

Table 4: Chemical-based methods.

Sl. No.	Method	Properties	Advantages	Disadvantages	References
1.	SAL-PROC	This is a patented process used for the extraction of dissolved elements from seawater in a sequential process and gives out valuable chemicals in the slurry, crystalline, and liquid forms. In one of the studies at the laboratory scale, sodium bicarbonate, sodium carbonate, ammonium chloride was obtained from concentrated brine by ammoniating the solution and bubbling carbon dioxide through the brine solution. It is a simple process of evaporation and cooling that is accompanied by chemical and mineral processing.	● The recovery of valuable salts from these waste concentrate streams improves the cost-effectiveness of the desalination process. ● In an estimation that took place regarding desalination of the Petroleum Development Oman's (PDO) four desalination plants, commercial salts worth USD 895,000 could be recovered at the most using this process. ● Chemical recovery can make an expensive process economic due to the profit gained.	● The storage of chemicals required, chemicals produced will generate a significant footprint. ● It will also have high investment costs due to the continuous need for reactant chemicals.	(Jibril & Ibrahim 2001, Morillo et al. 2014, Ahmed et al. 2003)
2.	Chlor-alkali	This potential process of profitable concentrate treatment is similar to BMED where an electrochemical cell is used to oxidize chloride ions to chlorine gas and sodium ions and water to sodium hydroxide.	● Hydrogen gas obtained at the cathode can be used on-site, as a commodity, or released into the atmosphere. ● If a membrane electrolytic cell is used, pure NaOH will be produced that deals with environmental concerns. ● The chlorine produced by SWRO concentrate treatment can be utilized for the disinfection of drinking water. ● When a cost analysis was carried out on this method, it was concluded that after ten years, the profit obtained could pay off the capital costs.	● The brine has to be free of Ca, Mg, Ba, Sr, and organic matter. ● The profitability was sensitive to changes in the prices of the product. ● The energy demand for generating chlorine from the concentrate stream is approximately 2100 kWh.t^{-1}chlorine. Therefore, unless the product generates enough profit, the energy consumption will be quite disadvantageous.	(Schantz et al. 2018, Shahmansouri et al. 2015, Morillo et al. 2014)
3.	Chemical Softening	Chemical softening is done by the addition of chemicals to the concentrate, giving out the precipitate. This process commonly precipitates Ca^{2+}, Mg$^{2+,}$ and Sr$^{2+.}$ Dosing alkaline chemicals such as $Ca(OH)_2$, NaOH, and Na_2CO_3 precipitates scaling chemicals such as $CaCO_3$. A Solid Contact Reactor was used to carry out softening and the precipitate was separated from water efficiently.	● In 2014, this method was used to treat seawater brines from Mediterranean and Red Sea RO plants and synthetic seawater. ● The efficiencies obtained for calcium were 89%, 95%, and 95.5% respectively.	● There is a high chemical demand for precipitation of the scalants. ● Large quantities of waste sludge are produced. ● There is a requirement for a filtration step before sending the feed for secondary RO. ● Retardation of the rate of desupersaturation due to the presence of antiscalants is another drawback.	(Qu et al. 2009, Gabelich et al. 2007), Schantz et al. 2018, Sorour et al. 2015)
4.	Degasification	Degasification/CO_2 stripping can be used for obtaining carbon dioxide from seawater RO concentrate. In one of the studies when carbonate-rich RO concentrate was treated, air stripping the CO_2 precipitated the solids with increasing pH.	● An environmental and economically favorable way of removing CO_2 is by stripping CO_2 using aeration, without the use of any chemicals. ● The recovery increases due to an increase in pH	● Blockage of air aperture nozzles can take place, leading to diminished air flow rate, and a decrease in $CaCO_3$ precipitation rate. ● There is a requirement for additional chemicals. ● The production of large quantities of sludge can be a hindrance. ● Availability of area for storage of chemicals, and space requirements of the respective reactors are also possible concerns.	(Hasson et al. 2011, Segev et al. 2011, Cohen & Kirchmann 2004)

haven't been researched further (Lew et al. 2005). In a study, the concentrate was treated using the ED-Pellet Reactors combination (Tran et al. 2012). Whereas in another study RO concentrate with EDR was tested and gave a high recovery (Turek et al. 2009). Studies that combined ultrafiltration, activated carbon filtration, and nanofiltration giving high recoveries, have also been studied (Heijman et al. 2009). Some of the methods have been discussed in Table 5.

