ASSESSMENT OF FARMLAND REVERSE OSMOSIS UNITS IN KUWAIT AND STRATEGIES TO MANAGE REJECT BRINE

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ABSTRACT

Irrigated farming practices depend on the availability of an adequate supply of usable water. The limited groundwater resources of Kuwait are mostly brackish to saline in nature. The poor groundwater quality and the lack of adequate freshwater supplies have prompted many local farmers in Kuwait to use RO desalination units to treat the brackish/saline groundwater to acceptable quality levels that meet the irrigation needs of the locally grown crops. Although these RO units produce good quality water for irrigation purposes, they also generate highly saline reject brine that can ultimately have negative environmental effects on the groundwater reserves and the soil fabric. This study assessed the performance of farmland RO units in Al-Abdally agriculture area in Kuwait to augment the water recovery and explore the best practices to manage the brine reject water from these RO units. RO feedwater, product water and reject brine water samples were collected from selected farms in Al-Abdally area. The collected water samples were analyzed for major ions, nutrients and trace metals. The performance of each RO unit was evaluated in terms of water recovery ratio. The results obtained suggest that the average water recovery of the RO desalination technology at Kuwait farmlands stands at ~32.30%. The study recommended several management approaches to enhance the freshwater recovery rate and to reduce the reject brine volume of these units.

Keywords: Groundwater, Brackish, Irrigation, Environment, Major Ions

1 INTRODUCTION

Kuwait is an arid country with limited natural water resources, no surface water, scant rainfall with an average of 115 mm/y and high evaporation rates (Al-Rashed & Aliewi, 2018). Irrigation water for agricultural purposes in Kuwait is primarily obtained from the limited saline to brackish groundwater reserves. Due to the poor groundwater quality and the lack of adequate freshwater supplies, many agricultural farms in Kuwait use RO desalination units to treat the groundwater to acceptable quality levels to irrigate edible and non-edible crops. These units, however, produce highly saline reject brine containing concentrated organic salts, anti-scalants, washing solutions, backwash slurries, and other chemicals (Mohammed et al., 2005). These constituents are expected to negatively impact the quality of the groundwater reserves in the study area. Additionally, the uncontrolled pumping of groundwater is expected to cause further decline in the groundwater levels and soil salinization issues, all of which could jeopardize the attempts of the country to achieve the much-needed partial food security. The main objective of the present study is to evaluate the performance of these RO units and recommend best practices to manage the RO units performance as well as brine reject water.

1.1 Study Area

Located in the northern part of the country, Al-Abdally is one of the main agricultural areas of Kuwait. Groundwater has been excessively extracted from the shallow Kuwait Group Aquifer in this area to irrigate locally grown crops (Fig. 1). The aquifer is recharged by the lateral flow of brackish water and by direct percolation of precipitation during the rainy season. The salinity level in the upper horizon of the aquifer is mostly influenced by rainfall infiltration, and to a lesser extent, by the freshwater flow from the neighboring Al-Raudhatain depression. The groundwater quality in the lower horizon is of brackish quality and becomes more saline with depth (Senay, 1985). Farming activities in Al-Abdally started in the early 1960s of the past century. Since then, the farming areas have been increasing in size and number. The number of farms increased from 260 in 1989 (Al-Sulaimi et al., 1994) to 1012 in 2009, covering an area of over 180 km^2. The expansion of the farms area has been associated with an increase in groundwater extraction for irrigation and other purposes. The groundwater is heavily extracted through pumping wells and hand-dug wells. The heavy extraction of groundwater has significantly depleted this important source of water, causing serious deterioration in the groundwater quality and considerable decline in the groundwater table (Akber et al., 1999). Almost all of the fresh groundwater in this area has been exploited, leaving the brackish to saline groundwater as the only natural source of water.

