Membrane Desalination and Water Re-use for Agriculture: State of the Art and Future Outlook

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Abstract

Membrane-based desalination technologies for agricultural applications are widely applied in many countries around the world. Sustainable and cost-effective desalination technologies, such as reverse osmosis (RO), membrane distillation, forward osmosis, membrane bioreactor, and electrodialysis, are available to provide treated water, but the pure water product does not contain the required level of nutrients to supply agricultural fields. This can be overcome by the use of blended water to meet the required quality of irrigation water for crop production, which is expensive in areas lacking in freshwater resources. The adoption of a hybrid system offers many advantages, such as generating drinking water and water enriched with nutrient at low cost and energy consumption if natural power is used. This review focusses on summarizing the current and recent trends in membrane desalination processes used for agricultural purposes. The challenges being faced with desalinating seawater/brackish water and wastewater are discussed. A specific focus was placed on the viability of hybrid desalination processes and other advanced recovery systems to obtain valuable irrigation water. A comparison between various membrane desalination technologies in terms of treatment efficiency and resource recovery potential is discussed. Lastly, concluding remarks and research opportunities of membrane technologies are analyzed. We concluded that the ED process can be utilized to minimize the energy requirements of other membrane technologies. The MD coupled with ED system can also be utilized to generate high quality irrigation water at low energy requirement. The FO-ED hybrid system exhibited excellent performance and very low energy consumption as compared to other hybrid systems.

Key words: Water desalination, membrane technology, hybrid system, agriculture, crop production

Highlights

1-Membrane desalination technologies play a major role in satisfying increasing demand on irrigation water for fertigation.

2- Seawater and wastewater are the most common inlet source for treatment processes to provide valuable nutrient water.

3- Desalinated water integrated desalination processes can become a continuous water source for crop growth.

4- Low energy desalination process for fertigation by electrodialysis combined with forward osmosis hybrid process.

5- Efforts should be increased to decrease cost and energy consumption by using renewable power resources.

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1. Introduction

The global demand for drinking water, food security concerns, and climate change effects on farming have motivated scientific communities to search for alternative resource management strategies [1, 2]. Since petroleum resources are being reduced, most countries have looked for agriculturally produced materials to be used for manufacturing and trade, which imposes further demand on crops [3]. The consumption of plant waste is a promising resource for energy extraction and conversion to electricity [3]. The existing demands on these agricultural products are expected to increase in the future, imposing challenges to developing nations. It has become necessary to explore additional water resources to increase agricultural materials production and support ever-growing requirements [4, 5]. There is an intensive use for irrigated water estimated at 70% of total usage, followed by industrial utilization, around 21%, and domestic use around 9% [1].

There has been a renewed interest in the treatment of wastewater to irrigate crops in greenhouses. Membrane based desalination processes used to treat wastewater are reverse osmosis (RO) [6, 7], nanofiltration (NF) [8], membrane bioreactor [9, 10], membrane distillation (MD) [11], and electrodialysis [12]. For example, to remove nitrogen from wastewater, high energy input is required around 45 MJ per kg nitrogen to extract nitrogen gas [11]. NF membranes can be used to separate various nutrients such as ammonium, phosphate, and potassium from sewage sludge [8], achieving a high rejection rate of these nutrients at low hydraulic pressure. However, the wastewater feed solution is composed of various chemical species which may result in fouling and membrane deterioration. Fouling is created due to the adherence of solutes and particulates on the membrane surface leading to cake layer formation and pore clogging [13, 14]. Another study reported that there were limited wastewater resources and that its price is high in many developing countries. Thus, researchers shifted to desalinate natural groundwater or brackish water for crop growth due to availability and low salinity ($5 \leq S \leq 5$ g/kg) [15].

To maximize the agricultural output and minimize impacts on natural water resources, many countries are beginning to utilize irrigated water produced from different saline water sources to cope with high food production demands [16]. Some potential solutions are to develop low cost and climate-independent water resources for fertigation, which are related to desalination technologies. Efficient desalination technologies for irrigated agriculture depends on water desalination and wastewater reclamation [17]. Many countries have started using desalinated water for agricultural purposes to meet their water needs. For instance, Spain consumed 22% used of desalinated water for fertigation from a total desalination capacity of 1.4 million m^3/day [16], whilst Kuwait has a desalination capacity higher than 1 million m^3/day and 13% for fertigation. Still, only 0.5% of desalinated water overall is currently being used for fertigation. Italy and Bahrain implemented a desalination capacity of 64,700 m^3/day and 620,000 m^3/day while they used only a small proportion of desalinated water of 1.5% and 0.4% for agriculture. The USA and Qatar used only 1.3% and 0.1% of desalinated water for agricultural purposes.

Brackish water desalinated via RO is the most common practice due to high purity product water [18, 19]. Additionally, brackish water can be desalinated by other membrane-based desalination processes such as NF [20, 21], ion exchange resins [20], forward osmosis system (FO) [22], closed-circuit reverse osmosis (CCRO) [23], and electrodialysis reversal (EDR) system [24]. Monovalent-selective electrodialysis reversal (MS-EDR) has been employed to concentrate sodium chloride from seawater [15]. Among these desalination technologies, RO is the leading system for seawater desalination due to minimum energy expenditure relative to other desalination processes [25, 26]. When the seawater was replaced by brackish water in a BWRO plant at Almeria Cuevas de Almanzora, the product water was used for fertigation [18]. The most important advantage of this process was the generation of a variety of water qualities, which could be used as irrigation water and for golf land irrigation. The potable water can also be obtained by mixing the permeate stream with raw water. Spain and Australia depend on SWRO desalination technology for seawater desalination to produce irrigation water for agricultural uses. Australia pioneered the use of reverse osmosis capable sub-surface drip irrigation (ROSDI) for fertigation [17]. This process does not require high hydraulic pressure because it operates based on tension on the soil side to draw water into the system. An acceptable amount of water-rich nutrients of around 0.25 and 1.5 $L/h.m^2$ and salt rejection of around 50% were achievable. Some hurdles associated with the RO process hampered its utilization for agricultural aspects. For instance, the desalinated water does not contain an acceptable amount of nutrients or boron or chloride for irrigation water, a high quantity of brine is discharged to the sea, harmful gases may be released into the air, the excess sodium affected the soil and productivity and energy consumption and cost are high [18]. Moreover, recovery strategies have been suggested to concentrate nutrients and ensure suitable quality of irrigation water. Some of these methods are adsorbents such as carbon-based adsorbents [27] and sepiolite [28] along with membrane technologies such as FO [29] and RO processes [30].

This paper is a timely critical review of recent advances in membrane-based desalination technologies for producing agricultural irrigation from saline water and wastewater. It addresses the main limitations associated with membrane-based treatment processes development. It discusses the performance of advanced membrane technologies during seawater/brackish water desalination and wastewater reclamation in terms of treatment efficiency and resource recovery potential. It also highlights the potentiality of the hybrid desalination process and other complementary processes for recovering nutrients. Finally, conclusions and remaining drawbacks that need to be further investigated are summarized.

2. Applicability of membrane desalination technologies for fertigation

Membrane technology is the leading process for treating seawater and wastewater, providing sustainable development and targeted process efficiency [17]. Many countries over the world have begun to use membrane technology to produce water-rich nutrients for agriculture. Nutrient concentrations by membrane technology is a powerful treatment option for combined production of crops and potable water [20]. One of the advantages of membrane desalination in agriculture is the generation of additional water resources, known as irrigation water. During the late 1950s to the 1980s, asymmetric cellulose acetate membrane was the first membrane used for the RO process [31]. After that, the development of RO membranes continued to enhance the performance of membrane desalination processes. Although the high cost of the RO process remains the major hurdle to the application of RO to seawater desalination and reuse, RO membranes are the most technically viable membranes for producing irrigation water [32]. For agricultural fields, RO membranes or membranes in the hybrid system can generate a high quantity of drinking water and water suitable for irrigated agriculture at relatively low cost and environmental effects [17]. RO membrane can also be used to desalinate brackish water, with the cost estimated to be a third that of seawater desalination [20]. Several industrial seawater and brackish water plants were developed by TEDAGUA to supply irrigation water for agriculture [33]. In 1987, RO was operated in the seawater desalination plant located in Gran Canaria [33]. The salinity of the seawater feed was about 34,000 mg/L. The production capacity of irrigation water was 6,900 m^3 /d, and a further increase in the capacity by 500 m^3 /d was expected in the future. The water permeate had an acceptable level of salinity of about 200 mg/L.

Electro-dialysis reversal (EDR) technology was installed in Gran Canaria to produce pure water for agricultural fields [33]. This process is able to desalinate brackish water with a low concentration of around 3,000 mg/L. The predicted energy consumption to treat this brackish water was around 1–2 kWh/m^3 [33].

Membrane distillation is currently being researched to generate irrigation water from seawater. It has been found that the desalinated water recovery was high, resulting in a decrease in the discharge cost per unit of water distillate [20].

The membrane bioreactor (MBR) is a widespread technology used to treat municipal wastewater for agricultural purposes [10]. MBR consists of biological processes coupled with membrane filtration to remove organic and inorganic pollutants and microorganisms from wastewater [9, 34]. This system can be used in countries that rely on agriculture to grow their economy and can be implemented in rural areas or modern cities. There are many industrial plants around the world able to reclaim wastewater for agricultural fields. An example is an MBR employed to purify wastewater for irrigating vegetables in Chania on the island of Crete [10]. The cost of the MBR system was estimated to be a few cents/m^3 to 1 or 2 USD /m^3 when treating wastewater to produce irrigation water for food production. This value is assumed to increase based on the water-scarcity factors. The low price of purified water relative to the traditional freshwater would encourage farmers on the island to utilize the purified water and improve water resource management. Mixing MBR and RO effluents could achieve the required quality of irrigation water including acceptable amount of salts [35]. In this way, the reclaimed wastewater has negligible impact on the soil, and there is no need to dispose of the reclaimed wastewater. To that end, membrane technologies are regarded as key elements of providing the feasibility of extracting irrigation water with appropriate salinity for food productivity by either using desalinated water or reclaimed wastewater.

3. Water quality required for agricultural irrigation

Water quality plays an important role in determining the suitability of a water supply to be used for agricultural applications. Nowadays, new resources with lower quality are being used for irrigation projects because many good quality water supplies have been intensively used [36]. There are some restrictions for using wastewater effluent directly for vegetation, such as negative impacts on the physio-chemical properties of the soil, increasing microbial activity in the soil, aggravation of crop production and yield, and contaminating groundwater with undesired elements [37]. The most significant characteristics in the treated water used as irrigation water are salinity, sodium content, trace elements, excess chloride, and nutrients [38]. High salinity in the irrigation water influence plant health and productivity along with deterioration of the soil structure and properties [38].

The product water from the desalination process includes total dissolved solids (TDS) with very low concentrations of less than 20 mg/L, which can be used as drinking water [16]. If the concentration of the inlet fed to the desalination unit is low, the final volume of the permeate could be maximized by blending the permeate with the inlet water, thereby decreasing the unit cost of irrigation water [16].

In general, the permeate water has a minimum quantity of calcium and magnesium and is slightly acidic [16]. Therefore, it should be re-mineralized and balanced to reach the required quality for irrigation water. The needed mineral content for agricultural applications is estimated at 0.75 g/L.

The essential nutrients for plant growth are N, P, K, Ca, and S [39]. Amongst these elements, Nitrogen (N)/ Phosphorus (P)/ Potassium (K) are the most significant nutrients for mineral or artificial fertilizer. Therefore, the water-soluble fertilizer to be added should contain a suitable quantity of N/P/K nutrients. The concentration of these nutrients in the fertilizer solution depends on the type of crops, cropping seasons, and soil nutrient amounts [40]. The suggested concentration for N / K/ P in the irrigation water is ranged from 50 to 200 mg/L, 15 and 250 mg/L, and up to 1mg/L [37, 41]. According to the United Nations Food and Agricultural Organization (FAO), the recommended concentration of calcium and magnesium in irrigation water is around 400 mg/L and 61 mg/L, respectively [42]. Besides, the acceptable phosphorus concentration in the product water from a wastewater plant should be as low as 1.0 mg/L in most countries in which polyphosphates and organic phosphate species derived from orthophosphate compounds are the wastewater [41]. The acceptable level of Mg^{+2} is from 48 to 65 mg/L, while it is around 321 mg/L for $SO^{-2}{}_4$ constituents [37].

The main physicochemical factors for assessing the quality of effluent wastewater are chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammonia-nitrogen, total organic carbon (TOC), and total suspended solids (TSS) [43]. It is, however, impossible to use these physicochemical factors in determining the acute toxicity and genotoxic hazards to aquatic organisms present in the effluent. Aquatic organisms are an effective way to assess the toxic impact of the treated water and evaluate the detoxification efficiencies of many systems [44]. Other parameters, such as boron concentration or Sodium Adsorption Ratio (SAR), should be taken into account. The concentration of boron in seawater has been recorded between 4.5 and 6.0 mg/L, whilst according to the World Health Organization, the acceptable level of boron in irrigation water is below 0.50 mg/L [32]. The potassium adsorption ratio (PAR) is also used determine water quality. It demonstrates the adverse impact of potassium on soil permeability properties[42]. The water infiltration issue is known as relative to SAR (Sodium Adsorption Ratio) with reference to electrical conductivity. Sodium toxicity can be measured based on RSC (residual sodium carbonate), SSP (soluble sodium percentage), and ESP (exchangeable sodium percentage) [38].

Blending of the treated water with freshwater can minimize the concentration of toxic compounds and make it reusable for fertigation. This method is successful in reducing the sodium toxicity because its adsorption in the soil depends on the proportion of monovalent (Na^+) and divalent (Ca^{+2}) cations [38]. When diluting the treated water, the soil would prefer to adsorb the divalent salts like calcium and magnesium ions more than the monovalent sodium.

4. Challenges in membrane technology development

The most important challenges in the membrane desalination and wastewater treatment industries involve the characteristics of the feed solution, the standard quality of the treated water, materials development, process advancement, brine discharge, energy consumption, operational and capital costs of facilities and instruments [11, 45].

The desalinated water should possess low salinity, meeting the quality standard, and the required nutrient levels for irrigation water. This is because the desalinated water or treated wastewater containing a high concentration of total dissolved solids (TDS) like Sodium (Na^+) and Chlorine (Cl^-) can deteriorate soil properties, inhibit crop productivity and affect negatively the environment [45, 46]. On the other hand, the desalinated water may miss some important mineral nutrients for plant growth, and hence adding complementary minerals to the desalinated water is essential [26]. Other very important problems are the product water quality accuracy, the difference in nutrient requirements for targeted crops, and demand. In light of this, recovery methods for concentrating nutrients should be utilized to ensure a product of acceptable quality for agricultural fields. Another drawback is the emission of CO_2 into the atmosphere, which estimated to be 0.9 kg CO_2 per cubic liter of purified wastewater [11].

Membrane technology based on electricity and thermal energy, such as electrodialysis/electrodialysis reversal, reverse osmosis, and membrane distillation, are energy-intensive processes and very expensive [46-48]. The thermal desalination process is not cost-effective, and hence it is rarely used for brackish water desalination. The cost of ion exchange membranes in the voltage-driven membrane process is higher than for RO [49]. In parallel, the salt separation efficiency is low when using seawater as the feed solution compared to the RO process. Therefore, some developing countries cannot afford these desalination technologies for irrigated agriculture. Additional issues are the high electrical resistance of the membrane causes a reduction in the non-Ohmic voltage [49]. This occurs when voltages move across the membrane, thereby influencing the energy expenditure of the system. This electrical resistance is strongly correlated with the solution concentration. The membrane perm-selectivity can be reduced due to severe concentration polarization phenomena arising from the solute leakage. Since this process is operated using two electrodes, a large size and quantity of the electrodes are required for industrial plants [50]. This increases the operating and investment costs, and therefore, it is difficult to be commercially acceptable for water desalination.

The MD process is not practical for brackish water due to high energy consumption [20]. However, it might be effective for desalinating high salinity brackish water (up to 15,000 mg/L) or seawater. In comparison, anaerobic membrane bioreactors (An-MBRs) combined with low-pressure microfiltration (MF) or ultrafiltration (UF) has shown low rejection towards dissolved organic carbon [51]. The treated water has quality like that for effluent generated through aerobic treatment [52]. However, membrane fouling causes high energy demands and therefore this technology is not suitable for energy recovery.

Pressure driven membrane processes, especially RO, suffer from fouling due to complex feed streams (such as municipal wastewater) impacting the long-term performance of the membrane and the management of brine discharge [48, 53]. This can cause the accumulation of various constitutents on the membrane surface. This leads to low water permeation and poor water quality, thereby increasing energy input. However, if the feed pressure is raised to ensure consistency of the water flux, this imposes an additional energy requirement [38, 53]. It has been suggested that the energy expenditure and overall cost could be reduced if the membrane pore size is increased. Therefore, when operating a brackish water feed with a salinity of 15,000 mg/L, the estimated total cost to generate irrigation water approached 0.13 $\$/m^3$ along with an investment cost of $17.54 million.