8400m^3/day of concentrated brine from Pozo Izquierdo desalination plant with a capacity of 33000m^3/day was used to test Chlor-alkali/chemical precipitation combination. Once the brine was treated, it was fed to an electrolyzer to separate chlorine gas and NaOH. The results showcased a production of 253.71kt/y NaOH, 2.82kt/y hydrogen, and 101.16 kt.y^{-1} chlorine. In HERO, the combined overall recovery was seen to be 90% (Subramani & Jacangelo 2014). Another alternative to SPARRO is a two-pass process. Firstly, a tubular nanofiltration (NF) system with seeded slurry recycle was employed and in the second step, a spiral wound RO system was used. It's called a double pass preferential precipitation RO system. It achieved a recovery of up to 92-96% (Peters et al. 2007).

DISPOSAL METHODS

If treatment methods are ZLD type then there won't be any residue left over. But when treatment methods cannot suffice to eliminate residue, disposal methods should be opted to take care of the concentrate leftover. Carrying out treatment

Table 5: Integrated methods.

Sl. No.	Method	Properties	Advantages	Disadvantages	References
1.	WAIV/MCr	In this method, the BW was first pretreated and then passed through RO. Upon recovery, the concentrate was further treated using WAIV. WAIV super concentrates were fed to the MCr semi-pilot plant.	● NaCl can be crystallized in different shapes and sizes. ● The cost of treatment can be reduced to 64% by using WAIV instead of evaporation ponds. ● In the presence of antiscalants, 88% recovery was possible. ● The combined system was able to obtain up to 88.9% recovery. ● The savings for this system was over one magnitude greater than the reduction in the footprint for concentrate disposal.	● A fouling layer may be found in the MCr unit. ● The external substances existing in the brine may deter the kinetics of crystallization, causing a reduced growth or inferior product quality.	(Subramani & Jacangelo 2011, Tularam et al. 2007)
2.	Chlor-alkali/ Chemical Precipitation	Chlor alkali feed must be free of Ca, Mg, Ba, Sr, to obtain chlorine gas. Thus, an integrated method combining Chlor-alkali with chemical precipitation was tested. A multiple-effect evaporator was used to carry out chemical precipitation. Calcium, sulfates, and magnesium were removed with chemical precipitation.	● Using the concentrate stream reduced the energy required to start with fresh seawater directly. ● The hydrogen gas generated can be used to generate electricity in the plant. ● This method is economic as it involves the production of economic products	This method needs further research and may have high-energy consumption depending on the electrolytic cell used.	(Morillo et al. 2014)
3.	High-Efficiency RO (HERO)	RO concentrate is treated with ion exchange to remove hardness and degasification methods, and a secondary RO treatment is carried out in the end. Carbon dioxide removal is obtained using the degasification step. The RO concentrate was treated with weakly acidic cationic exchange resins that caused the removal of divalent ions	● Due to the degasification, an increase in pH increased the recovery of the secondary RO. ● Weakly ionized species such as SiO_2 and boron were reduced by a factor of 10 or more.	● Its estimated energy requirements were from 11-19 kWh.m^{-3}. ● Complete coverage of the membrane with aluminosilicate was obtained. ● This is a patented process, hence leads to high capital costs.	(Xinyang et al. 2012)
4.	Slurry Precipitation and Recycling RO (SPARRO)	Crystals such as gypsum are added to the concentrate solution, upon which scaling compounds precipitate on the seed compounds rather than on the membrane surface. A hydro-cyclone removes the crystals formed in the concentrate.	Overall recovery was estimated to be greater than 90%.	● When the seed slurry is recirculated within the membrane system, plugging might occur. ● To avoid this, tubular membrane systems are desirable.	(Peters et al. 2007)

methods is important because it reduces the volume by a large factor but disposal methods should also be discussed (Table 6) to identify the ideal disposal method for each process. When installing a desalination plant, the site location should be chosen such that no other sources of discharge are present or where a stream is available for its dilution to carry out the disposal effectively and in an environmentally acceptable manner (Mauguin & Corsin 2005).