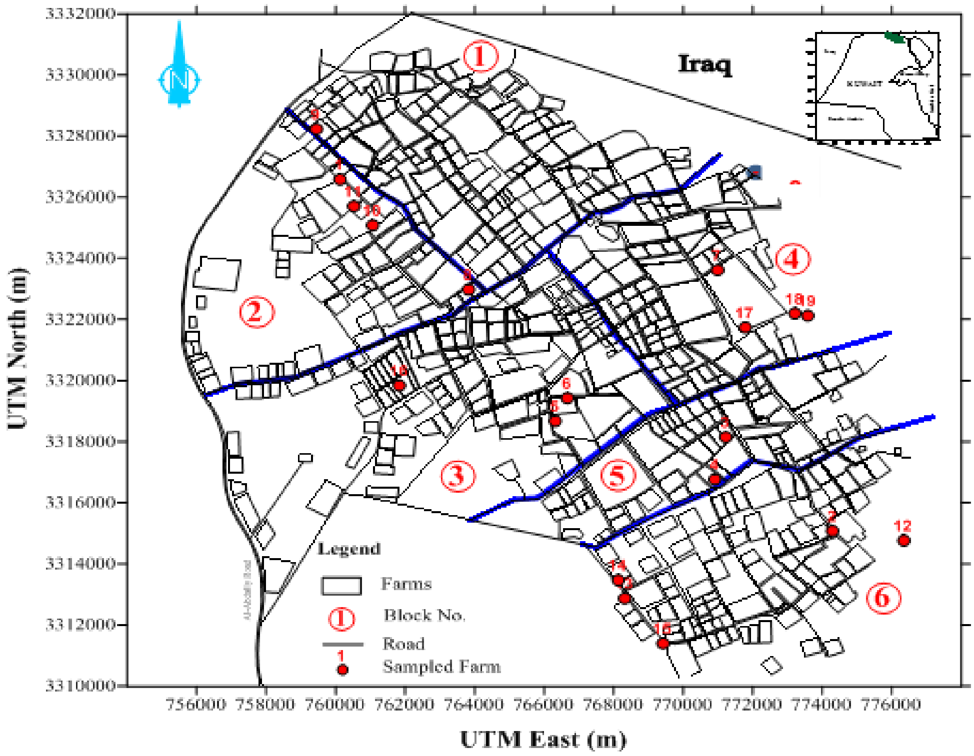

Figure 1. Map showing the location of Al-Abdally area and the farms using RO desalination units

2 METHODOLOGY

To evaluate the performance of the RO desalination units in the study area, water samples were collected from 20 farms that use these units (Fig. 1). The samples were collected from the groundwater that is used as the RO feedwater, effluent (product) water, and reject brine from the RO units. The collected water samples were analyzed for major cations, anions, nutrients, and trace metals. The analyses were carried out at the ISO-certified laboratories of the Water Research Center (WRC) of Kuwait Institute for Scientific Research (KISR) as per the procedures and protocols explained in the 22nd Edition of Standard Methods for the Examination of Water and Wastewater. The total dissolved solids (TDS) of Feed water of the RO units, groundwater, and the TDS of brine reject water of the same RO units were used to calculate the recovery ratio of each RO unit in the study area. The literature review was carried out to augment the water recovery from these RO units and to manage the brine reject water from these RO units was discussed.

3 RESULTS AND DISCUSSION

Reverse osmosis (RO) water has recently gained popularity as a viable source of water that could potentially replace traditionally produced and/or imported freshwater. Therefore, some of Kuwait's agricultural farms have started to use RO desalination units to treat the brackish/saline groundwater to acceptable levels that meet the irrigation needs of the grown crops. Brackish saline groundwater is a better alternative feed water source for RO desalination than saltwater since it has lower salinity, causes less membrane fouling, and costs less to pretreat. The main challenge associated with the RO technology is the negative environmental ramifications of disposing the reject brine that is generated as byproduct from these units. Treatment and/or disposal of the reject brine take several shapes and forms. They also range in complexity and cost, depending on the brine quality and quantity, geographic location of the disposal site and the availability of the receiving site (Panagopoulos et al., 2019).

Analyses results of the quality of groundwater used as feedwater for the RO units in the study area indicated that the average TDS was about 10,592 ppm. The highest and lowest TDS recorded were 15,127 and 6,885 ppm, respectively. The major ions contributing to the TDS were Chloride (Cl^-), Sulphate (SO_4^{2-}), and Sodium (Na^+). On the other hand, the average TDS of the brine discharge stream was 15,642 ppm. Preliminary assessment of the average values of the water quality of the RO units suggested that the minimum water recovery rate was 14.05%, while the maximum rate was 54.81%, with an average rate of ~32.30% (Table 1). The low water recovery rate is believed to have resulted from the large volumes of reject brine of the RO units that stands at ~68%. Therefore, it is recommended that advanced water treatment technologies be used in these units to augment their water recovery, minimize the reject brine discharge and attain a low-energy desalination process as detailed in the next section.

Table 1. Average Recovery Efficiency of the RO Units in Al-Abdally Farms.