On the other hand, the salt rejection was decreased from 97% to 88% resulting in irrigation water of unacceptable quality. Even though the RO membrane achieves good quality desalination water when utilizing seawater/brackish water membranes, some of the removed mineral nutrients (calcium, magnesium and sulfate) are necessary for plant growth [17]. As boron, which can retard plant growth, can transmit easily through the RO membrane, a second RO cycle in many industrial plants is needed. It has been highlighted that boron concentration can be further reduced from 1.5 to 0.5 mg/L in the nutrient water through multistage RO, electrodialysis and adsorption-membrane filtration hybrid systems [54]. The Ashkelon and Palmahim seawater desalination plants in Israel produced high quality desalinated water with boron concentration lower than 0.4 mg/L [55]. Municipal wastewater includes a high quantity of colloidal particles, suspended solids and dissolved organics, which induces membrane fouling [38]. In this respect, a pre-treatment process is needed to decrease the concentration of these species. Another significant concern is brine disposal which contains high concentration of different salt species. This causes adverse impacts on the aquatic ecosystem.

Osmotic gradient processes, such as FO, have potential for agricultural irrigation. Although the individual FO process requires lower energy input and less influenced by fouling, it has some disadvantages, like the separation of the draw solution and loss of nutrients [56, 57]. To separate the draw solution effectively, a post-treatment strategy is required, which increases energy consumption. The solute leakage allows accumulation of solute in the feed solution leading to reduced effective osmotic pressure gradient and fouling/scaling on the membrane surface, which reduces the productivity and lifetime of the membrane [58-60]. When the draw solution is being diluted through the support layer as a result of the convective flow of water across the selective layer, a severe dilutive internal concentration polarization occurs [61, 62]. Thus, there is a drop in the osmotic pressure gradient leading to low water permeation. If using fertilizer as draw solute, the draw solution will require further dilution to meet the quality standard of irrigation water [29, 56, 63].

5. Water nutrient production from seawater/brackish water

5.1 Pressure-driven membrane process

5.1.1 RO process

Over the years, pressure-driven membranes, such as RO and NF membranes, have been used for desalinating saline water for agricultural purposes and drinking water consumption [19]. The common characteristics of pressure driven membrane applications is outlined in Table.1.

RO has the greatest total capacity worldwide relative to other membrane technologies. RO membranes have a high rejection rate towards salt, high water permeation, and good tolerance at very high hydraulic pressure. Improvement in membrane materials and fabrication of membrane modules with a large surface area per unit volume has leaded to a reduced price of membrane and water production cost [64]. In parallel, the recovery ratio was improved from 35% in the 1990s to around 45% now, and it can be further increased to 60% when using the second pass RO process. RO membrane can be utilized to desalinate seawater with salinity in the range of 2.5 to 35 g/L for agricultural irrigation and drinking water extraction at a cost of US$0.50/m^3 to US$1.00/m^3 [65]. Seawater desalination plants in Israel, such as Sorek, Hadera, and Ashkelon, were the top seawater desalination globally due to high water capacity of around 540,000, 456,000, and 392,000 m^3/day respectively [17]. Another plant located in Australia, operated through a two-pass reverse osmosis membrane system, provided 17% of potable water to 1.6 million users in Perth [20, 66]. The seawater plant required energy input between 4 and 12 kWh/m^3. All these factors contribute to high operating costs as the energy is responsible for 30–50% of the operation cost. The Australian RO plant produced a high amount of concentrated brine, as much as 55–60% of the total feed stream [20].

Owing to the above restrictions, brackish water with lower salinity has replaced seawater to obtain irrigation water. The first commercialized brackish water desalination plant was first operated in 1979 [65]. The total water capacity was about 20–21 m^3/h when using water with salinity in the range of 4–15 g/L. Earlier, PA TFC RO membranes were used in six brackish water desalination plants, and the performance of this membrane was investigated in terms of permeate water quality [67]. All plants achieved similar productivity with little variation in the water capacity and cost per cubic meter of treated water. The water recovery was adjusted at 83% for plant-D and at 70% for plant B. Excellent performance of the RO membrane was observed, providing water permeate at the required standard for irrigation water. The results revealed that the membrane was effective in removing nitrate reaching 50 mg/l in the purified water, and the fluoride concentration was at an acceptable level according to WHO and PS standards. The chloride, sulfate, sodium, magnesium and potassium concentrations in the purified water of all plants met the quality standard for potable water. Production capacity approached 640 m^3/day upon raising the flow rate to 80 m^3/h.

Garcia et al. [68] used Polyamide Thin-Film Composite (PA TFC) (BW30-400 Filmtec™) membrane to treat groundwater well brackish water with a salinity of about 3.1 and 7.8 g/L to generate irrigation water. The design of the RO system is provided in Fig.1. The membrane generated product water with acceptable salinity for fertigation. It was found that membrane scaling and frequent chemical cleaning affected the water recovery and energy consumption. The fractional water recovery decreased to 0.6 due to scaling. Another problem was an increase in the feed pressure by 980.67 kPa after 40,000 h running time. The specific energy consumption was relatively high at around 1.4 and 1.7 kWh/m^3 after 5 years, along with the specific cost of water.

Ismail et al.[69] investigate RO to desalinate brackish water (groundwater) with various salinities (1,000-3,000 mg/L). Desalinated water from feed with a salinity of 500 mg/L contained a sufficient concentration of nutrients for crop production. Therefore, the RO permeate caused an increase of 56% and 73% in crop yield. The yield and profit of crops were maximum when using the treated water with this feed.

5.1.2 NF process

In comparison with RO membranes, the NF membrane can be operated under lower hydraulic pressure leading to lower energy consumption and cost [70]. Birnhack et al. [71] utilized TFC NF membranes in a pilot-scale seawater desalination unit to concentrate Mg^{+2} ions while reducing the addition of unnecessary seawater ions such as Cl$^-$, Na$^+$, B, Br$^-$ in the treated water for crop production. The principle of this NF desalination process involved circulating seawater across the NF membrane, while Mg^{+2}-rich brine was added into the treated water. It was observed that the highest salt rejection rate approached 97% when raising the hydraulic pressure to 28 bar at a recovery ratio of 40%. However, the rejection rate declined to 90%, 94%, 95% when increasing the recovery ratio at varying hydraulic pressure of 10, 18, 28 bar respectively. The concentration ratio between Mg^{+2}: Na^{+1} was decreased upon increasing the recovery ratio, but there was a negligible change at high hydraulic pressure.

Ghermandi et al. [70] investigated the viability of the NF membrane in purifying brackish groundwater with salinity of 1,577 mg/L for agricultural farms. A comparison between NF and RO membranes was also carried out. According to simulation data, the NF permeate had higher concentrations of the required nutrients such as calcium (14.1 mg/L), magnesium (7.9 mg/L), and sulfate (33.5) than RO permeate, which were within the quality standard for irrigation water. It was suggested that when using the NF membrane, lower brackish water volume by 34% was needed compared to the RO membrane. However, using NF permeate was assumed to increase the biomass activity by 18% while the RO permeate had an insignificant impact.

Lew et al. [72] examined the performance of various membranes, such as NF with 86% rejection and high flux, NF membrane with 91% rejection and medium flux, RO membrane with 99.7% rejection and high flux, RO membrane with 99.2 % rejection and very high flux. An analytic hierarchy process (AHP) model and the multi-dimension scaling (MDS) models were used to find out the optimal design of the membrane process for brackish water desalination. The theoretical outcomes indicated that the NF membrane with low rejection and high flux was likely to have the best performance and produce irrigation water with sufficient nutrients concentration. This water product showed a low sodium absorption ratio (SAR). Both the NF membranes consumed low energy of 0.26 and 0.20 kWh/m^3, respectively, and hence low investment cost.

NF membranes were also used in a desalination plant in Saudi Arabia because they are less prone to fouling relative to PA TFC RO membranes [65, 73]. It was reported that the salinity of the desalinated water decreased from 45,460 to 28,260 mg/L, and the chloride concentration was lowered from 21,587 to 16,438 mg/L. The NF membrane achieved maximum rejection rate of sulfate (SO^{-2}_4) of up to 99% while it was lowered to 98%, 92%, and 44% for magnesium (Mg^{+2}), calcium (Ca^{+2}), and bicarbonate (HCO^{-}_3), respectively. The hardness of the desalinated water was lowered from 7,500 to 220 mg/L. The desalinated water contained less than 2 mg/L of SO^{-2}_4, 29 mg/L of Mg^{+2}, 40 mg/L of Ca^{+2}, and 17 mg/L of HCO^{-}_3, which is lower than the recommended concentration level for drinking water.

Although the NF membrane generates high water permeation under low hydraulic pressure, the membrane can separate divalent ions only, while allowing the permeation of monovalent ions. Thus, the irrigation water ends up with a low concentration of required nutrients such as SO^{-2}_4 and Mg^{+2} and a high concentration of unwanted monovalent ions such as Na^+ and Cl^-.

5.1.3 FO process

Fertilizer drawn FO processes for fertigation has been given much attention. A diverse range of commercial fertilizers can be utilized as a draw solution, which when diluted can be used in irrigation water [74]. Because the high amount of nutrients in the diluted draw exceeds the quality standard of irrigation water it requires further dilution. This FDFO process needs a perfect membrane to separate different types of nutrients effectively. However, most of the developed membranes are not yet commercialized [22, 59]. For example, Lotfi et al. [75] used a TFC hollow fiber membrane and brackish water feed to generate irrigation water as demonstrated in Fig.(2). The draw solutions were inorganic fertilizers including ammonium sulfate (SOA) $(NH_4)_2SO_4$, calcium nitrate (CAN) $Ca(NO_3)_2$, mono-ammonium phosphate (MAP) $NH_4H_2PO_4$, diammonium hydrogen phosphate (DAP) $(NH_4)_2HPO_4$. Since the polyamide selective layer is negatively charged, the divalent salts like Ca^{+2} and Mg^{+2} were efficiently separated and accumulated on the membrane surface, causing scaling. Also, Ca^{+2} could be transferred to the feed solution due to the reverse solute flux and interaction with nutrients such as $SO^{+2}_{4,}$ creating gypsum scaling ($CaSO_4$) on the membrane surface. Other nutrients with small hydrated ionic radii, like NO^{-3} and NH^{+4}, were poorly rejected and permeated rapidly through the membrane to the feed solution. The forward diffusion of nutrients such as Ca^{+2} or Mg^{+2} to the draw solution which interacted with phosphate resulted in calcium phosphate scaling. This adversely affected the membrane performance and the quality of the water permeate. The SOA fertilizer draw solution achieved the highest water flux around 11.2 LMH While CAN and DAP solutions had the lowest water flux of 10.4 and 8.7 LMH.

Phuntsho et al. [63] used a cellulose triacetate (CTA) FO membrane and eleven commercial fertilizer draw solutions such as urea, ammonium nitrate (NH_4NO_3), $(NH_4)\ _2SO_4$, Monoammonium phosphate (MAP), potassium chloride (KCl), potassium nitrate (KNO_3), Monopotassium phosphate (KH_2PO_4), calcium nitrate $Ca(NO_3)_2$, sodium nitrate ($NaNO_3$), Diammonium phosphate $(NH_4)_2HPO_4$), ammonium nitrate (NH_4Cl) for brackish water desalination including blended solutions. It was highlighted that when blending two or three fertilizers in the draw solution, the product water contained a lower concentration of nitrogen, phosphorus, potassium (NPK) nutrients relative to the individual fertilizer draw solution. KCl and $NH_4H_2PO_4$ draw solution included only a small quantity of N nutrient (0.61 g/L), P nutrient (1.35 g/L), and K nutrient (1.70 g/L) as compared to which individual fertilizer draw solution having a high concentration of the single nutrient. However, it was observed that there was a significant nutrient loss due to reverse solute flux. For example, the urea draw solution experienced a high drop by 65% in the amount of N nutrient relative to other draw solutions. The membrane performance was also influenced by mixing two fertilizer draw solutions as the osmotic pressure, and water permeation was decreased compared to that of individual draw solutions.

Kim et al. [76] evaluated the performance of PA (TFC) FO membrane in an FDFO system using RO brine as a feed solution and ammonium sulfate (SOA), calcium nitrate (CAN), di-ammonium phosphate (DAP), potassium nitrate (KNO_3) as draw solutions. The membrane separation performance was affected by scaling and reverse solute flux at a varying rate. For example, the lowest water flux, along with reverse solute flux, was assigned to the KNO_3 draw solution. The fast transfer of calcium ions and accumulation in the feed solution lead to the most significant membrane scaling (calcium nitrate). The solute leakage of nutrients ordered from the lowest to highest as follows, SOA (2%), DAP (5%), CAN (4%), and KNO_3 (21%). Interestingly, KNO_3 showed the highest nutrient loss due to its high extraction capacity, which accelerated the reverse solute flux. In terms of water recovery rate, a maximum recovery rate was observed for the DAP draw solution (95%), followed by SOA (80%), KNO3 (79%), and CAN (70%). The draw solution with low concentration and high osmotic pressure had the highest extraction capacity according to the osmotic equilibrium. As a result, the total recovery rate grew significantly. In term of N/P/K nutrients, the final product water contained higher concentrations of N (268.40 mg/L) from CAN, N (201.19 mg/L) and P (222.45 mg/L) from DAP, N (230.63 mg/L) from SOA, N (114.76 mg/L) and K (320.33 mg/L) from KNO_3. This indicated that the nutrient solution needs further dilution by potable water to lower the concentration of phosphorous and potassium nutrients while the nitrogen nutrient concentration meets the recommended standard for irrigation water. The FO membrane was effectively cleaned using 5% citric acid yielding a complete recovery of the initial water flux.

Sahebi et al. [77] evaluated the performance of pressure-assisted FDFO using a flat sheet cellulose triacetate (CTA) FO membrane, brackish water feed (10,000 mg/L) and four fertilizer draw solutions ($(NH4)_2SO_4$, NH_4H_2PO and KCl) for fertigation. It was revealed that the membrane achieved higher water permeation corresponding 7.38, 8.62, and 9.42 LMH for 0.1 mol/L

$NH_4H_2PO_4$, KCl, and $NH_4H_2PO_4$, respectively at a hydraulic feed pressure of 10 bar. This was related to to 1928%, 345%, and 237% growth in the water permeation upon using 0.1 mol/L draw solutions as compared to 38%, 29%, and 69% at a draw solution concentration of 3 mol/L. This additional water flux produced when using a low concentration of the draw solution at high hydraulic pressure, improved the draw solution dilution beyond the osmotic equilibrium point. A small reduction in the specific reverse solute flux was noticeable when increasing the hydraulic pressure to 10 bar. For instance, the specific reverse solute flux was reduced from 0.77 g/L and 0.60 g/L for NaCl and KCl, respectively, at 0 bar to 0.49 g/L and 0.45 g/L at 10 bar. Therefore, the final water product contained acceptable nutrient concentrations for direct irrigation without the need for a post-treatment stage to lower the fertilizer concentrations.

Recently, Lima et al. [78] proposed a new principle of FO desalination that depends on a subsurface irrigation procedure for fertigation. It involves using irrigation pipes made of the BW30 RO membrane and FO 8040 FO membrane. The brackish water feed rich-nutrients passed through the pipes to the soil and crops, which decreases soil deterioration and yield. It was found that the FO membrane supplied the soil with a higher amount of water permeate than that for the RO membrane after six days. For instance, the FO membrane produced 11 times higher water balance leading to efficient soil hydration as compared to that for the RO membrane. The soil treated with RO permeate was dried after the third day and remained dry throughout the experiment. To that end, the FO membrane performed better, and its productivity is complying with the control membrane for the duration of the experiment.

5.2 Chemical-driven membrane processes

5.2.1 Electrodialysis (ED)

A new membrane-based technology rarely used for seawater/brackish water desalination is electrodialysis. There are two types of electro-membrane processes, reverse electrodialysis (EDR) and electro-deionization (EDI) for desalinating low salinity streams.

The ED system is operated based on converting the salinity gradient between the concentrated solution (i.e., seawater) and diluted solution (i.e., river water) into voltages using ion-exchange membranes [49, 79]. In this system, cation and anion exchange membranes are arranged alternately and isolated from each other by spacers to make channels. Fig. (3) shows the normal EDR stack model where the ion flux transports from the concentrated stream to the diluted stream, the selective membrane allows the penetration of cations across a cation exchange membrane (CEMs) and the anions across an ion-selective anion membrane (AEMs). This leads to the generation of an ionic current through the multi-membranes in which can be converted into voltage due to reactions occurring on the electrode [79]. The electricity can be collected using an electrical conversion device. In 2015–2016, the first ED/EDR and EDI electro-membrane process plants were operated using saline water as a feed solution. An EDR plant implemented in South Africa produced water capacity in the range of few tens of m^3/day up to 10,000 m^3/day from the brackish water inlet.

Eberhard et al. explored the feasibility of the electrodialysis process for separating micronutrients such as copper chloride and copper sulfate from brackish water and coal seam gas water [80]. The electro-membrane had an active area of 207 cm^2, and 20 cell pairs, including the cation/anion membranes in alternated series, were employed. One of the important findings is that the rejection rate of the copper and the sulfate reached 98 % and 100%, respectively, after three hours of operation time at 23 °C. In comparison, the removal efficiency of both the copper and sulfate was faster than that for NaCl with a rejection rate of around 72%. The water content in the diluted solution was reduced by only 10%, which minimized brine disposal. The theoretical work suggested that the mass /charge ratio of Sulphur ion with large ionic radii could reveal the separation efficiency. For instance, the ions with small ionic radii can be removed rapidly as compared to that with larger ionic radii. The diluted solution contained 3.0 mg/L of copper nutrients and 2.7 g TDS/L, which can be used directly for fertigation.