CONCLUSION

The disposal of SWRO concentrate directly into the sea would cause adverse effects to the marine ecosystem of the sea, especially at the point of discharge. To avert this adverse damage to the aquatic life, treatment methods are to be developed to minimize the volume of concentrate or better yet, eliminate it. Zero liquid discharge is based on improving or maximizing the efficiency of the primary RO treatment. Treatment methods were divided based on the main princi-

Table 6: Disposal methods.

Sl. No.	Method	Properties	Advantages	Disadvantages	References
1.	Direct discharge	The discharge entering receiving water such as the sea forms a highly saline plume that may sink, float or stay in the water depending on the density of the water.	It is the most cost-effective and simple method.	● The concentrate goes directly to the bottom of the sea due to its high density, causing harm to the marine ecosystem as they consume heavy metals in the dissolved solids. ● Plenty of degradation and depletion of marine life has been witnessed.	(Younos et al. 2005, Chelme-Ayala et al. 2009, Li et al. 2012, Abdul-Wahab 2007, Leong et al. 2014).
2.	Discharge to trenches	Some small desalination plants use this method where they make use of perforated pipes buried at shallow depths parallel to the sea.	● Concentrate seeps slowly away from the shore, diffusing and dispersing with no impact on the benthic community, ● It does not affect animal life such as nesting sea turtles.	The apt way of construction of this method is to be tested further and a successful design should be accomplished.	(Missimer & Maliva 2018)
3.	Single pipe discharge	A single pipe with an inclined open end is available. When the concentrate is sent through the pipe to deep waters, it ascends at the end and descends back to the bottom of the seawater due to gravity.	It can be used at a large depth to avoid harm to marine life and coastal environments near the surface. ● If the seabed is inclined, upon passing down, the concentrate gets diluted due to the level difference.	The natural dilution of this concentrate depends on waves, currents, bathymetry, and tides present at the point of discharge.	(Missimer & Maliva 2018, Bleninger & Morelissen 2015, Younos et al. 2005)
4.	Discharge mixed with cooling water	The cooling water used in power plants can be mixed with the concentrate water before its discharge into the sea. The factors to consider for this are the difference in the densities of the cooling water and the concentrates, momentum, and velocity of the water getting discharged.	● The power plant will acquire a stable customer for electricity, as desalination plants require electricity for operation. ● The heavy saline discharge draws the lighter cooling water into the entire depth of ocean water, accelerating its mixing and blending with ambient water in the sea.	● This can only be done if the power plant is present at the site of the RO plant. ● It only works if the power plant cooling water discharge flow is greater than the proposed RO intake flow.	(Younos et al. 2005, Missimer & Maliva 2018, Voutchkov 2011)
5.	Deep well injection	The discharge zone is usually a dolomite transmissivity fractured zone called the boulder zone. The well depth can be from 0.2-1.6 miles below the Earth's surface. Florida is considered a safe location geologically for deep well injection.	● The concentrate stays underground permanently. ● It doesn't harm aquatic life.	● If the geography of the area does not permit the injection, this method cannot be used. ● In the United States, earthquakes have been linked to this. Increased pressure causes the weakening of a pre-existing fault leading to earthquakes. ● When the pore pressure increases more than the effective normal stress across the fault, the movement of concentrate takes place. This may result in the start of an earthquake. ● The overall cost of this system is high because of the monitoring wells, tests for leakage, tests for strength during pressure, etc.	(Chelme-Ayala et al. 2009, Li et al. 2012, Younos et al. 2005, Missimer & Maliva 2018, Leong et al. 2014)

Table cont....