Farm No.	TDS (Feed) (mg/L)	TDS (Brine) (mg/L)	Recovery %
GW-1	12937	20050	35.47
GW-2	12995	24400	46.74
GW-3	10370	18100	42.71
GW-4	9855	13800	28.59
GW-5	12975	21900	40.75
GW-6	12952	18150	28.64
GW-8	8270	18300	54.81
GW-9	15127	17600	14.05
GW-10	8408	13800	39.07
GW-11	10640	16150	34.12
GW-12	10940	16150	32.26
GW-13	6975	9350	25.40
GW-14	6885	9300	25.97
GW-15	10065	14900	32.45
GW-16	9525	12000	20.63
GW-17	9128	12600	27.56
GW-18	11647	14500	19.67
GW-19	11310	16600	31.87
GW-20	10665	15900	32.92

Note: Water recovery was calculated using the equation $R = 1-(S_f/S_b)$, Where S_b and S_f are the salinities of the brine feedwater (Bashitialshaaer et al., 2009).

3.1 Advancement of Existing RO plants in Farms

The performance of the existing RO desalination units in Kuwait's farmlands can be enhanced by optimizing their operational parameters, utilizing advanced groundwater pretreatment techniques, using high water recovery RO membranes, and switching to alternative RO desalination based on the feed groundwater quality. Data on the operating parameters of the RO desalination units and the types of membranes used in the study area were collected. As shown in Fig. 2, the RO unit used in one of Al-Abdally farms utilizes brackish water RO membrane manufactured by Toray (code: TM720D-400). In this unit, maintaining the operating pressure at ~210psi (14 bars) yields an average water recovery of 20%. Although the RO module of this unit can withstand a maximum operating pressure of 40 bars, the farm owner maintain the pressure at only 14 bars as recommended by the manufacturer. A study by Ansari et al., (2021) recommended conducting a process optimization scheme after commissioning of the brackish water desalination unit to identify their optimized parameters. A brackish water desalination unit with a capacity of $50m^3$/day was tested for the process optimization under different operating conditions of feed pressure and salinity. The results indicated that the performance of the RO unit was largely dependent on the feed pressure and that the permeate salinity drastically decreased with increased RO pressure. Despite the fact that the membrane used in the desalination unit shown in Fig. 2 has a maximum operating pressure limit of 600psi (40 bars), the low operating pressure of 14 bars may have limited the water recovery to 20%. It is important to note that the percentage of water recovered from these units varies linearly with the operating pressure; hence, this percentage can be increased if the operating pressure was increased just below the maximum operating pressure limit of 40 bars (say 30 bars). In addition, the amount of salt reject of the unit will increase with increasing the operating pressure during the RO process (Ansari et al., 2021), hence the permeate water quality can be improved by doing so in the RO desalination unit shown in Fig. 2.

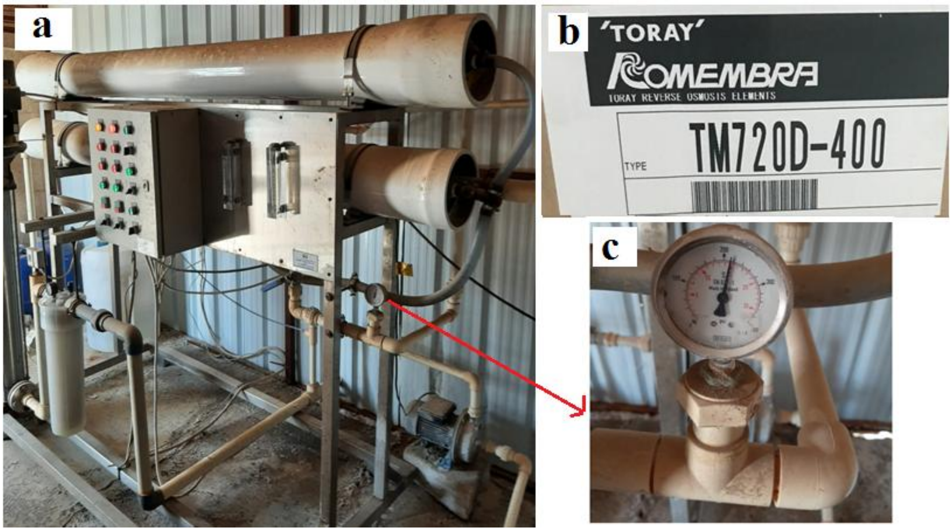

Figure 2. a) RO desalination unit in Al-Abdally farm; b) brackish water RO membrane code of the unit; c) pressure gauge indicating the operating pressure of the RO process