Zhang et al. [81] studied the possibility of using a novel selector-dialysis membrane to separate ions having the same charge signs. He attempted to separate divalent ions such as $SO^{-2}{}_4$ from monovalent, such as Cl^-, via the same membrane. The feed was composed of a mixture saline solution ($NaCl/Na_2SO_4$) with initial concentrations of 7.61, 0.32, 4.48, and 0.43 mmol L^-1 for all ions, respectively. The membrane achieved excellent selectivity at the highest pH. When increasing the pH value, the current efficiency of the selector-dialysis system was also increased. There was a strong correlation between sulfate concentration and pH value. The membrane was capable of concentrating sulfate to 4 and 3.5 mmol L^{-1} at the optimal conditions of current densities (31.2 and 46.8 A m^{-2}) and a pH of 10. The purity of sulfate in the product water was higher than 85% at a current efficiency of greater than 50%. This indicated that the selector-dialysis system was viable for separating monovalent ions (Cl^-) from multivalent ions ($SO^{-2}{}_4$), and therefore, the final product water can be used for agricultural irrigation.

A new approach for brackish water desalination is using monovalent selective cation exchange membranes in the ED process. This special membrane can be fabricated by adding a poly-cation layer on the membrane surface to reject monovalent salts such as Na and Cl while retaining divalent salts such as Ca, Mg, and SO_4 ions. A recent work described the use of this membrane for desalinating brackish water to obtain irrigation water containing the required amount of mineral nutrients [82]. To select the best performing commercial monovalent selective ion exchange membranes (MIEM) in removing the monovalent ions, the process conditions were optimized, and the effect of membrane selectivity was investigated. All MIEM membranes exhibited superior selectivity for sulfate than chloride. The performance of these membranes was more efficient than monovalent selective cation exchange membranes when using brackish water with low conductivity. It was noticed that the anionic membranes purchased from MVK and CMS exhibited the good perm-selectivity for Ca^{+2} and Mg^{+2}. The removal ratio of these cations was about 80% and 70%, respectively, while it was only 37- 48% for Na ions. An anionic membrane manufactured by CSO produced superior monovalent perm-selectivity of less than 1 upon using brackish water with conductivities of less than 4.5 dS/m. The removal ratio of Na^{+1}, Ca^{+2} and Mg^{+2} amounted to 52%, 44%, and 24%, respectively. To achieve the best selectivity of monovalent ions, the current densities should be maintained lower than the limiting current corresponding to sodium concentration. When the total salinity of the product water decreased by 50%, the removal efficiency of Cl and SO^{-2}_4 was as high as around 90% and 12% for CSO membranes-modified with polyethyleneimine. Lastly, the SAR in the final product water was 2.3 making it suitable as irrigation water for crop production. It was concluded that this novel procedure facilitated the generation of irrigation water, which provides another water resource for fertigation and eliminates negative effects on the environment.

5.2.2 Capacitive Deionization (CDI) process

Capacitive Deionization is a desalination technology that depends on an electrical capacitance to separate or release charged ions from/into solutions [47, 83]. Both CDI and ED had a similar operating principle, especially the ions, transfer through the solution and across the membrane. However, CDI does not need a membrane and is considered a low-pressure process. This means that the CDI process is competing with the pressure-driven processes (RO) and temperature-driven processes (MD), which is capable of producing pure water at a lower operating cost [50].

The principle of the CDI can be explained as follows [49, 84]. We can see in Fig. (4) that a saline solution passes into a channel between capacitive electrodes that are separated by an ion-selective layer. This selective layer is used to increase the voltage efficiency and improve the performance of the system. The transfer of ions towards the capacitive electrodes is induced by applying an electrical potential difference between the electrodes. Thereafter, the ions are adsorbed on this electrode, and hence the ions from the feed solution are removed. As a result, the feed solution becomes almost free of salt ions providing pure water. It should be mentioned that, at the saturation point of the electrode, the salt ions are released from the electrode and transported through a purge stream to the channel. This causes the accumulation of ions in the solution generating a concentrated brine. The most widely used applications are seawater desalination, brackish water desalination, wastewater reclamation, and water softening [47, 83]. Industrial plants for numerous applications are operated in the Netherlands and China, achieving water capacity around up to 2000 m^3/h [85].

The CDI process for brackish water desalination has been evaluated in two stages [86]. In the first stage, the electro-sorption capacity of the lab-scale CDI rig was assessed. In the second stage, the salinity removal efficiency and energy consumption were investigated for the prototype CDI system in the Wilora area, Australia. The possibility of implementing this system in this field with a temperature of 45 °C and humidity of 80% was explored along with, the separation efficiency of the system. The theoretical data indicated that there was an increase in the electro-sorption capacity and adsorption rate constant upon increasing the feed concentration. The electro-sorption rate was 48.29% for a salt solution having a concentration of 1500 mg/L. The selectivity of the system was excellent, and the highest salinity removal was achieved at the lowest flow rate (1.0 L/min). The removal efficiency of metal ions and non-metal ions was roughly 89%, 85%, 73%, 84%, 74%, and 80% for Ca^{+2}, Mg^{+2}, Na^{+}, Nitrate, and Arsenic, respectively. Raising the flow rate to

7.0 L/min yielded a minimum energy expenditure of about 1.89 kWh/m^3 for the desalinated water. A total water recovery around 75 to 80% was achievable. These findings make the CDI system a potential alternative for desalinating brackish water.

To further improve the removal efficiency, Liu et al. [87] developed membrane capacitive deionization (m-MCDI). Here, the electrodes were manufactured from carbon nanotubes incorporating a cation exchange polymer (Polyethyleneimine (PEI)) and an anion exchange polymer (dimethyl diallyl ammonium chloride (DMDAAC)). It was found that the new electrodes achieved high removal efficiency for NaCl of 93%, greater than that for other CDI systems. A CDI unit using carbon nanotube electrodes and MCDI unit with commercial anion and cation exchange membranes had a lower removal efficiency of 25% and 74% under the same electrical current of 1.2 V and solution conductivity of 50 µS/cm. The modified MCDI also achieved superior electro-sorption of 0.159 mmol/g and charge efficiency of 0.70 at less than 2.0 V. At the same time, the commercial MCDI cell demonstrated an electro-sorption behavior around 0.114 mmol/g and 0.53. This enhancement can be attributed to incorporation ion-exchange polymers, which adhered strongly to the electrodes leading to lower co-ion expulsion impact compared to the commercial MCDI system.

More recently, Bales et al. [85] developed a simulation model to predict the performance of the MCDI process and combined it into an agricultural economics model. In this model, the environmental conditions in Australia and a crop-water-salinity function were used to estimate crop yield and profits. The MCDI consisted of an ion exchange membrane attached to each carbon electrode to eliminate the passage of ions during the recharge cycle. The current adsorption remained constant at zero-volt desorption leading to reduced energy consumption relative to commercial CDI. According to the theoretical information, this system can be utilized to irrigate many valuable crops, and it can be optimized based on the environmental conditions of any agricultural area. Different salinity limits were used according to thresholds for different crops of 4.2 dS/m, 5.5 dS/m, 4.4 dS/m, 14 dS/m, and 8.5 dS/m for grapes, oranges, almonds, apples, and tomatoes for a 60 ha crop and investment period of 10 years. The cost of the treated water was varied in each scenario, and it was estimated to be less than AUD$ 1/kL. Therefore, this cost-effective MCDI system is feasible to desalinate brackish water providing irrigation water after further dilution by freshwater.

6. Water nutrient production from industrial wastewater

6.1 Pressure-driven membrane process

An alternative source of water for many agricultural applications is treating different types of wastewater. Pressure driven membrane processes are effective methods for wastewater treatment due to high productivity and selectivity towards organic and inorganic contaminants [88]. Bunani et al. [38] used brackish water reverse osmosis (AK-BWRO) and seawater reverse osmosis (AD-SWRO) membranes in an RO system to generate irrigation water from mixed secondary treated urban effluent. The performance of this membrane was tested under a hydraulic pressure of 10 bar. It was observed that both the membranes exhibited good rejection, and adjusting the pressure showed an insignificant impact on the rejection efficiency. At 10 bar, the BWRO membrane achieved rejection of 94.6%, 95.2%, 85.8%, 76.4%, and 91.3%, respectively against conductivity, salinity, chemical oxygen demand (COD), total organic carbon (TOC) and color whereas these values were 98.3%, 98.3%, 84.6%, 69.7%, and 86.6%, for the BWRO membrane. The water permeation was varied for both the membranes as the AK-BWRO membrane permeate approached 38.0 LMH. The AD-SWRO membrane permeate was as low as 3.81 LMH, and it was maximized to 14.8 LMH at 20 bar. The AK-BWRO membrane showed the best water quality with higher water recovery. When adding 20-30% of secondary treated urban effluent to 70–80% of the final product water, acceptable SAR values of around 6.41–7.67 and 7.36–8.31 with EC_w values of 1.62–2.25 dS/m and 1.52 to 2.10 dS/m for AD-SWRO and AKBWRO membranes were achieved. Therefore, this mixture solution was suitable for fertigation meeting the standard of irrigation water.

Ranganathan et al. [89] assessed the behavior of RO for purifying tannery wastewater and stated the cost analysis of this process. It was confirmed that the RO membrane was efficient in separating organic components and the total dissolved salts in the desalinated water. The membrane demonstrated a rejection rate of 93-98%, 92-99%, and 91-96% for TDS, sodium, and chloride, respectively. It was suggested that the wastewater was recovered by 70-85%, and the TDS in the desalinated water approached 118-438 mg/L, meeting the quality standard of potable water. The overall operating and maintenance costs of the RO unit were low.

UF membrane was also examined for treating wastewater under two different experimental conditions of “stressed operating conditions” against “conventional operating conditions” [43]. The stressed operating conditions phase consisted of three typical process cycles while the conventional operating conditions consisted of one typical process cycle. Experimental results showed that the desalinated water from both the conditions contained a minimum amount of Total Suspended Solids (TSS) < 10 mg/L; Chemical Oxygen Demand (COD) < 100 mg/L and Escherichia coli < 10 CFU/100 mL. The quality of this desalinated water satisfied the Italian guidelines for irrigation water produced from wastewater. However, the desalinated water obtained using the conventional operating condition satisfied the quality standard of irrigation water issued by the State of California. This desalinated water was free of TSS and turbidity while the total coliforms were less than 2.2 CFU/100 mL. This can be ascribed to a localized membrane pore micro-enlargement mechanism that controlled the permeability and transmembrane pressure during the experiment. Consequently, a thin cake layer created on the membrane surface contributed insignificantly to the fouling and pore blocking. The treated water from both the conditions did not include any *E. coli* microorganisms. It was suggested that the conventional operating condition is the best option for operating the UF membrane in the process of achieving a good quality of irrigation water.

Balcıoglu et al. [90] made a study of using different membranes (FM UP020, FM UP005, NF 270, NF 90, and Desal 5DL) to treat baker's yeast wastewater for agricultural irrigation. The effect of the operating conditions on fouling, water permeation reduction, and quality of the permeate was explored. Membrane separation performance and fouling analysis suggested that the Desal 5DL and NF 270 membranes were feasible for treating baker's yeast wastewater due to excellent rejection rate, reduced flux declines, and low water contact angles. This is because the Desal 5DL membrane achieved a removal efficiency of 90%, 87%, higher than 88% for the COD, chloride, total dissolved solids, respectively. NF 90 membrane demonstrated rejection efficiency against total dissolved solids around 88%. The NF membranes showed total hardness and sulfate removal efficiency in the range of 70–98% and 97–99%. The removal efficiency of chloride corresponded to 13%, 25%, and 87% chloride removal for NF 270, Desal 5DL, and NF 90 membranes, respectively. However, the chloride was not rejected by the FM UP020 membrane. The NF membrane rejected the suspended solids completely, while the UF membrane showed rejection of only 75–81%. The FM UP020 membrane exhibited poor color rejection, which was above the discharge limit values while the NF membrane rejected the color completely. In terms of fouling impacts, the water flux reduction was dropped by 68% for the FM UP005 membrane, while NF 270 and Desal 5DL membrane achieved the lowest water flux reduction around 5% only. Similarly, the Desal 5DL membrane had better antifouling property at operating parameters of pH 7, 12 bar, and 25 °C as compared to other membranes. The product water purified by two NF 90 passes met the standard regulations for irrigation water.

6.2 FO process

In the FO process, the feed water will be converted to nutrient water for agricultural purposes when using a fertilizer draw solution and, therefore, there is no need for a recovery system to separate the draw solution [91]. Research was conducted using three commercial all-purpose solid fertilizers with concentrations ranged from 1.0-3.0 mol/L to draw pure water from wastewater [92]. The performance of a commercial cellulose triacetate membrane with an active area of 0.0025 m^2 was evaluated in terms of water permeation and water recovery. The nutrient concentrations in both the draw and feed solutions and nutrient loss were analyzed and the energy required to operate the FDFO system was optimized. The results revealed that the fertilizer DS-F1 (N=24/P=8/K=16) was the best performing draw solution when using wastewater as the feed solution due to the low concentration of urea. Also, water extracted was around 324 mL, which amounted to 41% of the total water required to dilute irrigation water within 72 hours of running time. Likewise, the highest water permeation approached 4.2 LMH while the reverse solute flux was estimated at 92%, 98%, 75%, and 81% for NH_4-N, TN, K, and P nutrients. The final diluted draw solution (F-1) included N from NH_4 at 12.0 mmol, N from urea of around 30.6 mmol, P nutrient around 5.9 mmol, K nutrient around 16.5 mmol. Phosphorus was rejected by the FO membrane leading to a high amount in the feed solution, but the amount of total nitrogen and potassium increased in the FS due to reverse solute flux. Finally, reducing the flow rate from 100 to 10 mL min-1 resulted in energy consumption reduction from 1.86 to 0.02 kWh m^{-3}. Although the reverse solute flux was challenging, the commercial solid fertilizers as a draw solution showed potential for obtaining irrigation water from wastewater.

Li et al. [44] used the PA TFC FO membrane to treat landfill leachate containing a high amount of undesired species such as dissolved organic matter, inorganic components, heavy metals, and other compounds. Different concentrations of the NH_4HCO_3 draw solution and the flow rate were investigated. The water recovery rate corresponded to 91.6% within 72 hours, which is higher than that for the Changsheng Bridge Landfill plant located in Nanan District, Chongqing, China. The water permeation increased to 6.7 LMH when increasing the DS concentration to 3.0 mol/L. However, it declined after 5 hours. When the flow rate was raised to 8.4 cm/s, the water permeation was increased to 7.5 LMH due to improved fluid shear stress at the membrane leading to a thin boundary layer. As a result, the accumulation of solute and concentration polarization was mitigated across the membrane. After 48 running hours, the product water was free of the metals Hg, As, Cr, Cd, Pb, had no odor and negligible precipitates, pH within the recommended value, minimum TOC (42.2 mg L^{-1}) and chloride (38.5 mg L^{-1}). The product water met the standard regulation of commercial liquid fertilizer, and therefore it can be reused for fertigation.

Iskander et al. [93] estimated the energy consumption of the FO system for purifying landfill leachate. Several operating parameters, such as the draw solution concentration and flow rate, were optimized. The treatment performance and energy consumption were compared when varying the landfill leachate properties. Cellulose triacetate commercial membrane was tested in the FO process, and the effect of membrane fouling on energy expenditure was also explored. Experimental data showed that the water recovery rate increased from 63.8 ± 7.7 mL to 277.3 ± 3.8 mL when using concentrated draw solution (3.0 mol/L). The reverse solute flux was slightly increased from 4.60 ± 0.59 to 5.37 ± 1.15 gMH. It was observed that raising the flow rate to 110 mL/min at a draw solution concentration of 1.0 mol/L resulted in higher energy requirements estimated at 0.276 ± 0.033 kW h m^{-3}. This energy expenditure was minimized to 0.005 ± 0.000 kW h m^{-3} upon decreasing the flow rate to 30 mL/min, increasing the water recovery rate, and higher draw solution concentration of 3.0 mol/L. The fouling was easily removed from the membrane through osmotic backwashing. Simultaneously, the leachate with a low amount of pollutants required low energy consumption due to high water recovery. The FO process can be used to lower the volume of leachate whilst extracting highly pure water for direct reuse.

Very recently, Volpin et al. [94] proposed a new concept of the FO process as $MgSO_4$ and $Mg(NO_3)_2$ fertilizer draw solution was employed to dewater synthetic human urine. The diagram of the fertilizer driven FO process is shown in Fig. (5). It was assumed that the reverse solute flux of Mg^{+2} would trigger P-recovery through struvite precipitation. Next, the leakage and precipitation of urea in the Mg-fertilizer draw solution will increase the amount of N nutrients. Also, a lower volume of urine at the end of the experiment leading to enhanced productivity in downstream processes for N-recovery. The $Mg(NO_3)_2$ draw solution produced higher water flux by 3-fold (31 LMH) as compared to that for the $MgSO_4$ draw solution at a concentration of 1.0 mol/L because of high mass transfer through the FO membrane. Similarly, the reverse solute flux was higher at 0.89 g/L for $Mg(NO_3)_2$ draw solution and 0.1 g/L for $MgSO_4$ draw solution. It was reported that the urea was not rejected completely by the PA TFC FO membrane, but it was recovered in the Mg-based draw solution. The volume of urine was decreased to 60%, which can promote efficiency in downstream processes. Accordingly, a high amount of nutrients amounted to 40% of the P as struvite fertilizer, and 50% of the N in the urine were recovered when urine was concentrated by 60%. The agricultural companies can be supplied with solid struvite as the diluted fertilizer can be utilized as irrigation water for green walls, parks, and farms. The new development of the FO process opened an opportunity to effectively extract nutrients from human urine and reused for sustainable agriculture.