Sl. No.	Method	Properties	Advantages	Disadvantages	References
6.	Diffusers	It involves the use of a diffuser attached at the end of the discharge pipe. Diffusers essentially comprise a series of nozzles that spread the concentrate amongst the seawater to prevent its accumulation at the bottom of the sea. The diffuser and the ambient seawater zone sandwich the mixing zone.	• In a study in Spain, a substantial decrease in the population of polychaetes families was found due to a salinity of 49ppt. • When a diffuser was employed, later on, the polychaete families returned to the area due to salinity reduction. • In Perth Seawater Desalination Plant in Australia, the University of Western Australia analyzed that negligible impacts were present in the surrounding environment due to the discharge.	The dilution zone depends on diffuser design, size and shape of mixing zone, prevailing marine currents, and concentrate salinity.	(Voutchkov 2011, Missimer & Maliva 2018, Christie & Bonnélye 2009)
7.	Reflux	The concentrate is sent back to the feed to increase the water recovery as well as decrease the concentrate volume.	• The normal RO systems operated with a reflux rate of 60%. • Increasing the reflux rates up to 75% was also probably for BWRO systems.	Careful measures must be taken to not give high reflux rates as it increases the salinity beyond tolerable levels deteriorating the membrane life.	(Younos et al. 2005)
8.	Evaporation ponds	This method will be useful for areas with high evaporation rates, low annual rainfall, and cheap land costs. These ponds may be shallow with 25-45cm depths.	It is easy to operate and construct.	Seepage prevention should be managed to prevent underground aquifer contamination, land-intensive.	(Xinyang et al. 2012, Schantz et al. 2018, Chelme Ayala et al. 2009, Leong et al. 2014)
9.	Agriculture	In some areas of Palestine, the olive and jujube tree is irrigated by concentrate from the desalination plant. This is carried out without an assessment of the impact caused on the soil, trees, and land around it.	Minimizes the price of concentrate treatment as it irrigates salt-resistant crops.	Saline aquaculture development limits due to the usage of concentrate therefore reuse for agriculture is highly site-specific.	(Li et al. 2012, Al-Agha & Mortaja 2005, Younos et al. 2005)

ple involved, namely; membrane-based, electricity-based, thermal-based, and chemical-based methods.

Thermals methods are conventional and well-established methods, which are popularly used in countries with high fuel resources and cheaper sources. These methods are however losing popularity due to the harm caused to the environment by the gas emissions along with the large expense of fuel for their functioning. The membrane-based methods are attaining popularity due to their lower energy requirements and better quality of the water recovered. The problem with these may be the life cycle due to scaling and fouling of membranes and therefore would require care to prevent added expenses. Chemical-based methods, although requiring expensive chemicals are also economic, considering the profit gained from the recovered chemicals. However, these have only been utilized as a pretreatment step in reverse osmosis of water. Electricity-based methods are very expensive due to the additional requirement of electricity which again adds to the environmental concerns, even though they are found to be quite efficient.

Apart from these, integrated methods employ two or more methods based solely on the characteristics, volume, and concentrations of the concentrate stream generated. These methods aim for zero liquid discharge to eliminate the aspect of disposal. These newly developed methods have mostly been tested at pilot scales and require further examination of economic aspects before being employed industrially. Although membrane and chemical methods are developing, an optimum solution would be to develop an integrated system involving one or more types of treatment methods suitable for the characteristic feed water and test it at a pilot scale before industrial usage. This would most likely give the best results for a system and can be tuned such that low energy is required but high efficiency is obtained. At the pilot scale, brackish water has been tested but seawater treatment must also be carried out to attain sufficient data.

