ABSTRACT

The exponentially multiplying population of the world demands increasing freshwater resources. The limited 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-

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### 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) |
MEMBRANE 3-4

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°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 CaCO₃ and CaSO₄ cause scaling, which can be reversible by washing and chemical cleaning. | (Lawson 1997, Xian-hui 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⁻³ 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, Marti-enetti et al. 2009, Liyan-aaraachchi et al. 2020). |
| 3.     | Bipolar Membrane Electro dialysis (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). |

Specific energy consumption of 7.7 kWh.m⁻³ was obtained with feed and distillate temperatures of 60°C and 20°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...
In a recent study where seawater desalination was carried out in a two-stage ED plant, energy consumption was found to be around 3.6 kWh.m\(^{-3}\) where the concentration decreased to 11.4 mM, 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) |
havent’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.

8400 m³/day of concentrated brine from Pozo Izquierdo desalination plant with a capacity of 33000m³/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 253.71 kt/y NaOH, 2.82 kt/y hydrogen, and 101.16 kt/y 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

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### Table 5: Integrated methods.

| Sl. No. | Method                  | Properties                                                                                                                                             | Advantages                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Disadvantages                                                                                                                                                                                                                       | References                                |
|--------|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|
| 1.     | WAIV/MCr                | In this method, the BW was first pre-treated 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, Tullarem 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 SiO₂ and boron were reduced by a factor of 10 or more. | Its estimated energy requirements were from 11-19 kW.h.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).

| 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. | (Younos et al. 2005, Chelme-Ayala et al. 2009, Li et al. 2012, Abdul-Wahab 2007, Leong et al. 2014), (Missimer & Maliva 2018) |
| 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. | The apt way of construction of this method is to be tested further and a successful design should be accomplished. | (Missimer & Maliva 2018, Bleninger & Morellissen 2015, Younos et al. 2005) |
| 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. | ● 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, Chelme-Ayala et al. 2009, Li et al. 2012, Abdul-Wahab 2007, Leong et al. 2014), (Missimer & Maliva 2018) |
| 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. | ● This can only be done if the power plant is present at the site of the RO plant. | (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. | ● If the geography of the area does not permit the injection, this method cannot be used. | (Chelme-Ayala et al. 2009, Li et al. 2012, Younos et al. 2005, Missimer & Maliva 2018, Leong et al. 2014) |

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-
| 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) (Li et al. 2012, Al-Agha & Mortaja 2005, Younos et al. 2005) |
| 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. | (Younos et al. 2005) |

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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