6.3 Temperature-driven membrane system

The basic concept of MD lies in the thermally driven transference process across a hydrophobic membrane [56]. A wide range of commercial membranes was used as the MD membrane such as polypropylene (PP), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), and polyethylene (PE) [95]. The selection of membrane configuration (flat sheet or capillary) and type depends on the MD application, if highly pure water or concentration of the ionic solution is required. The most important characteristics of MD membranes are high hydrophobicity, high porosity; pore size ranged from several nanometers to few micrometers, small pore size distribution, high liquid entry pressure, thick single-layer to produce low thermal conductivity, antifouling material and excellent chemical and thermal stabilities [96, 97]. In comparison with pressure-driven membranes, the MD process needs low hydraulic pressure, produces a high water recovery rate, integrates with natural energy to generate heat, thereby reducing energy consumption [95]. The MD process is effective in extracting nutrients from wastewater effluent. For example, Zarebska et al. [98] made a study on the removal of ammonia from swine manure and examined the membrane anti-fouling resistance. In this study, tubular polypropylene membrane and a liquid fraction of undigested manure as feed solution were used in the FO system. The feed solution contains valuable nutrients such as potassium, ammoniacal nitrogen, sodium, phosphorus, sulphur, calcium, magnesium and iron for plant growth. During the test, there was a fast drop in the ammonia flux from 42 kg·m^{-2}h^{-1} to 3 kg·m^{-2}·h^{-1}. This is because of reduction in the ammonia partial pressure after 25 hours of operation time. It was found that the membrane was affected by accumulation of proteins, some inorganic components such as O, S, Fe, Na, Mg, K and microorganisms leading to serious fouling. This resulted in altering the surface characteristics and the membrane surface was converted from hydrophobic to hydrophilic in nature, thereby hampering the separation of ammonia. The fouling layer was thick (10-15 mm) after a week of running the experiment.

To improve the membrane performance for rejecting ammonia, research was carried with a modified direct contact membrane distillation (MDCMD) process to remove ammonia from municipal wastewater [99, 100]. The PVDF membrane was operated in the system, and its characteristics were 80% porosity, mean pore size of 0.22 µm, liquid entry pressure of 250 kPa, and water contact angle of 87°. This membrane was tested in three different process modes: a conventional direct contact MD, a hollow fiber membrane contactor, and a modified DCMD apparatus. The influence of operating conditions such as feed pH, temperature, flow rate, and concentration on the ammonia stripping was explored. It was observed that the removal efficiency of ammonia for direct contact membrane distillation (DCMD), hollow fiber membrane contactors (HFMCs), and MDCMD modes amounted to 52%, 88%, and 99.5% after 105 minutes of running time, respectively. This meant that MDCMD was the best process for removing ammonia from water/wastewater. A negligible effect on the removal efficiency of ammonia and the distillate flux was noticed at an optimal feed pH value of 12.2. However, adjusting the cross-flow velocity from 0.15 to 0.5 m/s caused an increase in the water flux from 5.75 to 11.75 LMH and high diffusion of ammonia through the membrane leading to improved vapor mass transfer. When raising the feed temperature and feed flow rate, separation efficiency towards ammonia and the water permeation were enhanced. However, the separation efficiency was independent of the initial feed ammonia concentration in the MDCMD process.

Macedonio et al. developed a PVDF MD membrane and compared its performance with two polypropylene MD commercial membranes for treating saline oily wastewater [101]. The impact of feed temperature and hydrodynamic conditions on the rejection efficiency was studied. Furthermore, an economic analysis was performed to determine the viability of the direct contact

MD process for saline oily wastewater treatment. The experimental results demonstrated that the new PVDF2 membrane had the highest water flux of 6.0 LMH and rejection rate of TDS and total carbon of 99.8% and 90.6%, respectively. Overall, the rejection rate was greater than 99.0% and 90.0% against TDS and TC for all the fabricated membrane modules. The distillate included TDS, Total carbon (TC), total inorganic carbon (TIC), total organic carbon, and conductivity of about 415 mg/L, 91.36 mg/L, 48.46 mg/L, TOC= 42.9 mg/L, and 614 µs/cm respectively. The cost analysis showed that the water production cost of the PVDF-2 membrane reached 0.72 $\$/m^3$ at a recovery rate of 70%, the temperature of the produced water passed to the unit was 50^{o}C, and the lifespan was 10 years. The cost was higher of about 1.28 $\$/m^3$ when the temperature of the produced water passed to the plant reached 20 ^{o}C and lifespan of 5 years. Thus, these findings proved that the developed membrane is a cost-effective alternative method for industrial wastewater treatment.

6.4 Membrane bioreactor (MBRs) process

Membrane bioreactor (MBR) has been commonly used for wastewater treatment as an alternative process to traditional treatment systems due to a simple design and high-quality product effluent [102]. It consists of a classical biological sludge process coupled with a micro- or ultrafiltration membrane module. The biological process is used to decompose the waste species or microorganisms while the membrane separates the water from the mixed liquor [103, 104]. The membrane has pore diameter ranged from 0.01 to 0.1 µm to reject contaminants and bacteria, so it was an alternative method to gravity sedimentation system in the biological sludge process. The practicality of the MBR process has been shown through lab and pilot plants for wastewater applications.

Matosic et al. [105] studied the performance of a pilot MBR plant with a hollow fiber membrane for treating wastewater from a soft drinks production facility compared with the performance of a traditional treatment process (biological activated sludge system). The biological activated sludge process failed to completely remove COD, leading to a high concentration in the effluent. The MBR performed better in rejecting organic contents, and the amount of COD and TOC was decreased by 94% in the effluent. This can be attributed to the higher concentration of activated sludge biomass in the bioreactor governed by the rejection of these species by the hollow fiber membrane. The membrane was effective in removing total suspended solids and other contaminants, which improved the quality of the effluent. The initial water permeation was 5.43 LMH but declined due to fouling. The fouling was caused by a high amount of total hardness and high pH value in the influent, leading to precipitation of scale precursors. The most severe fouling was after the first 10 days of the operating period, and then it decreased slowly. The initial water permeates value was restored after chemical cleaning via hypochlorite, acid, and alkaline solutions. For instance, the water recovery rate reached 72% when immersing the membrane in a hypochlorite solution. The superiority of the MBR treatment proved its feasibility in treating wastewater rather over the traditional treatment process.

Prieto et al. [106] invented a gas-lift anaerobic membrane bioreactor (Gl-AnMBR) for household wastewater treatment. The performance of the Gl-AnMBR was evaluated, and a comparison between membrane fouling mitigation strategies was addressed. PVDF UF membrane combined suspended-growth bioreactor and synthetic household wastewater was used for the treatment operation over 100 days. It was found that the highest water flux corresponded to 18 LMH at a constant cross-flow velocity of 0.3 m/s and constant transmembrane pressure, and the water flux was independent of the higher cross-flow velocity. This means that the membrane permeate was controlled by mass transfer resistance across the membrane during the process. After 100 days of the operation period, the water permeation declined to 10-15 LMH. Fouling was alleviated by backwash cleaning every week. A further improvement in the water flux was achieved by to backwash cleaning every 4 hours. There was an excellent removal efficiency against sewage organic matter as the removal efficiency of COD and organic carbon removal approached up to 98% and 95%. Methane as biogas was released around 4.5 L/d, which is beneficial for energy recovery and membrane cleaning. The product water contained 95.5% of the cumulative recovery for nitrogen and 93.4% of the cumulative recovery for phosphorous after 100 d of running time. Therefore, the product water included an acceptable amount of nutrients from sewage organic matter, and it can be used for fertigation depending on the specific nutritional requirements of the crop.

Bolzonella et al. [107] highlighted the results of 10 years of investigations on the performance and feasibility of the MBR process for removing various contaminants from industrial wastewater. The MBR system was effective in rejecting solids, nutrients, and micropollutants as the removal efficiency of nitrogen, phosphorus, and heavy metals was 80%, >60%, and 10-15%, respectively, whilst COD was reduced from 100 mg/L to < 40 mg/L. The removal efficiency of the toxic compound ,2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), was superior as the concentration decreased to <0.5 pg/L in 60% of the samples while the concentration of other dioxins was less than 10 pg/L. The removal efficiency of organic pollutants was enhanced when using a high concentration in the influent while there were no *E. coli* bacteria in the effluent. The total coliforms in the effluent ranged from 0 to 240 MPN/100 mL in the MBR-1 and higher around 13 and 460 MPN/100 mL in the MBR-2. Therefore, the treated water had high quality, and was appropriate to be reused directly or after treatment with another method. The operating and maintenance costs were reduced significantly to between 0.11 and 0.15 USD/m^{3,} which indicated the workability of the system in treating wastewater and reuse of the treated water in the Mediterranean Region.

7 Application of hybrid systems for agriculture

The development and performance of existing integrated systems in different agricultural applications are discussed.

7.1 Seawater/brackish water desalination

7.1.1 RO integrated system

To reach the required quality of irrigation water, some membrane processes need an additional pass to recover nutrients. For instance, seawater desalination plants use several passes to polish the desalinated water and remove boron and chloride [32]. When using low hydraulic pressure and neutral pH, the removal efficiency of boron was 83%. The removal efficiency of boron can be maximized to 99% when using high hydraulic pressure and pH 10.5 [108]. Generally, the second RO pass requires high energy consumption of about 0.5 kWh/m^3 [32]. A SWRO industrial plant used multiple RO passes to effectively reject boron and chloride from the treated water [32]. However, energy consumption is a crucial hurdle for the SWRO facility for generating irrigation water. The pre-treatment or post-treatment stage of the RO membrane can consume energy of 0.7-0.9 kWh/m^3. This accelerated the total energy consumption for the facility reaching 3–7 kWh/m^3 of produced water.

Altaee et al. [109] explored the efficiency of RO membranes as a post-treatment stage coupled to a NF system to recover nutrients from seawater with a salinity of 35,000 mg/L to improve the quality of irrigation water. The NF/RO process did not efficiently separate the NO^{-3} nutrient, and hence it was mixed with KNO^{-}_3 to increase the rejection. The solution contained KNO^{-}_3 as the main component, and a high rejection by the RO membrane was noticeable. When two BWRO membrane passes were used to recover nutrients from the Ca $(NO_3)_2$ draw solution, the membrane achieved high rejection, and another RO cycle was also applied to provide an acceptable level of NO^-_3 and K^+ nutrients in the product water. It was important to use two RO stages for recovering the nutrients, and the permeate was further recovered to obtain the required concentration of NO^-_3 and K^+ nutrients in the final product water. In the first RO pass, a high rejection rate of around 99.5% was achieved for monovalent ions while it was decreased to 90% for $MgCl_2$ and KNO_3. However, the BW30-440i RO membrane exhibited the greatest rejection rate of about 99% against monovalent ions, but the power expenditure was relatively high. The final product water contained the recommended level of nutrients for agricultural irrigation when two RO stages were used as the recovery processes. It was reported that when increasing the recovery rate, the energy expenditure was minimized. The specific energy consumption for the RO recovery stage was 3.0 kWh/m^3, which was lower than for a conventional RO desalination plant.

To recover nutrients in the desalinated water with minimum energy, Atab et al. [110] applied an adsorption cycle (AD) after the RO membrane process. The layout of this hybrid system is presented in Fig. (6). Although the temperature influenced the performance of the RO membrane, increasing the temperature to 85°C led to the high water capacity of the AD cycle of about 6.3 m^3/day. The salinity can affect membrane performance, but there was a negligible impact on the AD cycle. It was found that this desalination plant generated 24,000 m^3/day of irrigation water with salinity less than 1600 mg/L. The total water recovery achieved was around 65% for the hybrid system. The estimated energy consumption of the hybrid system at a water recovery of 45% was about 0.8 kWh/m^3. This resulted in a reduced cost of around 0.54 \$/m^3 as compared to the stand-alone RO system. The significance of desalination by combining RO and a post-treatment method is not only to minimize the energy expenditure but also to enhance the quality of irrigation water.

7.1.2 FO integrated system

FO coupled with another membrane-based process could be beneficial and comparable to the RO process in terms of operating cost and energy saving. The FO integrated process has potential in treating complex impaired water sources from the oil and gas industry, brine desalination, and drilling flow back water [111]. Many earlier patents reported the use of the FO combined heating process to extract a volatile fertilizer solution from the product water [48]. In this respect, a dual-stage of the FO/heating process was used for seawater/brackish water desalination. The heating system was employed to recover a volatile fertilizer draw solution, including ammonia and carbon dioxide. The theoretical results indicated that the hybrid system consumed power of 0.25 kWh/m^3 at a water recovery rate of 64%. Also, the energy consumption was very high for the heating recovery system approaching 75 kWh/m^3, which hindered the feasibility of this recovery strategy. Other drawbacks are the high reverse solute flux and the accumulation of ammonia in the product water.

A closed-loop FO-NF hybrid system could be an effective process for seawater desalination, with the NF stage used to recover the nutrients from a fertilizer draw solution [112]. Experimental results showed that the water permeation of the hybridized FO-NF process reached 10 LMH, while the solute rejection by the FO membrane was as high as 99.4% for all the tested draw solutions. The solute rejection by the NF membrane was lower, around 97.9%.

Furthermore, dual NF passes were applied to purify the diluted draw solution obtaining high-quality potable water. According to Chekli et al. [48], the second stage is necessary to remove Na$^+$

and Ca^{+2} from the diluted draw solution completely. Another negative impact is that the passage of salt solution through the membrane may deteriorate the lifespan of the membrane. After that, the final product water contained a minimum amount of TDS of about 113.6 mg/L, which is lower than the recommended level for drinking water (500 mg/L).

Phuntsho et al. [111] reported the effect of operating conditions on each other in a closed-circle large-scale FDFO-NF hybrid process according to the mass balance of the flow rates, the draw and the feed solutions. The theoretical information suggested that when the capacity and feed concentration in the FO/NF hybrid system are constant, the initial flow rate of the draw solution was inversely proportional to the initial concentration of the draw solution or other way around. The mass flow rate of the draw solution is correlated to the concentration of the feed solution and the constant capacity of the closed-cycle FO/NF plant. The data shows that when one of the conditions or both got higher, the mass flow rate can be grown, causing an increase in the concentration of the diluted draw solution and the energy requirements of the NF recovery system. Besides, the initial concentration and the flow rate of the draw solution were crucial conditions. They can influence the water recovery rate of the NF system, thereby imposing a higher energy input. One of the practical hurdles is the nutrients loss and accumulation in the concentrated feed solution resulting in highly concentrated brine exceeding the standard limit for brine disposal. This issue can occur when running the FDFO system at a high recovery rate, and therefore a highly selective membrane is needed to minimize the reverse solute flux. Since the electricity requirement and operating cost are not validated for the closed-loop hybrid system, a quantitative economic analysis and energy consumption estimation are essential for the large-scale plant.

7.1.3 MD integrated system

Widespread studies on MD hybrid processes in various applications have been reported for its high contribution to treat complex impaired water, high rejection towards different organic and inorganic components, improve water recovery, recover valuable nutrients, alleviate fouling/scaling, reduce brine disposal, low energy if natural power source used, and cost-effective [113]. It has been utilized in many fields such as seawater desalination, wastewater treatment, agriculture, oily wastewater, landfill leachate, and pharmaceutical industry [113, 114]. Because the commercial membrane provided high quality and stable permeate, thereby improving the efficiency of the processes and preventing the drawbacks that hampered its realization in large-scale operations [114]. An example is the hybrid MD- crystallizer, which is capable of recovering various mineral nutrients from seawater and wastewater and can improve the production of drinking water by up to 95% [113]. The function of a crystallizer is to reach the supersaturation level of the saline solution to capture solid salts in a tank through water recovery. The most common salt nutrients extracted from seawater and wastewater brine are sodium ($NaCl$, Na_2SO_4, and Na_2CO_3), calcium ($CaCO_3$, $CaSO_4$), and magnesium ($MgSO_4$, $MgOH$). Ji et al. utilized the hybrid MD- crystallizer to obtain NaCl from RO brines. The performance of the hybrid system was investigated in terms of crystallization kinetics, productivity, controlled size and shape distribution of the solid nutrient salts. A comparison between actual and synthetic RO brine was carried out to understand the impact of organic matter dissolved in raw seawater on the water permeate, suspension density, and nucleation and growth rates of NaCl. The results revealed that when using synthetic RO brine, the system captured 21 kg/m^3 of NaCl crystals having common cubic shape with size ranged from 20 to 200 µm. The system achieved much higher water recovery factor of 90%. However, when using actual brine, the growth rate of NaCl crystals was reduced by 15–23% as compared to that for the synthetic brine. The dissolved organic matter in the real brine influenced the water flux and the quantity of salt crystals and the reduction was estimated at 20%

and 8.0 %, respectively. Consequently, a pre-treatment step before the RO is necessary to remove dissolved organic matter and avoiding their effects on the MD membrane. Since the supersaturation of the solution was effectively controlled along with the polarization issue, nucleation process and hydrodynamics, the distillate permeate during 100 hours in the MD process was stable.