The common disposal methods used to dispose of the minimized concentrate are discussed where evaporation ponds are found to be effective in only certain areas. They can be used if appropriate geography is found. Methods such as discharge into the sea have been made more efficient using single pipe discharge, trenches, and diffusers. Innovative discharge methods such as agriculture, recycle, reflux, and incineration have also been discussed which could help in the reuse and utilization of the waste stream in a more advantageous way. Despite the efforts in developing integrated methods, increasingly environment-friendly disposal methods need to be developed to ensure that current waste streams are disposed of securely. The establishment of integrated methods at an industrial scale is currently far off as prior pilot testing is compulsory. Until then, a safe disposal method should be established for existing waste streams such as discussed in the paper.

AUTHOR'S PERSPECTIVE

In the authors' perspective, as emphasized by the conclusion, the integrated system can theoretically provide zero liquid discharge. Even in situations where it doesn't attain zero discharge, a simple environment-friendly disposal method such as direct discharge with the help of a diffuser will have a lesser amount of environmental impact. As seen in the integrated methods section, the recovery rates are higher than 90% and this can be improved further with increased efficiency and better research. The minimal amount of concentrate left can be disposed of with the help of environmental measures to direct discharge. The authors highly encourage this system but plenty of further research is needed in this arrangement.

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REFERENCES

Abdul-Wahab and S. A. 2007. Characterization of water discharges from two thermal power/desalination plants in Oman. Environmental Engineering Science, 24(3): 321-337.

Ahmed, M., Arakel, A., Hoey, D., Thumarukudy, M.R., Goosen, M.F.A., Al-Haddabi, M. and Al-Belushi, A. 2003. Feasibility of salt production from inland RO desalination plant rejects brine: A case study. Desalination, 158(1-3): 109-117.

Al-Agha, M.R. and Mortaja, R.S. 2005. Desalination in the Gaza strip: Drinking water supply and environmental impact. Desalination, 173(2): 157-171.

Badruzzaman, M., Oppenheimer, J., Adham, S. and Kumar, M. 2009. Innovative beneficial reuse of reverse osmosis concentrate using bipolar membrane electrodialysis and electrochlorination processes. Journal of Membrane Science, 326(2): 392-399.

Bleninger, T. and Morelissen, R. 2015. Intakes and Outfalls for Seawater Reverse-Osmosis Desalination Facilities. In: Environmental Science and Engineering book series (ESE). Proceedings of Innovation and Environmental Impacts. 397-449.

Bond, R. and Veerapaneni, V. 2011. Zero liquid discharge desalination of brackish water with an innovative form of electrodialysis: Electrodialysis metathesis. In: American Water Works Association Annual Conference and Exposition 2011, Proceedings of ACE 2011, July, 4289-4317.

Cao, F., Liu, Q. and Xiao, H. 2020. Experimental study of a humidification-dehumidification seawater desalination system combined with the chimney. Int. J. Photoenergy, 19: 704.

Chelme-Ayala, P., Smith, D.W. and El-Din, M.G. 2009. Membrane concentrate management options: A comprehensive critical review. Can. J. Civ. Eng., 36(6): 1107-1119.

Chen, Q.B., Ren, H., Tian, Z., Sun, L. and Wang, J. 2019. Conversion and pre-concentration of SWRO reject brine into high solubility liquid salts (HSLS) by using electrodialysis metathesis. Sep. Purif. Technol., 213(38): 587-598.

Christie, S. and Bonnélye, V. 2009. Perth, Australia: Two-Year Feedback on the Operation and Environmental Impact. In: IDA World Congress Dubai, UAE. ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/BrinePanel/Resources/Perth_2YrReport.pdf. Accessed 03/07/2020.

Cohen, Y. and Kirchmann, H. 2004. Increasing the pH of wastewater to high levels with different gases - CO2 stripping. Water Air Soil Pollut., 159(1): 265-275.

Deshmukh, A., Boo, C., Karanikola, V., Lin, S., Straub, A. P., Tong, T., Warsinger, D. M. and Elimelech, M. 2018. Membrane distillation at the water-energy nexus: Limits, opportunities, and challenges. Energy and Environmental Science, 11(5): 1177-1196.