3.1.1 Achieving High Water Recovery Using Advanced RO membranes

The performance of the RO process in terms of recovery, salt rejection, energy consumptions, and eventually the cost of producing freshwater is determined by the RO desalination unit's configuration, type of membranes used, and the operating conditions. Using advanced brackish water RO membranes in the desalination unit can help the farmers achieve a high water recovery rate. Every year, the desalination market introduces a variety of advanced membranes and RO processes aimed at minimizing the specific energy consumption (SEC) to augment the water recovery. Membrane manufacturers focus nowadays on developing highly durable membranes with robust polymeric structure, surface chemistry, bulk texture, morphology, and spacer design. In a recent study, Alsarayreh et al., (2021) conducted a simulation investigation targeting specific brand names of commercially available brackish water RO modules to assess their performance in terms of water recovery, solute rejection, freshwater concentration and most importantly specific energy consumption (SEC). The study was carried out at fixed operating conditions of the RO desalination units, including brackish water salinity, flow rate, and temperature using gPROMS suite software. Of the nineteen most popular commercially available brackish RO membranes tested, Filmtec BW30LE-440 showed the highest performance with the lowest SEC value of 0.7593KW/m^3 and the highest water recovery of 68.99%. The second and third highest membrane brands were TORAY SU 820 and Toray TMG20D-400, respectively with water recovery percentages of 63.04% and 56.4%, respectively. The SEC values of TORAY SU 820 and Toray TMG20D-400 were 0.794 and 0.840 KWh/m^3, respectively.

3.1.2 Pretreatment of RO Desalination Systems

Proper brackish water pretreatment techniques before feeding the groundwater into the RO desalination system helps in achieving a relatively high water recovery rate, reducing SEC, and increasing the life expectancy of the RO membranes due to minimized scaling and fouling. The specific parameters of interest include water hardness, turbidity, presence of organic substances, and water temperature and pH. Chemical pretreatment is the most common technique used in Al-Abdally farms, where an anti-scalants such as Sokalan RO100 is added to the brackish water feed. The use of newly emerging innovative pretreatment techniques could open up avenues for increased water recovery of the RO desalination units in these farms.

The hardness ions of the brackish water can retard the water recovery efficiency of the RO units. Also, the high sulphate concentration in the groundwater can directly affect the net water recovery of these units. Membrane-based nanofiltration (NF) has been recently introduced as an efficient pretreatment technique for the RO feedwater and this technique can have positive ramifications if used in Al-Abdally farms. The NF membrane possesses a top loose separation layer compared to RO membranes and hence it can achieve higher removal of divalent hardness ions from the groundwater feed. Thus, the permeate from the NF system can reduce the net salinity of the feed groundwater for the RO unit and can also reduce the scaling and fouling prospects of the RO membrane modules which ultimately improves the unit's reliability. It should be noted that the NF pretreatment system can be easily retrofitted with the existing RO units in Al-Abdally farms to augment the water recovery rates.

3.1.3 Using "Seawater RO Membranes" in Place of "Brackish RO Membranes"

Switching to RO desalination is the most recent approach adopted by the farmers in Al-Abdally to achieve high water recovery from the desalination systems. In recent years, the elevated salinity levels of the groundwater in Al-Abdally farms has been a major cause for concern since it results in low water recovery rates of the brackish water RO membranes. Therefore, switching from "brackish RO membranes" to "seawater RO membrane" is a plausible approach that could achieve relatively high water recovery rates from the RO desalination units. Farmers who chose to use this approach in Al-Abdally were able to increase the net water recovery of the RO units by as much as 50%.

3.2 Solar-Based Desalination Systems

Renewable energy is expected to be a leading source of electricity on the global scale in the near future. Photovoltaic (PV) cells, wind energy, hydropower, and bioenergy are the main forms of renewable energy that are currently being considered for the generation of electricity. The energy required for brackish water desalination could be obtained from solar energy using PV technology. The main obstacle that stands in the way of using PV-based brackish water RO systems is the high capital cost of renewable energy systems in comparison to conventional energy systems. By adopting advanced techniques in PV cells, this problem could be solved. In recent years, solar energy technology has witnessed marked developments with the use of ultra-efficient solar cells, solar panels that collect energy at night, and the first commercially available perovskite-based photovoltaics. A study by Kaya et al. (2019) estimated that the total energy consumption of PV-based brackish water RO units could reach as low as 0.5–2.5 $kWhm^{-3}$ yielding a levelized cost of water at 0.2–0.4 $USDm^{-3}$. The Kuwait Institute for Scientific Research conducted a small-scale 2 kWp PV power system integrated with brackish water RO desalination study, which showed that the PV system was capable of supplying the necessary load and the RO unit displayed consistent salinity and permeate flow levels without any noticeable interruptions (Alghoul et al., 2016). The PV-BWRO system that was tested over 10 h during the day produced 5.1 m^3 of freshwater at a specific energy of 1.1 kWh/m^3.