Recovering nutrients can also be done by MD. The hybrid MD process can continuously re-concentrate the diluted solution and, at the same time generating drinking water in the outlet side. Suwaileh et al. [56] explored the efficiency of using the FO-MD hybrid process to treat brackish water and recover nutrients from fertilizer draw solution. It was assumed that the thermal heating for operating the MD system could be supplied from a renewable power source, such as solar heating, to reduce the overall energy requirement. The salinity of the feed solution and concentration polarization had no effect on the removal efficiency of the MD membrane. It was observed that when using a low salinity feed solution of 0.5 mol/L of KCl fertilizer draw solution, the water permeation reached 7.7 LMH. This flux value dropped to 4.9 LMH when using a high concentration feed solution of 1.4 mol/L. the average salt rejection was as high as >99.4% when using feed concentrations ranging from 0.1 to 0.8 mol/L. The water permeate had a conductivity value of less than 500 µS/cm, which satisfied the recommended standard of the drinking water. At an optimum temperature of 60 ^{o}C, the MD membrane produced distillate permeate around 5.7 LMH and excellent salt rejection around 99.55%. This can be attributed to low membrane fouling as the FO removed most of the salts from the feed solution before fed the MD process. Furthermore, the energy consumption was minimized significantly from 7.06 KWh/m^3 to 1.1 KWh/m^{3,} which confirmed the potentiality of the hybrid system in the separation of salts and recovering the fertilizer draw solution. The final product water can be directly used for fertigation.

The MD integrated PRO process is beneficial to recover the draw solution with low energy expenditure. Through using the osmotic power gradient process (PRO), the energy consumption can be reduced, and the concentration of the draw solution can be maximized to enhance power exploitation [115]. Lin et al. investigated the performance of an advanced closed-loop system involving PRO coupled MD to regenerate the low and highly concentrated feed solutions and produce drinking water. The PRO was used to extract useful power via a hydro-turbine. It was found that the energy efficiency of the system approached 9.8%, equivalent to 81.6% of the Carnot efficiency when using 60 ^{o}C for the hot stream, 20 ^{o}C for the cold stream, and 1.0 mol/L NaCl feed solution. However, increasing the concentration of the feed solution led to greater theoretical energy efficiency. It should be said that the experimental energy could be lower than the theoretical energy efficiency due to the impact of various operating conditions. Besides, operating different concentrations of feed solutions in the range of 1.0, 2.0, and 4.0 mol/kg NaCl needed very high hydrostatic applied pressure around 46, 100, and 220 bar in the PRO system. As a result, the PRO membrane can be deformed at high hydraulic pressure yielding lower water flux, poor salt rejection, low energy generation, and high membrane replacement cost. Thus, the development of membrane with high mechanical strength is essential to take advantage of the great power output at high feed solution concentration.

7.1.4 ED integrated system

RED is a voltage-driven process that produces electricity from a salinity gradient, and it can be combined with the NF or MD membrane process [113]. The ED process has been found to be a potential process for obtaining concentrated brine, although the monovalent ion-selective membrane is expensive. Liu et al. [116] employed a novel NF-ED hybrid system in which the NF membrane was to separate divalent ions like SO^{-2}_4 while the ED was to re-concentrate the water permeates from the NF. The applied pressure and feed stream concentration caused a reduction in the water flux and salt rejection. A slow increase in the water flux at higher applied pressure was noticeable due to membrane compaction. When using artificial seawater with a salinity of 88,000 mg/L at a hydraulic pressure of 32 bar, water permeation of 57.5 LMH was achieved. It was indicated that the NF membrane almost completely rejected SO^{-2}_4 from the brine solution. However, the rejection rate was lower of about 40% and 87% for Ca^{+2} and Mg^{+2} salt nutrients. The NF membrane showed poor rejection of less than 5% against monovalent ions such as Cl^-, $K^{+,}$ and Na^+. High concentration of Ca^{+2} were detected in the NF water permeate of 392 mg/L, which minimized ED membrane fouling when used as a feed solution in the ED process. When the NaCl was concentrated to 160 g/L at 15 V for over 5 hours in the ED system, the greatest water recovery was around 70%. This brine solution contained a total amount of mineral nutrients (K^+, $Ca^{+2,}$ and Mg^{+2}) around 5 g/L of the total TDS. The energy consumption was approximately 0.6 kW h/m3 for the NF system, and it was higher, around 1.4 kW h/kg NaCl for the ED process. To that end, the hybrid NF-ED system could be a prospective strategy to re-concentrate high salinity NaCl from seawater desalination brine.

The MD coupled RED can generate concentrated brine in the outlet, freshwater product, and power output. Long et al. [117] studied the performance of innovated MD-RED hybrid system using low-grade heat sources varying from 40 °C to 80 °C and the NaCl feed solution with different salinities of 1.0, 2.0, 3.0, 4.0, and 5.0 mol/kg. The concentrated brine from the MD fed to the ED to convert the mixing energy to electricity, thereby minimizing the energy consumption of the hybrid system. The operating conditions influencing the performance of the process were optimized. The energy efficiency of this hybrid system was also determined to evaluate its viability for the large-scale plant. In the analysis, the distribution of the mass flow rate and heat through the MD membrane was determined using the mass and heat transfer models. The energy efficiency of the MD system depends on the operating temperature and concentration of the feed solution. It was observed that the energy efficiency approached 1.15% at a temperature of 20 °C and 60 °C for the cold and the hot compartments, respectively, and feed NaCl concentration of 5 mol/kg. In the RED system, the efficiency of currents to extract low-grade heat was around 1.2%, with the regenerative efficiency being 50%. This calculated energy efficiency confirmed the feasibility of the system to generate low-grade heat that can be converted to electricity. However, to further maximize the extractable power, the electrode material should be improved. Since the properties of both the MD and RED membranes play an important role in determining the total energy efficiency of the process, advanced conductive materials for the membranes can be used. This hybrid technology has potential for harvesting natural power to heat water, which can be utilized for industrial and agricultural applications.

Recently, the hybrid MD-RED system was examined by Tufa et al. [118] for seawater desalination to generate freshwater production and power output. In this study, high energy efficiency was generated of 49% when operating the MD system with the temperature of the hot stream around 60 ^{o}C and synthetic seawater feed concentration around 0.5 mol/L NaCl, whilst the specific energy consumption was slightly reduced at 8%. The resultant brine from the MD with a salinity of about 5.0 mol/L NaCl was transferred to the RED system to boost the extractable power. It was reported that the power density approached 2.2 W/m^2 membrane pairs. This indicated that increasing the MD brine concentration to 5.0 mol/L caused an increase in the attainable energy from the RED system compared to RO brine (1.0 mol/L NaCl) in combination with seawater (0.5 mol/L NaCl). Overall, this reliable and cost-effective hybrid system offers several advantages, such as low brine discharge, harvesting low-grade heat to produce electricity, and is useable in various desalination processes where high-power input is needed.

7.2 Wastewater treatment

7.2.1 RO integrated system

Another water resource is secondary effluent wastewater, and treatment is required to remove pathogens, dissolved solids, and other pollutants to allow the water to be reused in sustainable agriculture. RO membrane-based process is frequently utilized for wastewater treatment globally, due to process enhancements, small footprint, uncomplicated maintenance, high water capacity, and workable process [6]. Among pressure-driven processes, UF coupled with RO is proven to be an effective hybrid system for wastewater reclamation. In line with this, Oron et al. [119] used a pilot plant composed of the UF membrane to separate suspended matter, organic matter, and microorganisms while the complementary RO membrane was used to reject total dissolved solids (TDS). After 681 hours of operation, the UF permeate showed very low turbidity of less than 1.0, low organic matter (BOD = 6.6 mgO_2/l, and COD =64 mgO_2/l), and was free of fecal coliforms. Next, the UF permeate entered the RO system for further purification resulting in water permeate with low organic matter (BOD = 4.8 mgO^2/l and COD = 16 mgO^2/l), lowered salts (TDS=69.8 mg/L, Cl^- = 65.6 mg/L, Na^+ = 42 mg/L, K^+ = 10.4 mg/L, Ca^{+2} = 6.6, Mg^{+2} = 4.4, N-NH^+=10.8 mg/L, and PO_4 = 1.8 mg/L). Treatment by RO membrane produced water permeate that is suitable for agricultural applications meeting the quality guidelines for irrigation water. The RO permeate with minimum dissolved solids, and the lowest SAR value was applied directly to a crop field. This type of treated effluent had a negligible effect on the groundwater salinization and enrichment with undesired nitrates. Despite that, the permeate from stabilization ponds, including high contents of organic matter and a medium level of salinity, led to a higher crop yield.

Shanmuganathan et al. [120] integrated the NF process with the RO process to treat biologically treated sewage effluent aiming at producing irrigation water. The results indicated that the NTR 729HF membrane achieved the greatest rejection rate towards bivalent ions around 99% for SO^{-}$^{2}_{4}$, 62% for Ca$^{+2,}$ and Mg^{+2}. However, a very low rejection was observed for monovalent ions like Na^{+}, Cl$^{-,}$ and NO^{-3} of about 19%, 11%, and 5%, respectively. The NF membrane separated most of the organic matter with a rejection rate around 76–95%, and the permeate contained only 0-0.8 mg/L of DOC. However, the concentration of pharmaceuticals and personal care products, Na^{+} (202 mg/L), Cl^{-} (110 mg/L), and SAR level, were still higher than the allowable level for irrigation water. Therefore, further treatment using the RO membrane was conducted, yielding maximum rejection rate reaching > 99%, 99%, 98%, and 88% for Na^{+}, Cl^{-}, SO$^{-2}_{4}$, Ca^{+2}, Mg^{+2}, and NO$^{-}_{3}$, respectively. The RO membrane rejected valuable nutrients required for crops, and hence 10% of feed water was blended with 90% of RO permeate. The final irrigation water included an acceptable SAR value of 6 and concentrations of Na^{+} (40 mg/L) and Cl^{-} (15.5 mg/L). The hybrid system has potential for the removal of pharmaceutical and personal care products from effluent wastewater to produce high-quality irrigation water and which will not contaminate soil and groundwater.

Later, NF and RO hybrid system was investigated to purify MBR treated wastewater to reuse for agricultural applications [35]. The analysis of the water permeates from the NF and RO processes was performed based on different international standards. It was found that the water permeate from NF is not suitable for irrigation water because the SAR level is 25.7, which may hinder the crop growth and affect the soil permeability. It is most likely that poor rejection of Na^{+} and Cl^{-} and high rejection of Ca^{+2} and Mg^{+2} by the NF membrane caused great SAR value. A second pass with RO was utilized to reduce the SAR value and create irrigation suitable water. The RO permeate showed the lowest concentrations of mineral nutrients, such as Na^{+} (7.83 mg/L) Cl^{-} (4.96 mg/L),

PO_4 (<0.05 mg/L), Ca^{+2} (1.56 mg/L), Mg^{+2} (0.06 mg/L), K^+ (0.93 mg/L), salinity of 0.37g/L, and low SAR value of 12.5. The turbidity of the permeate was reduced from 0.81 to 0.23, satisfying the acceptable level for irrigation water. As the sodium concentration was higher than calcium and magnesium, the water infiltration problem was low. The RO blended MBR with a ratio of 2:1 achieved the best SAR value of (5.30) and low salinity (0.57 g/L). By using this optimum ratio 2:1 of the product water, it can be reused directly for fertigation, improved waste management, and is cost-effective.

7.2.2 FO integrated system

FO treatment process using fertilizer draw solution is attractive because the fertilizer draw solution can be used directly or blended with potable water to irrigate crops. Several studies have been carried out utilizing the FDFO integrated process to treat wastewater due to excess of valuable nutrients for plant growth [48]. However, the diluted draw solution should be mixed with potable water [121]. This is challenging because in many parts of the world freshwater resources are limited. Therefore, the FDFO process, combined with another treatment process, can minimize nutrient concentrations in the diluted draw solution reaching the quality of irrigation water. MBR has been used commonly for wastewater reclamation giving clean water having adequate nutrients concentration for fertigation [17]. For example, the combination of FDFO and an anaerobic membrane bioreactor (AnMBR) was employed to treat wastewater and generate irrigation water for hydroponics [121]. Firstly, the optimum water recovery rate was determined by using Bio-methane potential (BMP) measurements. The performance of a wide range of fertilizer draw solutions in terms of water flux, water recovery, reverse salt flux, and final nutrient concentrations were evaluated in the FDFO when using synthetic municipal wastewater as the feed solution. Biogas generation was increased when increasing the water recovery, and the recovery rate of 95% demonstrated the greatest cumulative biogas production. It was reported that the water flux was strongly correlated to the water recovery, and therefore the performance of both KCl and NH_4Cl draw solutions was similar. Among the tested fertilizer draw solutions, the KCl and NH_4Cl fertilizer draw solutions generated the highest water permeation of 21.1 LMH followed by KNO_3 with 13.2 LMH. The KH_2PO_4 and ammonium phosphate dibasic (DAP) exhibited lowest water flux of about 13.3 LMH. Similarly, the highest water recovery achieved for NH_4Cl and KCl reaching 42.2% and 38.6%. The ammonium sulphate showed the highest water recovery rate around 76% followed by KH_2PO_4 with water recovery around 75% after hydraulic cleaning. The MAP and SOA fertilizer draw solutions exhibited the lowest reverse solute flux around 1.0 and 1.7 gMH, respectively. Although the MAP fertilizer liquid included minimum final nutrient concentration (N=54.1 mg/L/P= 10.8 mg/L / K=0 mg/L), it still needs further dilution by fresh water to reach irrigation water quality.

Another proposed desalination technology for leachate treatment is the combined chemical precipitation method and the FO process. Wu et al. [122] proposed using a pre-treatment strategy involving the addition of carbonate to improve the struvite precipitation and purity, followed by the FO desalination process as presented in Fig. (7). The researchers investigated three aspects to evaluate the performance of the new hybrid system. Firstly, the struvite recovery from landfill leachate, and the influence of the pretreatment method on recovery rate was sought. It was essential to understand how the pre-treatment stage impacted water recovery behavior in the FO system. Lastly, the optimal arrangement of chemical pretreatment, struvite precipitation, and FO water recovery was also assessed. When adding the calcium into the landfill leachate, the magnesium was precipitated as pure struvite. Then, the FO process was used to minimize the volume of wastewater, which eliminated the use of another post-treatment stage and reduced the investment cost. After applying the pre-treatment step with a molar ratio of 1:1.4 for Ca^{+2}: CO^{-2}_3, the Mg^{+2} leakage was decreased by 24.1 ± 2.0% while the rejection efficiency of Ca^{+2} amounted as 89.5 ± 1.7%. The high amount of Mg^{+2} can be recovered of about 98.6 ± 0.1%, and traces of PO^{-3}_4–P detected in the solution of less than 25 mg/L under the condition of (Mg + Ca residual): P molar ratio of 1:1.5 and pH 9.5. The struvite product created from the process showed crystal structure and composition mimicking the commercial struvite (19.3% Mg and 29.8% P). When using 4.0 mol/L NaCl draw solution in the FO system, the water extracted was around 621.5 mL over 95 hours of operational time, meaning 36.6% of recovery efficiency. The FO was capable of lowering the volume of wastewater by 37%. The optimal system configuration was chemical pre-treatment-FO- struvite recovery for the best FO performance.

The FO process can also be integrated with the bioelectrical process to control brine production and extract more pure water from wastewater. During the FO operation, the wastewater feed gets concentrated, and the brine caused more mass transfer resistance for the pure water, which is controlled by the osmotic difference through the FO membrane [123]. A microbial desalination cell (MDC) can be coupled with the FO system to further desalinate the diluted draw solution from the FO system and generate irrigation water. For example, Yuan et al. [124] used the MDC-FO hybrid system to improve the efficiency of the FO to treat wastewater over 16 hours, as illustrated in Fig. (8). The working principle depends on the blending the anode effluents together and using them as the feed solution for the FO process. Two different solutions were produced from the FO process. The concentrated feed solution is fed to the cathode of the MDC to remove the COD whilst the diluted draw solution was purified in the desalination cell of the MDC. The influence of initial COD, salt concentration, and hydraulic retention time were investigated to study the practicality of the hybrid system. In the hybrid system, a synthetic anode solution involving 750 mg/L COD, 35 g/L NaCl solution at the MDC anode, and HRT of 12 h was utilized. It was reported that the hybrid system produced a lower wastewater volume estimated by 64% due to water permeation in the FO and evaporation on the cathode as compared to the stand-alone MDC system (14%). The conductivity reduction in saline water (HRT) was improved by 2-fold as compared to individual MDC systems. The removal efficiency towards COD approached 93%, and the conductivity reduction improved to 99.4% when using a low concentration of NaCl. The efficiency of the hybrid system was promising, which makes it an appropriate desalination process for brackish water or as a pre-treatment method for hypersaline solution and wastewater.