Doornbusch, G.J., Tedesco, M., Post, J.W., Borneman, Z. and Nijmeijer, K. 2019. Experimental investigation of multistage electrodialysis for seawater desalination. Desalination, 464: 105-114.

Du, F., Warsinger, D.M., Urmi, T.I., Thiel, G.P., Kumar, A. and Lienhard, J.H. 2018. Sodium hydroxide production from seawater desalination brine: Process design and energy efficiency. Environ. Sci. Technol., 52(10): 5949-5958.

Fritzmann, C., Löwenberg, J., Wintgens, T. and Melin, T. 2007. State-of-the-art of reverse osmosis desalination. Desalination, 216(1-3): 1-76.

Gabelich, C.J., Williams, M.D., Rahardianto, A., Franklin, J.C. and Cohen, Y. 2007. High-recovery reverse osmosis desalination using intermediate chemical demineralization. J. Membrane Sci., 301(1-2): 131-141.

Gilron, J., Folkman, Y., Savliev, R., Waisman, M. and Kedem, O. 2003. WAIV - Wind aided intensified evaporation for reduction of desalination brine volume. Desalination, 158(1-3): 205-214.

Greenlee, L.F., Lawler, D.F., Freeman, B.D., Marrot, B. and Moulin, P. 2009. Reverse osmosis desalination: Water sources, technology, and today's challenges. Water Res., 43(9): 2317-2348.

Hamieh, B.M. and Beckman, J. R. 2006. Seawater desalination using Dewvaporation technique: theoretical development and design evolution. Desalination, 195(1-3): 1-13.

Hasson, D., Segev, R., Lisitsin, D., Liberman, B. and Semiat, R.. 2011. High recovery brackish water desalination process devoid of precipitation chemicals. Desalination, 283: 80-88.

Heihsel, M., Lenzen, M., Malik, A. and Geschke, A. 2019. The carbon footprint of desalination: An input-output analysis of seawater reverse osmosis desalination in Australia for 2005–2015. Desalination, 454: 71-81.

Heijman, S.G.J., Guo, H., Li, S., van Dijk, J.C. and Wessels, L.P. 2009. Zero liquid discharge: Heading for 99% recovery in nanofiltration and reverse osmosis. Desalination, 236(1-3): 357-362.

Herrero-Gonzalez, M., Admon, N., Dominguez-Ramos, A., Ibañez, R., Wolfson, A. and Irabien, A. 2020. Environmental sustainability assessment of seawater reverse osmosis brine valorization by means of electrodialysis with bipolar membranes. Environ. Sci. Pollut. Res., 27(2): 1256-1266.

Jibril, B.E.Y. and Ibrahim, A.A. 2001. Chemical conversions of salt concentrate from desalination plants. Desalination, 139(1-3): 287–295.

Jones, E., Qadir, M., Van Vliet, M.T.H., Smakhtin, V. and Kang, S.M. 2019. The state of desalination and brine production: A global outlook. Sci. Total Environ., 657: 1343-1356.

Kazner, C., Jamil, S., Phuntsho, S.K., Shon, H., Wintgens, T. and Vigneswaran, S. 2014. Forward osmosis for the treatment of reverse osmosis concentrate from water reclamation: Process performance and fouling control. Water Sci. Technol., 69(12): 2431-2437.

Korngold, E., Aronov, L., Belayev, N. and Kock, K. 2005. Electrodialysis with brine solutions oversaturated with calcium sulfate. Desalination, 172(1): 63-75.

Lawson, M. 1997. Membrane distillation. nanostructured polymer. Membranes, 1: 419-455.

Leong, J., Tan, J., Charrois, J. and Ladewig, B.P. 2014. Review of high recovery concentrate management options. Desal. Water Treat., 52(40-42): 7609-7627.

Lew, C.H., Hu, J.Y., Song, L.F., Lee, L.Y., Ong, S.L., Ng, W.J. and Seah, H. 2005. Development of an integrated membrane process for water reclamation. Water Sci. Technol., 51(6-7): 455-463.