Solar energy is regarded as an important source of power, especially for an arid country like Kuwait. Solar energy may also be used to produce water vapor, which is then condensed on a cooler surface to yield desalinated water. The low salinity brackish water desalination is better suited to solar desalination in conjunction with water-efficient greenhouses (Tinaut et al., 1978, Mashalya et al., 2015). As shown in Fig. 3, in this technology, the freshwater was evaporated and then condensed on the top glass to be subsequently collected at the roof eaves. Several studies compared solar collector-based desalination technologies with greenhouse-integrated systems. These studies concluded that solar and photovoltaic (PV) systems are more feasible and reliable with minimal investment and water cost. (Chaibi et al., 2013, Jones et al., 2016).

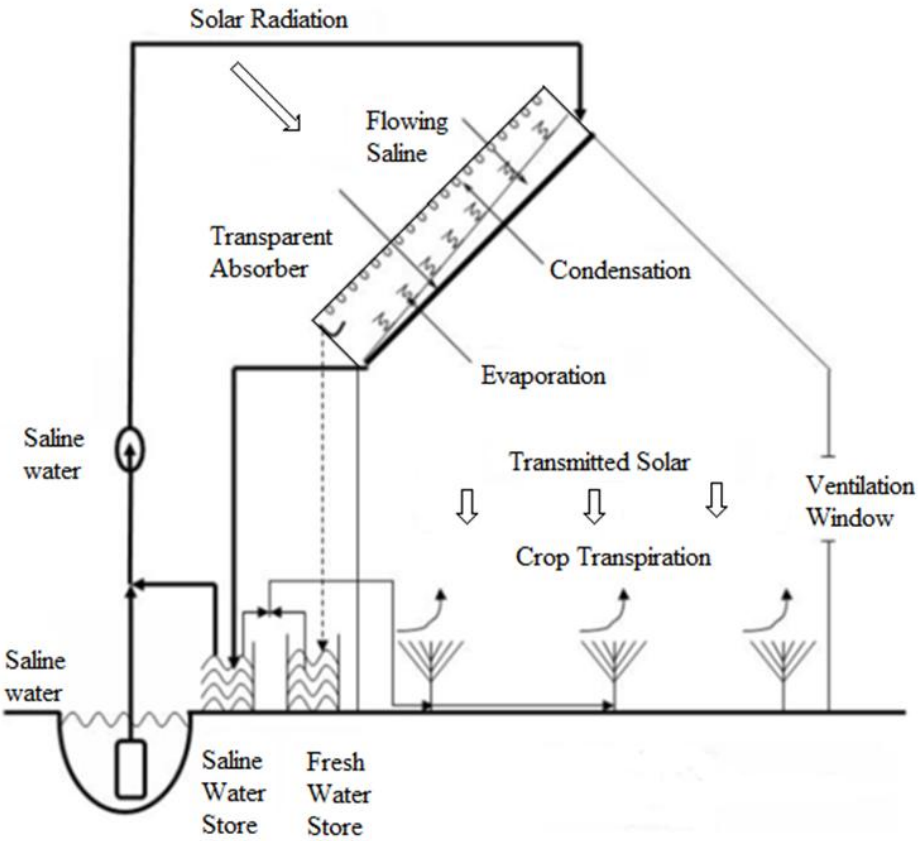

Figure 3. Schematic diagram of a greenhouse roof integrated with thermal-solar driven water desalination

(*Source: Jones M. A., Odeh I., Haddad M., Mohammad A. H. & Quinn J. C. 2016 Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture. Desalination 387, 35–45).*

3.3 Hybrid Desalination Systems

RO integrated with other low-energy desalination technologies has recently emerged as an efficient brackish water desalination technique. In most hybrid systems, a low-cost pretreatment process is integrated with the RO system to lower the operating expenses, increase the life expectancy of the RO membranes, enhance the treatment unit's reliability, augment the water recovery rate, and ultimately achieve savings in cost. An integrated forward osmosis (FO) and RO process can achieve the desired product water quality requirements for agricultural purposes by using less energy than a traditional standalone RO (Jose et al., 2020). A recent study on FO integrated RO technology for brackish water desalination was able to achieve energy savings as high as ~87%, with a much lower energy consumption of 0.9 kWh/m^3 compared to a standalone RO desalination (2.5-4 kWh/m^3) (Rasha et al., 2022*)*. Fig. 4 shows a schematic diagram of a typical FO/RO integrated system. The FO unit serves as a pretreatment stage for the RO unit in the integrated desalination process. The diluted draw solution in the FO stage is regenerated in the RO unit and recycled back into the FO unit. The permeate of RO unit can be utilized for agricultural purposes. This method has the potential to achieve low boron and chloride concentrations without the need for additional post-treatment reverse osmosis runs (Valladares et al., 2014). Few studies used a concentrated fertilizer solution as the draw solution in the standalone FO process so that the diluted fertilizer solution can be directly utilized in agricultural farms (Phuntsho et al., 2013, Alrehaili et al., 2020). However, the lack of control over the final concentration of the diluted draw solution achieved resulted in damages to the crops.