7.2.3 MD integrated system

Wastewater treatment by a MD membrane is an excellent opportunity to eliminate the technical barriers of the RO process. It can be coupled with another membrane process providing fresh water for industrial uses, for fertigation, and for domestic uses. Several studies highlighted that purified municipal wastewater could be reused for irrigation because it contains high quantities of nutrients for crop growth [17]. A group of researchers assessed the performance of a bench-scale FO−MD system to treat for direct sewer mining [125] as shown in Fig. (9). They studied the efficiency of the process based on water permeation and the rejection rate of trace organic contaminants (TrOC). Experimental data showed that the water flux was stable upon using natural sewage as the feed solution in the hybrid process at water recovery up to 80%. The removal rate of trace organic contaminants was high in the range of 91 to 98%. The high rejection of TrOC can be ascribed to the solute−membrane interaction of the FO membrane and, in the case of the MD membrane, was due to the volatility of these species. When the water recovery was increased, there was an increase in the TrOCs concentration in the draw solution. The TrOCs accumulation in the draw solution was probably due to the variation in the removal efficiency between the FO and MD membranes. To avoid this issue, activated carbon adsorption or ultraviolet oxidation can be used to separate these contaminants completely, achieving rejection of more than 99.5%. It was noted that the energy expenditure was high due to operating the MD at a temperature between 20 °C and 40 °C. In this respect, it can a promising process for agricultural purposes in arid areas where renewable power is available.

Xie et al. [126] employed a similar approach to separate phosphorus nutrient and freshwater from digested sludge centrate using a 1.5 mol/L $MgCl_2$ as draw solution. The bidirectional flux of magnesium and protons induces struvite precipitation. The role of FO was to concentrate orthophosphate and ammonium for phosphorus recovery when creating struvite ($MgNH_4PO_4{\cdot}6H_2O$). MD was utilized to regenerate the draw solution and obtain fresh water from the digested sludge centrate. A reduction in the water permeation obtained from the FO membrane due to fouling was observed; however, after the first and second cleaning stages, the water recovery was 82% and 68%, respectively. As a result, a high amount of water permeate was fed to the MD, which exhibited stable water permeation. The hybrid system achieved an excellent rejection of inorganic salts (ammonium and orthophosphate), organic matter (TOC and total nitrogen, TN). Because the magnesium transferred from the draw solution to the concentrated digested sludge and protons diffused in the forward direction, the struvite crystals were created. A decrease in the pH of the feed solution and the accumulation of magnesium facilitated the formation of struvite crystals. Thus, the hybrid system was effective in extracting phosphorus nutrients in the form of struvite precipitate.

A recent study was reported by Volpin et al. [114] using an FO-MD hybrid system to recover nutrients like nitrogen, phosphorous, and potassium from human urine. The optimization and performance of the hybrid system were explored. A novel protocol was developed to minimize the nitrogen transfer to the MD outlet, thereby obtaining water products for direct irrigation. The operating conditions in the FO, like urine pH and draw solution concentration, were optimized. The feed temperature, nitrogen concentration, and membrane properties were optimized for the MD process. It was noted that the FO water permeates ranged from 31.5 to 28.7 LMH upon utilizing 2.5 mol/L NaCl as a draw solution while the nitrogen flux was very low at 1.4 g/L. The nitrogen flux as NH_3/NH^+_4/Urea dropped significantly by 33% when decreasing the hydraulic pressure at the draw solution side to 2.0 bar, but a decline in the water flux by 42% was noticeable. When the feed solution became acidic (pH =6-7), the nitrogen rejection by both the FO and MD membranes was improved. The importance of acidification was to maintain a high rejection of nitrogen and to prevent the hydrolysis of urine. The MD membrane achieved maximum distillate permeate of 16 LMH due to high porosity and hydrophobicity. The ammonia vapor pressure was raised due to the high concentration of ammonia and inlet temperature of 60 °C. The membrane pore size and thickness controlled the transport of ammonia through the membrane. It was concluded that this dual separation process was reliable for wastewater treatment in space application and nutrient regeneration for urban applications.

7.2.4 ED integrated system

The membrane desalination technology operated based on thermodynamic reaction is an attractive method for converting extractable power to electricity that created with water recovery [127]. It is recognized that the accumulation of various nutrients on the feed stream due to reverse solute flux and salinity build-up from the membrane rejection is one of the key challenges in the FO process. To avoid this technical hurdle, the ED system was coupled to an FO system for further treatment of the concentrated feed solution and therefore controlling the salinity build-up on the feed stream [128]. The combination of FO and ED processes delivered a remarkable advantage for wastewater treatment. Zou et al. [129] followed this strategy to desalinate wastewater using $(NH_4)_2HPO_4$, fertilizer draw solution. A schematic of the hybrid system is demonstrated in Fig. (10). In the FO system, the influence of draw solution concentration on the water recovery and reverse solute flux was investigated. In the ED system, the removal efficiency, regeneration of the fertilizer draw solution, and energy consumption using different applied voltages was also studied. Experimental findings demonstrated that the FO process generated a stable water recovery volume around 375.5 mL when utilizing concentrated fertilizer draw solution (2.0 mol/L). A minimum specific reverse solute diffusion of 0.063 g/L and 0.083 g/L for NH_4-$^{+}$N and $PO^{-3}{}_4$–P nutrients, respectively, was observed upon using 1.0 mol/L draw solution. The negligible concentration of Na^+, Cl^-, and organic constituents was detected in the diluted draw solution, and therefore the diluted draw solution is reusable for fertigation. At the optimum applied current of 3.0 V, the ED showed excellent water recovery of 96.6 ± 3.0% reverse-fluxed draw solution. The specific energy consumption of the hybrid system was very low of about 0.72 kWh m^{-3} and 0.35 kWh m^{-3} (55.7% reduction) when applying 2.5 V and 3.0 V, respectively. The synergistic cooperation of both processes achieved excellent water recovery and consistent performance.

Ippersiel et al. [130] integrated an ED system with an air stripping method to concentrate ammonia nutrients followed by direct aeration or vacuum to separate the volatile ammonia from the concentrate solution by an acidic trap. The aim was to extract concentrated nitrogen fertilizer from liquid swine manure through the addition of acids to eliminate scaling stripping towers. In the ED process, the optimum applied voltage was 17.5 V resulting in efficient energy expenditure. The best pH values of the feed solution were ranged from 8.5 to 8.2, facilitating electromigration of NH_4. It was noted that the maximum achievable ammonia nitrogen recovered was 21 352 mg/L in the concentrate solution corresponding 7-folds the concentration in the swine manure. This value was greater by 33% than that extracted from the open-to-the-atmosphere system. In this work, 95% of the TAN was recovered from the swine manure utilizing a closed-to-the-atmosphere system. The increase in concentration of the solution was hindered during the process due to the transport of the pure water from the diluted stream governed by electroosmosis and osmosis. When the concentrate reservoir was exposed to vacuum, the ammonia recuperated was around 14.5% of the theoretical value of the NH_3 in the concentrate solution relative to 6.2% only when applying aeration. However, effective energy usage caused a lower concentration gradient between the concentrate and the diluted solutions by a factor of 10. This caused the presence of swine manure TAN traces in the diluted solution after shutting down the process. The pH of the concentrate solution should be increased to more than 8.6 further to improve the volatilization of NH_3 toward the acid trap.

Vecino et al. [131] proposed using liquid-liquid membrane contactors (LLMCs) to re-concentrate ammonia from wastewater as ammonium salts (NH_4NO_3 and $NH_4H_2PO_4$). Two different concentrations of ammonia fertilizer as feed solutions (1.7 g/L, N= 0.33% (w/w)-4.0 g/L, N= 0.14% (w/w)) were used to create ammonium salts by an acid stripping solution (nitric and phosphoric acid). After that, the ED system was connected to the LLMCs for further desalination of the LLMCs permeate and obtaining product water depicting the quality of irrigation water. In this work, over 29.0 hours of LLMCs experiment, the ammonia concentration declined to 0.03% (w/w) of nitrogen at 360 mg NH_3/L when utilizing high initial concentration of fertilizer feed solution. However, the ammonia concentration was further reduced to 0.02% (w/w) of nitrogen around 240 mg NH_3/L over 12.5 hours when using a low initial concentration of fertilizer feed solution. After that, the ED was capable of concentrating these ammonium salts by a factor of 1.6 ± 0.3, which created a liquid fertilizer contained 15.6% (w/w) and 16.2 ± 1.2% nitrogen as NH_4NO_3 by Fujifilm membranes and a PCCell, respectively. Under constant applied current of 7 V., The estimated energy consumption was as low as 0.21 ± 0.08 kWh/kg ammonium salt and 93.1 ± 4.2% of faradaic yield. This indicated that this novel hybrid system is a promising technology for the valorization and recovery of ammonia nutrients from wastewater solutions.

8 Conclusions

Water desalination and wastewater treatment could have useful impacts on fertigation and environment providing additional water resources and regenerating poor-quality water. Membrane technologies can supply water for agriculture and increasing food production. The stand-alone or hybrid RO and FO membrane-based processes are proven to be the most effective desalination technologies used in many countries around the world. Due to the efficient separation performance, low fouling tendency, reduced energy expenditure, widespread for saline water desalination and wastewater treatment, they can provide fertilizer solution and irrigation water with an acceptable level of nutrients for fertigation. The stand-alone RO and electrodialysis are available, have effective performance, and can provide high quality nutrient water, but the water production cost is still higher than that for common technologies used for agriculture. A potential approach to desalinate hypersaline feed solution is the MD system. It can produce high quality water, but it should be blended with liquid nutrients to reach the acceptable standard of irrigation water. Also, the MD system requires high thermal energy which increases the energy consumption and the operating cost. The MBR process generates water enriched nutrients from wastewater effluent and can be reused immediately for fertigation. On the other hand, membrane fouling is a serious problem due to high concentration of complex wastewater and the energy consumption of the system is considered high. Thus, the operating and maintenance costs are high due to frequent replacement of the membrane and high energy demand. Furthermore, hybrid FO process can achieve efficient nutrient recovery and low energy consumption only if natural energy is available for recycling of the draw solution. Integrating MD with another membrane desalination technology is promising for nutrient recovery when RO brine is used as the feed solution. This is because the concentrated brine is valuable source of mineral nutrients and therefore no need to discharge high volume of brine to the sea. Other technologies such as MD and ED processes will be applied for agricultural purposes where natural energy is abundant and can be utilized to reduce the energy requirements and overall cost. Among stand-alone and hybrid desalination technologies evaluated in this review, FO coupled ED processes showed superior performance efficiency and minimum energy expenditure around 0.35 kWh m^{-3}. Although these membrane technologies for treating saline water or wastewater are expensive, they could be cost-effective when producing nutrient water for fertigation, increasing crop production, and enhancing the quality of crop yield. To that end, all these membrane-based desalination technologies require advances in irrigation water practices, reducing the need for freshwater supply resources, and maximizing water reusability efficiency.

9 **Future prospects**

The membrane in an individual treatment process has often failed in providing the required quality for irrigation water for diverse types of feed salinities. The additional purification of the diluted draw solution to reach the quality water nutrient can be achieved using another desalination technology process. The recovery system should possess minimum energy expenditure and efficient output. The recovery process combined with the desalination process is necessary in some cases to re-concentrate the draw solution, extract valuable nutrients, and produce drinking water. Other merits are accelerating the water production, decreasing the energy requirement, recover nutrients from hypersaline solution and wastewater, and lowering the volume of brine and wastewater for discharge. The hybrid desalination systems in this review generated product water with varying qualities depending on the availability of freshwater resources, the type of crops, and soil. However, if a perfect draw solution in the FO system provided water nutrients suitable for direct irrigation, the recovery method can be ignored, and minimal power is needed. For instance, the FO integrated MD system can potentially generate irrigation water and drinking water when using a complex wastewater stream or brine containing nutrients and a thermolytic fertilizer draw solution. The implementation of the FO-MD process in the industry needs special consideration related to promoting system design and heat recovery. The use of a heat exchanger can improve the energy efficiency of the system [132]. Besides, this system can be considered energy-wise, cost-effective, and low environmental impacts, especially if low-grade heat source or natural power such as effective solar absorber, waste heat, geothermal heating, is supplied to the recovery system. The production of vapor by solar energy can be increased through efficient solar absorptive materials like carbon nanomaterials, plasmonic materials, metal oxide nanomaterials, and non-thermal-conductive material such as wood and foams. Currently, research is directed to maximize energy efficiency by determining latent heat recovery [132]. The improvement of latent heat recovery depends on optimizing the system design.

Another promising technology is the MD coupled ED system to recover nutrients and convert the thermal potential of MD brine and energy of mixing to electricity. To fulfill commercial potential for the MD-ED hybrid process, on-site optimization of membrane-based processes through the mobile pilot plant can be an effective suggestion for evaluating the operating parameters. Many works devoted to developing novel electrode materials like pseudocapacitive and carbon materials with superior electrical conductivity, fast rapid adsorption, and desorption of salts, and high salt adsorption capacity to promote the system efficiency [49, 132, 133]. Increasing the electrode capacitance is important because a lower amount of applied voltage would be required, and a certain amount of charges would be stored [132].

Another important aspect is developing revolutionary anti-fouling TFC membranes by impregnation of antibacterial nanomaterials like graphene oxide, carbon nanotubes, catalytic nanoparticles such as titania (TiO_2), silver or copper nanoparticles [134]. The long-term performance of the membranes can be further increased by removing foulants and their precursors through transparent exopolymer particles (TEP), and novel modification strategies such as layer-by-layer assembly, polymer grafting, zwitterionic coating with easy to scale up procedure and multifunctionality [135]. An alternative method to alleviate fouling is using a pre-treatment stage such as UF or MF membrane, but this practice can impose an additional energy cost. Therefore, employing real-time monitoring is a promising option to monitor fouling in early-stage, and its effectiveness needs to be tested during large-scale operations on-site [135].

As most of the alteration strategies consider improving the surface properties, other membranes (i.e., FO and RO) suffer internal fouling. To reduce internal fouling effects, designing and tailoring the porous support layer is essential [61]. A balanced permeability–selectivity tradeoff can be achieved when incorporating one-dimensional (1-D) nanotubes, two-dimensional (2-D) nanosheets, and biomimetic channels into membranes [132]. The water flow through the additional channels in the membrane governed by the improved diffusion under slip flow conditions. This slip flow conditions created when the water molecules interacted with the channel surface yielding a nonzero velocity and failure of no-slip boundary condition.

For MD membranes, the selection of membrane materials and characteristics is important to mitigate chemical deterioration and improving thermal conductivity. An advanced glass membrane showed excellent thermal and chemical efficiencies as compared to polymeric membranes [136]. The thermal efficiency can also be enhanced by incorporating self-healing metal nanoparticles or carbon-based sunlight absorbers into the MD membrane [118], photothermal surface coatings like plasmonic nanoparticles [132]. Furthermore, membranes with high hydrophobicity are required to reduce wetting, fouling, scaling, and purer condensate. Prior research suggested that scaling can be minimized when exposing the membrane to superhydrophobic fluorosilicone coatings [136], but the stability and separation performance in long-term experiments necessitate further investigations.

For the ion exchange membrane, high water–solute selectivity of higher than 95% and a low resistance material with a price less than 4 €/m^2 are the main elements to promote the membrane separation performance [137]. The performance of membranes incorporating polyolefin, polyaryletherketones, halogenated polyethers, polyethylene, and poly(arylene ether sulfone) opened room for further explorations. Moreover, researches should be dedicated to optimizing the stack design involving spacers and electrodes. The design and evaluation of new geometries and shapes of spacers to decrease pressure loss and polarization phenomena are necessary [49]. In parallel, a novel stack design involving manifolds layout can ameliorate the solution flow distribution in the feed channels and should be tested in a real application. It is possible to enhance the fluid dynamics, mixing behavior of the feed stream, lower resistance, and pressure drop employing by using an ion-exchange membrane with optimum geometry leading to extraordinary power output [137]. To exploit a large amount of natural power from the low-grade heat source, a closed-loop RED system is workable, especially when it is integrated with another desalination technology achieving low overall energy consumption [137]. To achieve commercialization of the hybrid system, accurate thermo-economic analysis, and cost assessment for a pilot plant in the field are needed [138]. Also, establishing thermodynamic models to evaluate the performance of the membrane and overall process is needed for scaling up the process and realization in the agricultural industry.

Although these membrane-based techniques present several challenges, they could be a viable option to produce irrigation water for agricultural applications. The prospect of implementing industrial plants with optimal operating conditions and system design does not depend only on the important requirements for each desalination process but also makes the membrane the most significant factor for water generation in the agriculture industry.

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Figure Captions

Figure.1: A diagram of the BWRO desalination plant located in the island of Gran Canaria [68].

Figure.2: A schematic diagram of the semi-pilot scale fertilizer drawn FO system (FDFO) utilizing hollow fiber membrane module. The lumen side of the hollow fiber membrane made of PA TFC active layer on top of the polyethersulfone (PES) support layer on the outer shell of the fiber. Adapted with permission from Lotfi et al.[75].

Figure.3: The common stack unit consisted of cation exchange membranes (CEMs) and anion exchange membranes (AEMs) arranged in alternating sequences. The electrochemical potential is produced when passing each high concentration compartment (HCC) and low concentration compartment (LCC) generated by aligning alternatively both membranes. The salinity difference between both solutions allowed the transfer of ions from the membrane to electrodes. This resulted in a redox reaction to extract electricity. Adapted with permission from Tufa et al. [137].

Figure.4: The design of the capacitive de-ionisation system. A circulation pump is used to drive the solution to the cell and the effluent return to the inlet tank with a volume of 25 liter. The cell is supplied with the required voltage via a power supply. The temperature of the solution was kept constant at 25 °C and the flow rate was fixed at 0.5 L/min. Reproduced with permission from Mossad et al. [86].