Liyanaarachchi, S., Jegatheesan, V., Shu, L., Shon, H.K., Muthukumaran, S. and Li, C.Q. 2020. Evaluating the feasibility of forwarding osmosis in diluting ro concentrate using pretreatment backwash water. Membranes, 10(3): 65-89.

Martinetti, C.R., Childress, A.E. and Cath, T.Y. 2009. High recovery of concentrated RO brines using forward osmosis and membrane distillation. J. Membrane Sci., 331(1-2): 31-39.

Mauguin, G. and Corsin, P. 2005. Concentrate and other waste disposals from SWRO plants: Characterization and reduction of their environmental impact. Desalination, 182(1-3): 355-364.

McCutcheon, J.R. and Elimelech, M. 2006. Influence of concentrative and dilutive internal concentration polarization on flux behavior in forwarding osmosis. Journal of Membrane Science, 284(1-2): 237-247.

Medeazza, M.G.L. 2005. Direct and socially-induced environmental impacts of desalination. Desalination, 185(1-3): 57-70.

Mericq, J.P., Laborie, S. and Cabassud, C. 2010. Vacuum membrane distillation of seawater reverse osmosis brines. Water Res., 44(18): 5260-5273.

Mickley, M.C. 2006. Membrane concentrate disposal: practices and regulation. Desal. Water Purif. Res. Develop. Program, 123(69): 298.

Missimer, T.M. and Maliva, R.G. 2018. Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. Desalination, 434: 198-215.

Mondal, P., Yadav, B.P. and Siddiqui, N.A. 2020. Removal of lead from drinking water by bioadsorption technique: an eco-friendly approach. Nat. Environ. Poll. Techn., 19(4): 1675-1682.

Morillo, J., Usero, J., Rosado, D., El Bakouri, H., Riaza, A. and Bernaola, F.J. 2014. Comparative study of brine management technologies for desalination plants. Desalination, 336(1): 32-49.

Ng, H.Y., Lee, L.Y., Ong, S.L., Tao, G., Viawanath, B., Kekre, K., Lay, W. and Seah, H. 2008. Treatment of RO brine-towards sustainable water reclamation practice. Water Sci. Technol., 58(4): 931-936.

Ning, R.Y. and Troyer, T. L. 2009. Random reverse osmosis process for zero-liquid discharge. Desalination, 237(1-3): 238-242.

Office, D. 2003. Novel Membrane And Device For Direct Contact Membrane Distillation-Based Desalination Process : Phase Ii New Jersey Institute of Technology. New Jersey Institute of Technology, Newmark. https://www.usbr.gov/research/dwpr/reportpdfs/report096.pdf. Accessed 06/06/2020

Ordóñez, R., Moral, A., Hermosilla, D. and Blanco, A.. 2012. Combining coagulation, softening, and flocculation to dispose of reverse osmosis retentates. J. Ind. Eng. Chem., 18(3): 926-933.

Panagopoulos, A., Haralambous, K.J. and Loizidou, M. 2019. Desalination brine disposal methods and treatment technologies: A review. Sci. Total Environ., 693: 133545.

Pérez-González, A., Urtiaga, A. M., Ibáñez, R. and Ortiz, I. 2012. State of the art and review on the treatment technologies of water reverse osmosis concentrates. Water Res., 46(2): 267-283.

Peters, T., Pintó, D. and Pintó, E. 2007. Improved seawater intake and pre-treatment system based on Neodren technology. Desalination, 203(1-3): 134-140.

Qasim, M., Badrelzaman, M., Darwish, N.N., Darwish, N.A. and Hilal, N. 2019. Reverse osmosis desalination: A state-of-the-art review. Desalination, 459: 59-104.

Qu, D., Wang, J., Wang, L., Hou, D., Luan, Z. and Wang, B. 2009. Integration of accelerated precipitation softening with membrane distillation for high-recovery desalination of primary reverse osmosis concentrate. Sep. Purif. Technol., 67(1): 21-25.