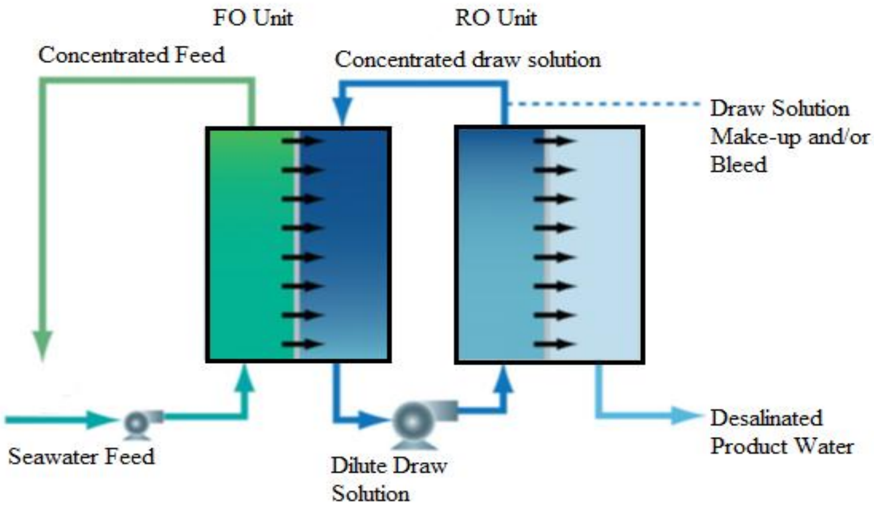

Figure 4. Schematic diagram of an integrated FO-RO desalination process

(Source: Jose, K., Gedeon, F. L., & Cheng, C. (2020). Organic-Inorganic Hybrid Membranes for Agricultural Wastewater Treatment. In (Ed.), Advances in Membrane Technologies. IntechOpen. https://doi.org/10.5772/intechopen.86787).

Another technique involves integrating RO with an efficient low-cost brine posttreatment system. Thus, the post-integrated process extracts more water from the waste brine, resulting in the discharge of the highly saturated brine. Thermally driven membrane process known as membrane distillation (MD) is also emerging as an energy-efficient process to integrate with the RO process. The MD membrane has low fouling tendency than the RO membranes and can be easily integrated with renewable energy sources to minimize the net cost of the RO-MD process. A schematic diagram of an RO-MD integrated system is presented in Fig. 5.

A study by Alrehaili et al., (2020) indicated that the implementation of MD as brine post-treatment can reduce reverse osmosis concentrate by >50%. MD operational cost could be as low as $0.4/m^3 if the process is integrated with the waste heat or other forms of renewable energy.

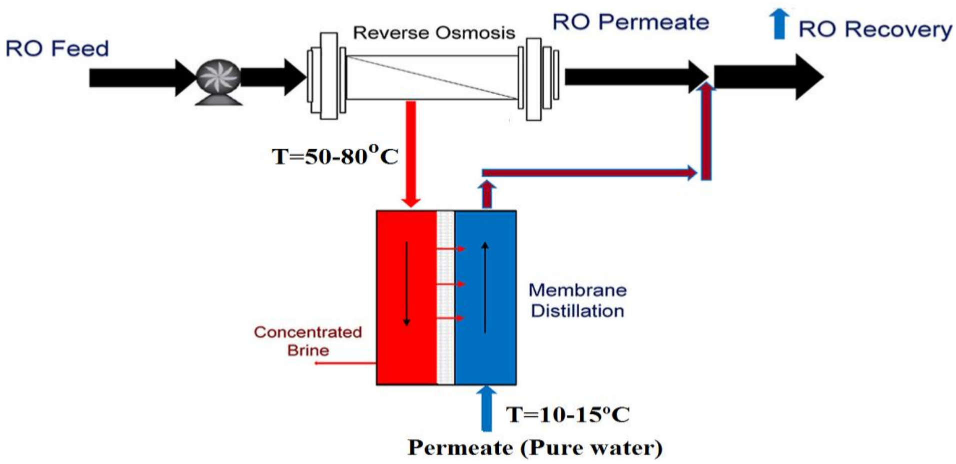

Figure 5. Schematic diagram of an RO integrated MD system to achieve high water recovery from brackish water desalination

(Source: Revised from, Omar Alrehaili, François Perreault, Shahnawaz Sinha, Paul Westerhoff, Increasing net water recovery of reverse osmosis with membrane distillation using natural thermal differentials between brine and co-located water sources: Impacts at large reclamation facilities, Water Research, Volume 184, 2020, 116134).