Figure.5: A schematic diagram of the fertilizer driven FO unit (FDFO). It consists of a membrane cell with dimensions of 2.6 cm width x 7.7 cm length x 0.3 cm depth. The membrane active area is of about 20.02 cm^2. The draw solution container is placed on a digital scale to calculate the permeate volume. Both conductivity and pH meters were connected to the feed container to measure the pH and conductivity of the feed solution. Reproduced with permission from Volpin et al. [139].

Figure.6: A schematic diagram of the RO combined adsorption system. The RO rig involves of several vessels containing membrane modules, pressure exchanger that generate energy from rejected solution to circulation pump. The adsorbent was made of Silica gel type-RD. Adapted with permission from Atab et al. [110].

Figure.7: The lab-scale unit of chemical precipitation pre-treatment procedure integrated the FO process. The FO process was arranged in three different modes: 1- FO – calcium pretreatment - struvite precipitation (C1), 2- calcium pretreatment - FO - struvite precipitation (C2) and 3- calcium pretreatment - struvite precipitation - FO (C3). Adapted with permission from Wu et al. [122].

Figure.8: A diagram showing the microbial desalination cells (MDCs) and forwards osmosis (FO) hybrid system. CEM is the cation exchange membrane while AEM is the anion exchange membrane. Adapted with permission from Yuan et al. [124].

Figure.9: The design of the FO−membrane distillation (MD) process composed of FO membrane channel, a direct contact MD membrane compartment, pumps, temperature monitoring sensors. Adapted with permission from Xie et al. [140].

Figure.10: A schematic diagram of the FO−Electrodialysis (ED) hybrid process with a semi-continuous configuration. Adapted with permission from Zou et al. [129].

Figures

Graphical abstract

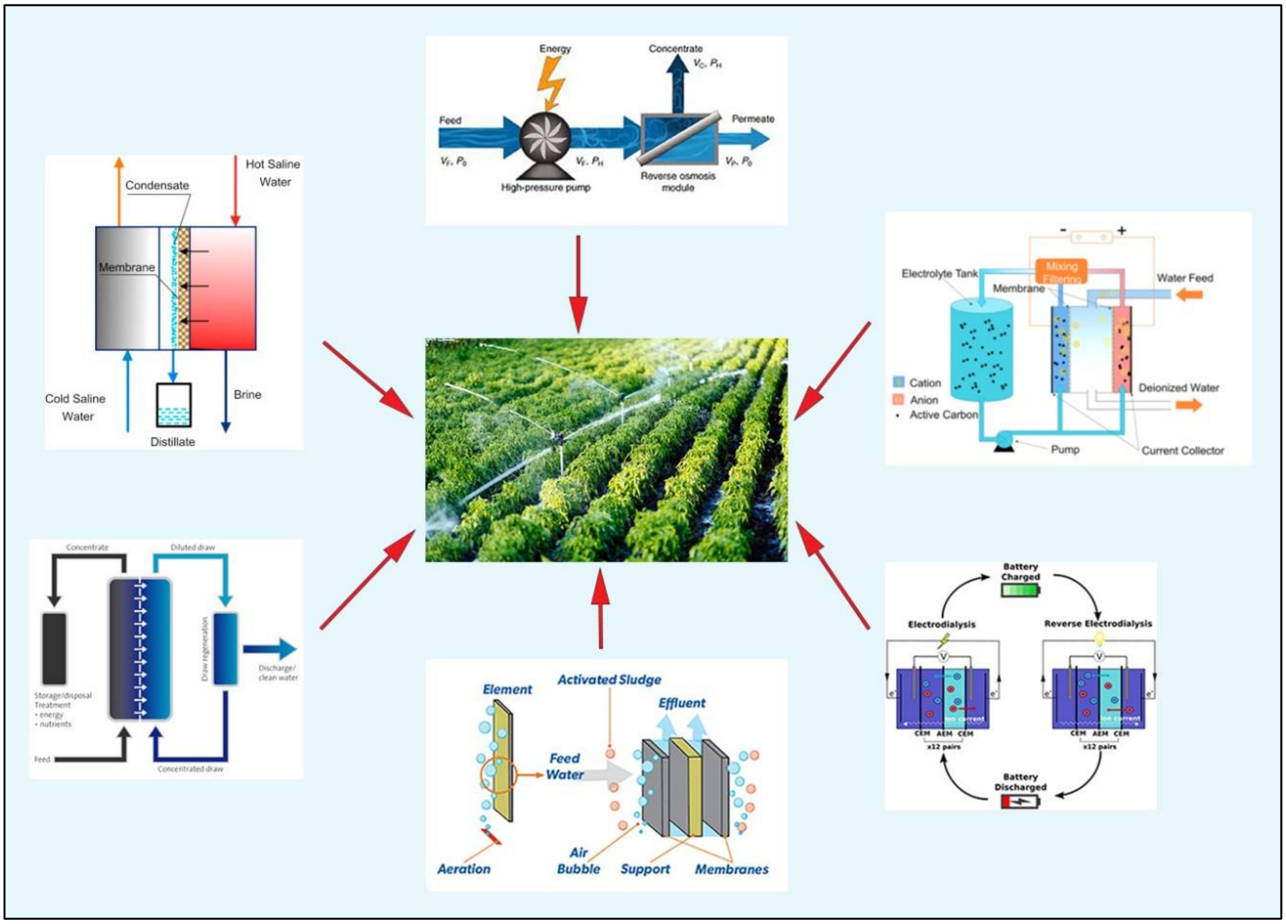


Figure.1

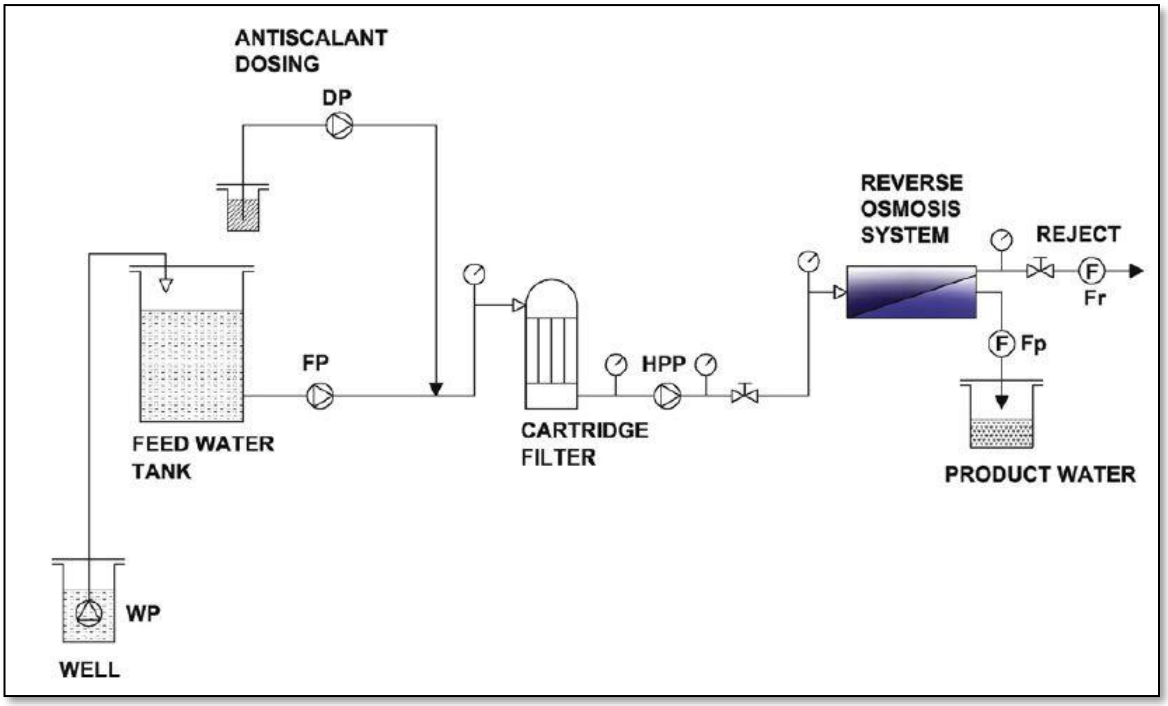


Figure.2

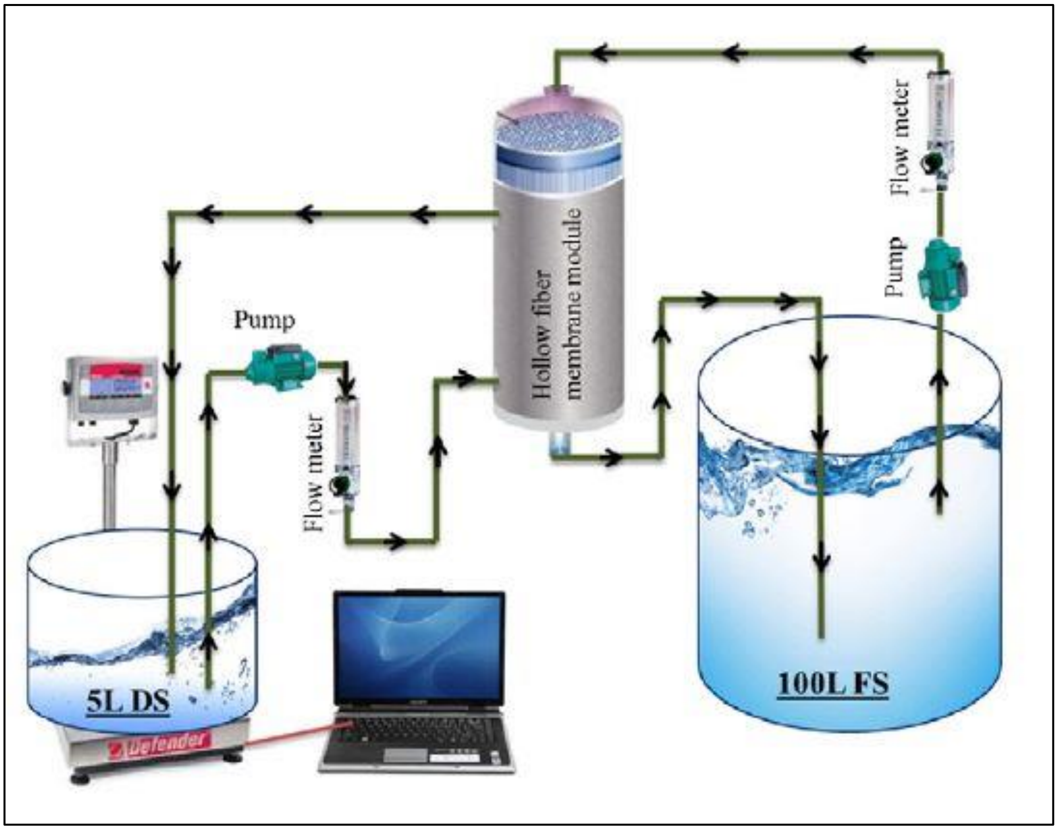

Flow meter
Pump
Hollow fiber membrane module
Pump
Flow meter
5L DS
Defender
100L FS

Figure.3

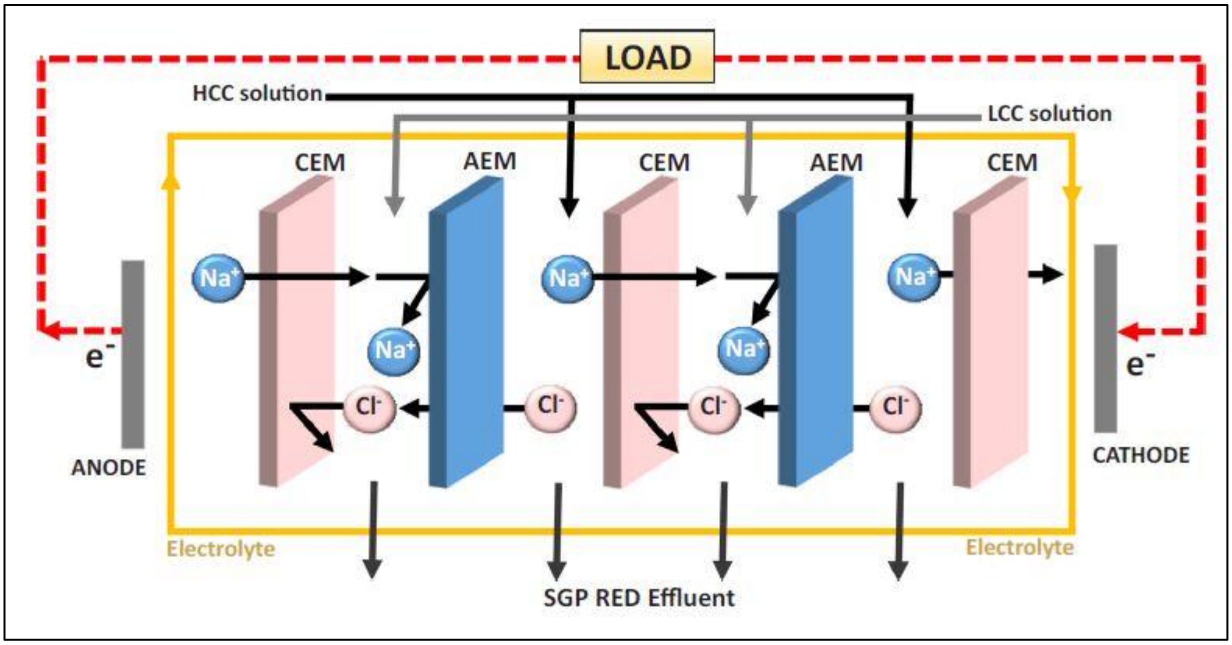

LOAD
HCC solution
LCC solution
CEM
AEM
CEM
AEM
CEM
Na+
Na+
Na+
Na+
Na+
Cl-
Cl-
Cl-
Cl-
e-
e-
ANODE
CATHODE
Electrolyte
Electrolyte
SGP RED Effluent

Figure.4

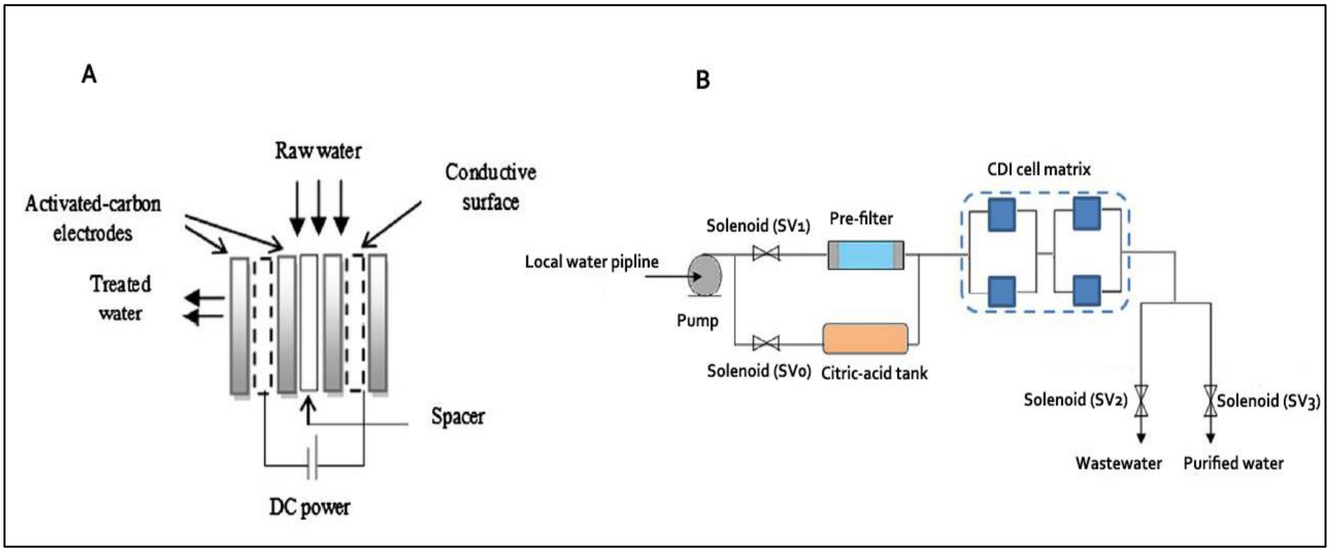

A
Raw water
Conductive surface
Activated-carbon electrodes
Treated water
Spacer
DC power
B
CDI cell matrix
Solenoid (SV1)
Pre-filter
Local water pipline
Pump
Solenoid (SV0)
Citric-acid tank
Solenoid (SV2)
Solenoid (SV3)
Wastewater
Purified water