Rautenbach, R. and Linn, T. 1996. High-pressure reverse osmosis and nanofiltration, a "zero discharge" process combination for the treatment of wastewater with severe fouling/scaling potential. Desalination, 105(1-2): 63-70.

Sanza, M.A., Bonnélyea, V. and Cremerb, G. 2007. Fujairah reverse osmosis plant: 2 years of operation. Desalination, 203(1-3): 91-99.

Schantz, A.B., Xiong, B., Dees, E., Moore, D.R., Yang, X. and Kumar, M. 2018. Emerging investigators series: Prospects and challenges for high-pressure reverse osmosis in minimizing concentrated waste streams. Environ. Sci.: Water Res. Technol., 4(7): 894-908.

Segev, R., Hasson, D. and Semiat, R. 2011. Improved high recovery brackish water desalination process based on fluidized bed air stripping. Desalination, 281(1): 75-79.

Shaffer, D.L., Yip, N.Y., Gilron, J. and Elimelech, M. 2012. Seawater desalination for agriculture by integrated forward and reverse osmosis: Improved product water quality for potentially less energy. J. Membr. Sci., 415-416: 1-8.

Shahmansouri, A., Min, J., Jin, L. and Bellona, C. 2015. Feasibility of extracting valuable minerals from desalination concentrate: A comprehensive literature review. J. Clean. Prod., 100: 4-16.

Sorour, M.H., Hani, H.A., Shaalan, H.F. and Al-Bazedi, G.A. 2015. Schemes for salt recovery from seawater and RO brines using chemical precipitation. Desal. Water Treat., 55(9): 2398-2407.

Strathmann, H. 2010. Electrodialysis, a mature technology with a multitude of new applications. Desalination, 264(3): 268-288.

Subramani, A. and Jacangelo, J.G. 2014. Treatment technologies for reverse osmosis concentrate volume minimization: A review. Sep. Purif. Technol., 122: 472-489.

Tran, A.T.K., Zhang, Y., Jullok, N., Meesschaert, B., Pinoy, L. and Van der Bruggen, B. 2012. RO concentrate treatment by a hybrid system consisting of a pellet reactor and electrodialysis. Chem. Eng. Sci., 79: 228-238.

Tularam, G.A. and Ilahee, M. 2007. Environmental concerns of desalinating seawater using reverse osmosis. J. Environ. Monit., 9(8): 805-813.

Turek, M., Was, J. and Dydo, P. 2009. Brackish water desalination in RO-single pass EDR system. Desal. Water Treat., 7(1-3): 263-266.

Voutchkov, N. 2011. Overview of seawater concentrate disposal alternatives. Desalination, 273(1): 205-219.

Xianhui, L., Hasson, D., Semiat, R. and Shemer, H. 2019. Intermediate concentrate demineralization techniques for enhanced brackish water reverse osmosis water recovery: A review. Desalination, 466: 24-35.

Xinyang, L., Zhang, L. and Wang, C. 2012. Review of disposal of concentrate streams from nanofiltration (NF) or reverse osmosis (RO) membrane process. Adv. Mater. Res., 518-523: 3470-3475.

Xu, P., Cath, T.Y., Robertson, A.P., Reinhard, M., Leckie, J.O. and Drewes, J. E. 2013. A critical review of desalination concentrates on management, treatment, and beneficial use. Environ. Eng. Sci., 30(8): 502-514.

Xu, P., Cath, T., Wang, G. and Dolnicar, S. 2009. Critical Assessment of Implementing Desalination Technology. The Drinking Water Inspectorate. http://dwi.defra.gov.uk/research/completed-research/reports/dwi70-2-208exsum.pdf. Accessed 12/07/20

Younos, T. 2005. Environmental issues of desalination. universities council on water resources. J. Contemp. Water Res. Educ., 132: 11-18.

Zhang, S., Wang, K.Y., Chung, T.S., Jean, Y.C. and Chen, H. 2011. Molecular design of the cellulose ester-based forward osmosis membranes for desalination. Chem. Eng. Sci., 66(9): 2008-2018.