The performance of a brackish water reverse osmosis (BWRO) desalination system can be enhanced in a number of ways. One typical technique is to rearrange the modules and adjust the amount of membrane elements in each module. Arranging the self-hybridized RO system in series as shown in Fig. 6 is a recent technique to enhance water recovery with drastic reduction in the waste brine discharge in farmlands. The development and implementation of an optimized configuration of this technique has led to a significant reduction in the energy consumption of the RO desalination units.

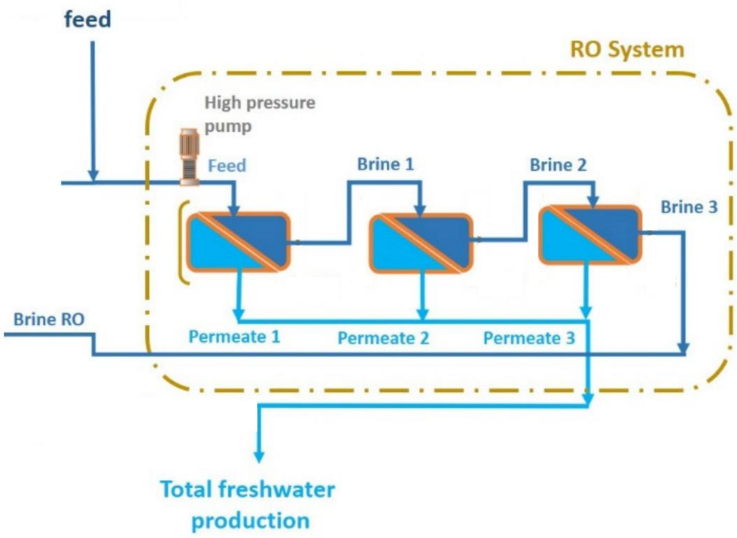

Figure 6. Brackish water reverse osmosis (BWRO) system with an additional membrane module connected to the reject water

(Source: Revised from Filippini, G.; Al-Obaidi, M.A.; Manenti, F.; Mujtaba, I.M. Performance analysis of hybrid system of multi effect distillation and reverse osmosis for seawater desalination via modelling and simulation. Desalination 2018, 448, 21–35).

To increase the system's net water recovery from 45% to 60%, the brine from the first RO stage was supplied to the feed side of the second RO unit and so on. The entire process requires a single high-pressure pump (Fig. 6). Eventually, the brine discharge volumes and the unit size were reduced by 2/3 each (Lin et al., 2017, Lin et al., 2015). The self-hybridized RO configuration is more suitable for brackish water desalination due to its low-pressure and energy consumption requirements (Kim et al., 2019).

3.4 Brine Management Using Zero Liquid Discharge (ZLD) Approach

One of the important issues of treating brackish/saline water using RO desalination units involves managing the reject brine of these units. Disposing the reject brine of RO desalination units onto the surface of farmlands is a common practice in Al-Abdally agricultural area. The high salinity brine can alter the chemical and physical properties of the soil fabric in these farmlands, which, in turn, necessitates using more effective and environment-friendly approaches. Zero liquid discharge (ZLD) is one such approach, where the discharged brine is concentrated using hybrid desalination technologies to almost completely dry salts. The ZLD approach has gained momentum in the past few years and is being adopted by numerous companies, including Veolia Water Technologies, Aquatech, Condorchem Envitech, Samco Technologies Inc., Aquarion Group, etc. (Panagopoulos et al., 2020). The approach can be achieved by hybrid desalination systems consisting of membrane-based and thermal-based desalination technologies. These technologies include reverse osmosis (RO), brine concentrators (BC), brine crystallizers (BCr), forward osmosis (FO), membrane distillations (MD), multi-effect distillations (MED), electrodialysis (ED), ED metathesis, (EDM), nanofiltration (NF), reverse ED (RED), wind-aided intensified evaporation (WAIV) and membrane crystallization (MCr).

Several pilot-scale studies have attempted to demonstrate ‘proof of concept’ of the ZLD process for brackish water desalination. Oren et al., (2010) developed a brackish water RO-Electrodialysis

Reverse (EDR)-WAIV System where a water recovery rate of 97-98% could be achieved (Fig. 7). The initial brackish water feed was concentrated from 0.3% to over 10% TDS super-saturated solution. This solution was further concentrated in a wind powered WAIV unit, bringing the final TDS of the brine to > 30%.