Figure.5

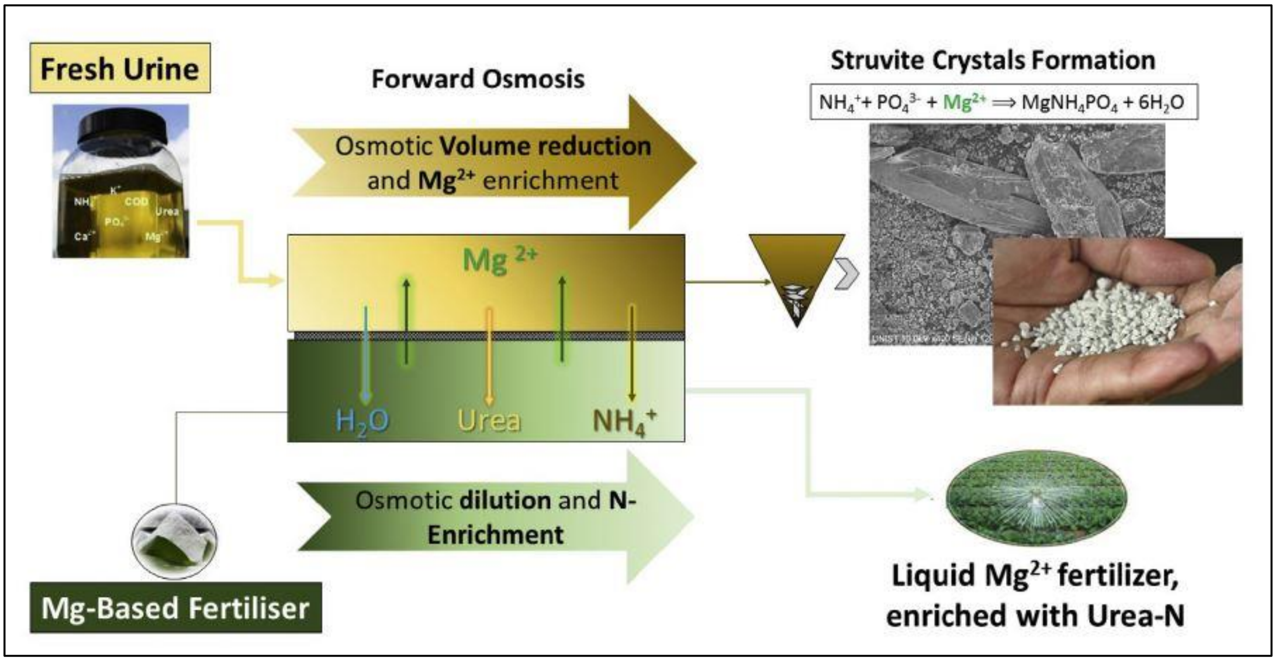


Figure.6

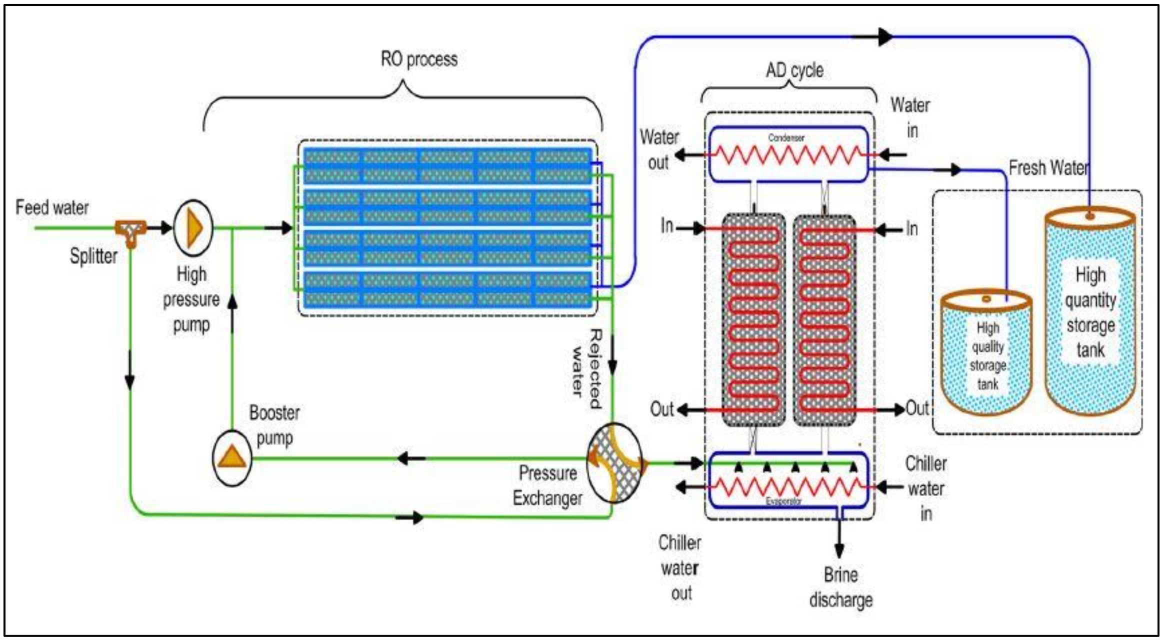

RO process
AD cycle
Water in
Water out
Condenser
Fresh Water
Feed water
Splitter
High pressure pump
In
In
High quality storage tank
High quantity storage tank
Rejected water
Booster pump
Out
Out
Pressure Exchanger
Chiller water in
Evaporator
Chiller water out
Brine discharge

Figure.7

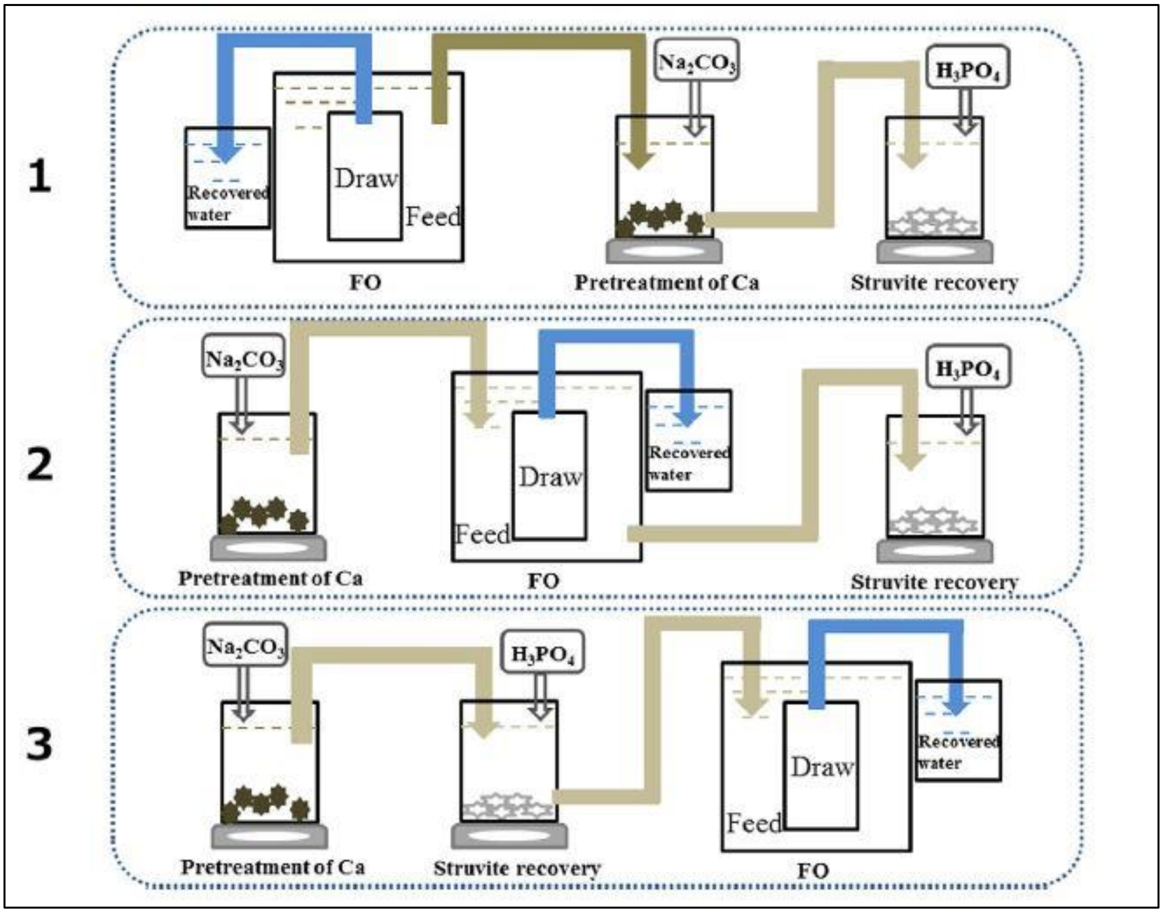

1
Recovered water
Draw
Feed
FO
Na_2CO_3
Pretreatment of Ca
H_3PO_4
Struvite recovery
2
Na_2CO_3
Pretreatment of Ca
Draw
Feed
FO
Recovered water
H_3PO_4
Struvite recovery
3
Na_2CO_3
Pretreatment of Ca
H_3PO_4
Struvite recovery
Draw
Feed
FO
Recovered water

Figure.8

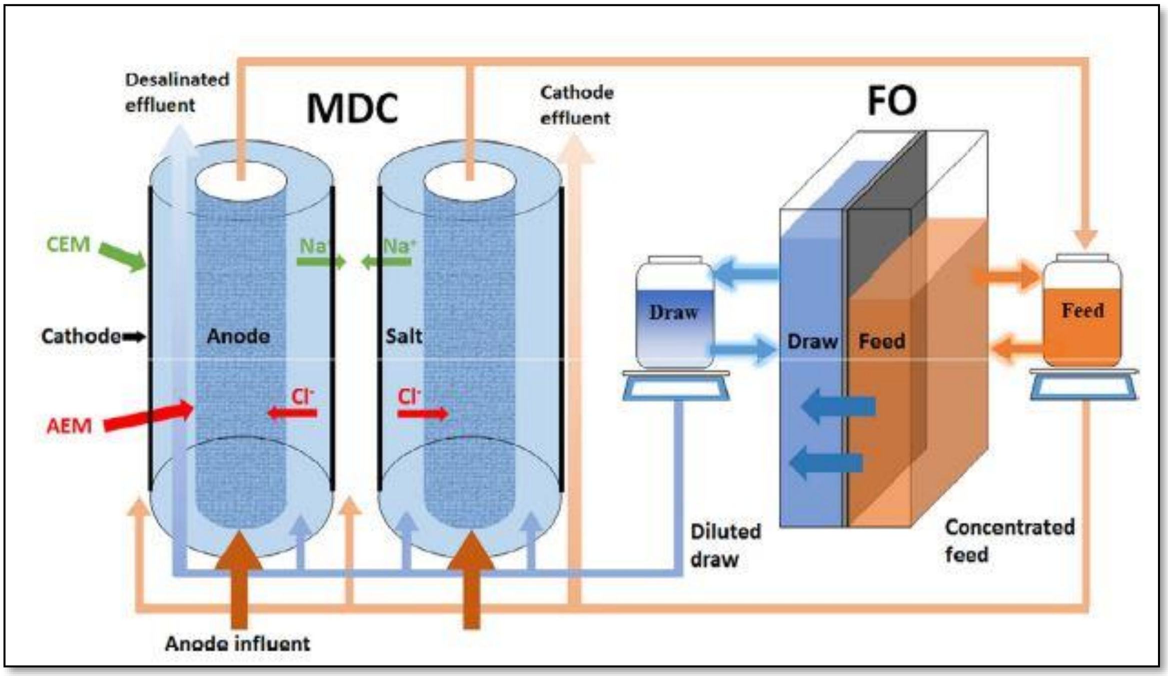


Figure.9

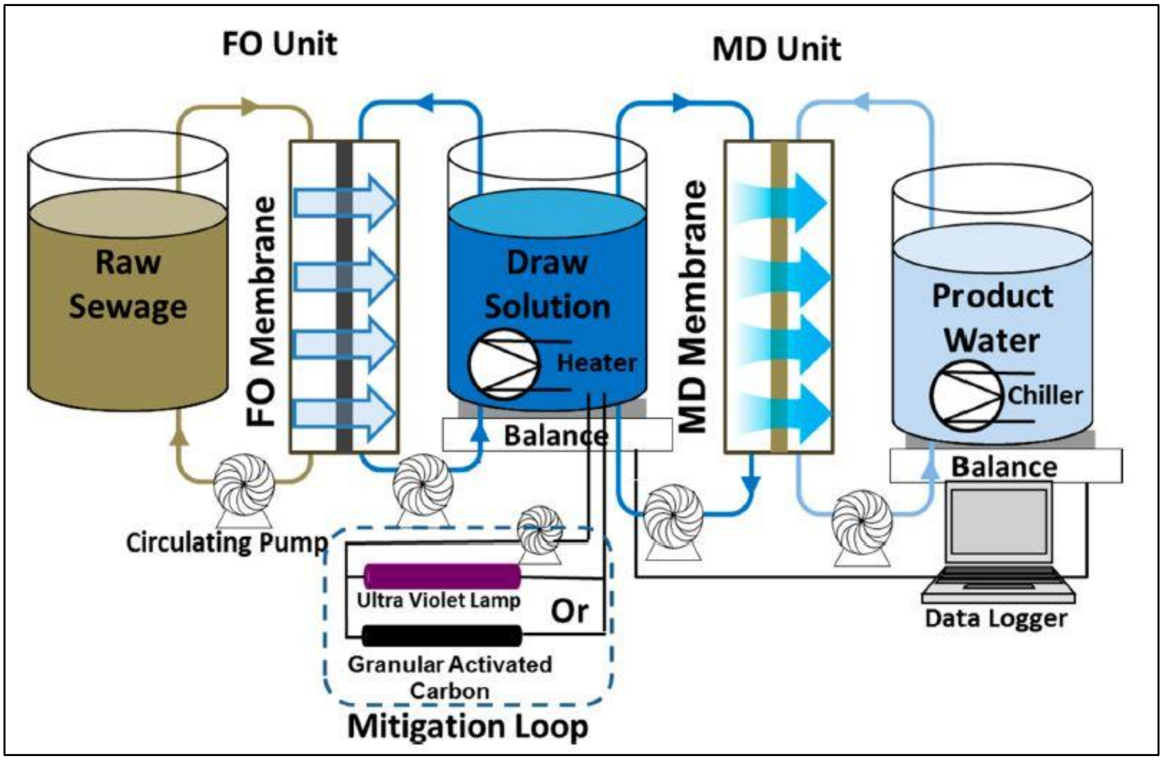
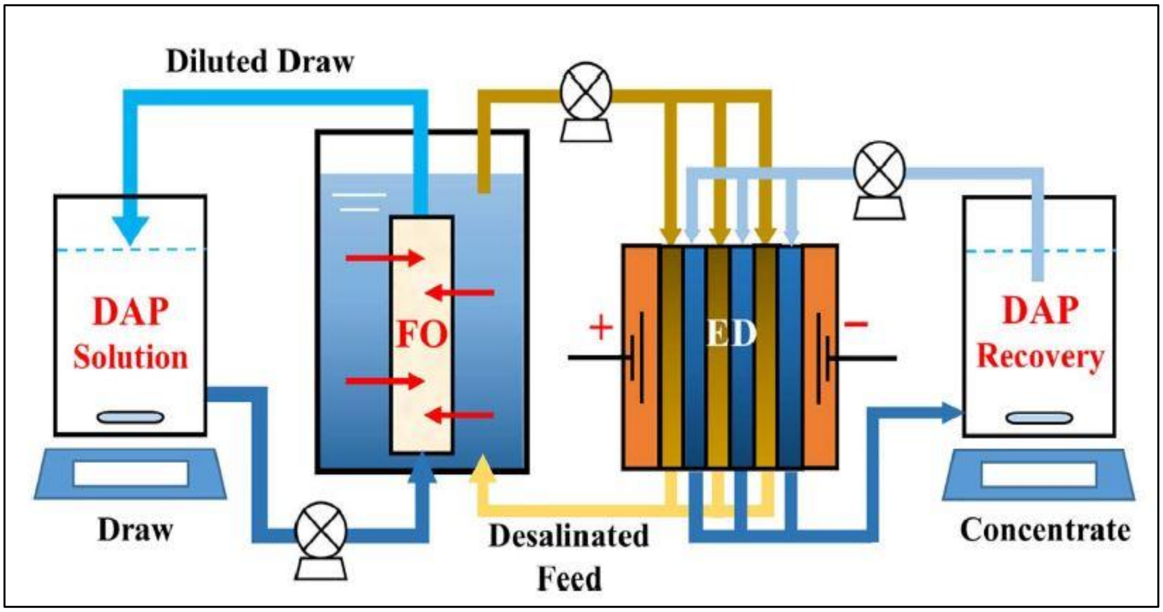


Figure.10


Diluted Draw
DAP Solution
Draw
FO
+
ED
−
DAP Recovery
Concentrate
Desalinated Feed

List of tables

Table.1: The important properties of pressure driven membrane processes which is classified into reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF). Reproduced with permission from Pangarkar et al. [95].

Membrane technology	Applied pressure (kPa)	Minimum particle size removed	Pollutant removal (type, average removal efficiency%)
Microfiltration	30–500	0.1–3 μm	Turbidity (>99%); bacteria (>99.99%)
Ultrafiltration	30–500	0.01–0.1 μm	Turbidity (>99%); bacteria (>99.99%); TOC (20%)
Nanofiltration	500–1000	200–400 daltons	Turbidity (>99%); color (.98%); TOC (>95%); hardness (>90%); sulfate (>97%); virus (>95%)
Reverse osmosis	1000–5000	50–200 daltons	Salinity (>99%); color and DOC (>97%); nitrate (85–95%); pesticide (0–100%); As, Cd, Cr, Pb, F removal (40–98%)

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