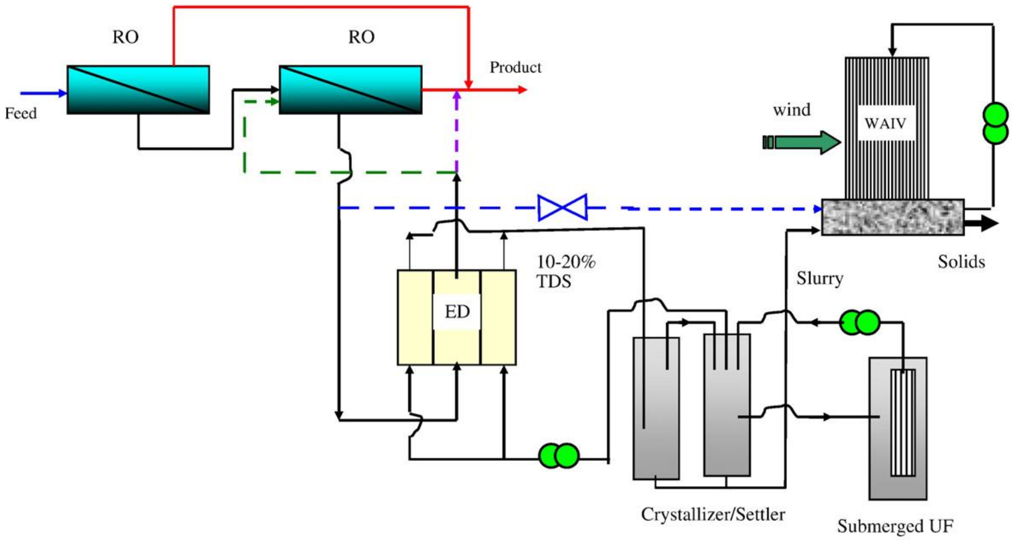

Figure 7. Schematic diagram of the BWRO-EDR-WAIV used for ZLD process

(Source: Modified from Y. Oren, E. Korngold, N. Daltrophe, R. Messalem, Y. Volkman, L. Aronov and J. Gilron, "Pilot studies on high recovery BWRO-EDR for near zero liquid discharge approach," vol. 261, no. 3, p. 321–330, 2010).

This approach demonstrated the potential for recovering mineral byproducts like magnesium salts from the saturated brine solution. The brackish water RO-EDR-WAIV process could compete with conventional standalone RO and other enhanced recovery processes for inland desalination using evaporation ponds. Similarly, Loganathan et al. (2015) developed a ZLD technique using an EDR-RO desalination system coupled with a low-temperature evaporator/crystallizer with the potential to achieve a 77% water recovery rate. The EDR-RO desalination system was successful in obtaining brine concentrations of up to 125,000 mg/L, while using an evaporator-crystallizer helped in obtaining a final brine conductivity of more than 250 mS/cm. Lin et al., (2017) studied brackish water desalination process approaching ZLD level using MD technology. The study used different anti-scalants to suppress the membrane scaling in order to reduce its effect on the overall process efficiency. Several other hybrid system ZLD techniques such as Membrane Distillation and Reverse Electrodialysis (Ramato et al., 2015) are under laboratory or pilot-scale investigations. Though ZLD approach addresses most of the challenges of brackish water desalination, the net energy consumption of the overall hybrid process is still high. Most of the studies reported are at pilot-scale level and commercial-scale ZLD units could be feasible in the near future, if the hybrid desalination process is integrated with a renewable energy source.

CONCLUSIONS

Increased dependence on RO desalination units in Kuwait's agricultural sector necessitates adopting advanced treatment methods to deal with and manage the generated brine from these units to reduce their negative environmental impacts. Reducing the volume of the reject brine of the RO desalination units is believed to be a suitable strategy to maximize the freshwater recovery rate. This can be achieved by optimizing the operating parameters of these units, using seawater RO membranes in place of brackish water membranes, using suitable pretreatment techniques and regularly maintaining the RO units. Hybrid desalination and zero liquid discharge (ZLD) systems can also offer adequate management options of the reject brine of these units.

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ABBREVIATIONS

BWRO Brackish Water Reverse Osmosis
ED Electro Dialysis
FO Forward Osmosis
MD Membrane Distillation
RO Reverse Osmosis
SEC Specific Energy Consumption
TDS Total dissolved solids
ZLD Zero Liquid Discharge

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