Desalination for agriculture: water quality and plant chemistry, technologies and challenges

Rajesha Kumar, Mansour Ahmed, G. Bhadrachari and Jibu P. Thomas

ABSTRACT

The growing scarcity of fresh water has motivated the use of non-conventional and re-used water resources for agriculture by applying some efficient technologies. The desalination technologies for agricultural irrigation play a major role in satisfying growing water demands in water scarce regions. Due to stringent ionic concentration standards for agricultural irrigation water, desalination for agriculture is more energy demanding and additional post-treatment is requisite. Reverse osmosis (RO) has emerged as an efficient technology, but the burning of fossil fuels to fulfil the energy requirements is becoming expensive and emission of greenhouse gases is recognized as harmful to the environment. Thus, efforts should be directed towards cost reduction by integrating renewable energy resources into the process. Many of the bench and pilot scale trials like integrated RO with low energy such as forward osmosis (FO), nanofiltration (NF), microfiltration (MF) and solar energy revealed significant improvements in cost savings. However, all these modern technologies have their own problems which can be overcome by further research and development. This paper aims to review the main benefits and constraints associated with desalination technologies for agriculture. The available water resources, the desired qualities of water for agriculture and the challenges and future of desalination in agriculture are discussed.

Key words | agriculture, desalination, plant nutrients, water quality

Rajesha Kumar (corresponding author)
Mansour Ahmed
G. Bhadrachari
Jibu P. Thomas
Water Research Center,
Kuwait Institute for Scientific Research,
P.O. Box 24885, 13109 Safat,
Kuwait
E-mail: *ralambi@kisr.edu.kw*

INTRODUCTION

Seawater desalination is playing an important role in addressing the challenge of global water scarcity. The most important drivers for water scarcity are growing water demands due to population growth and economic development, and increased per capita consumption of goods and services (Vorosmarty *et al.* 2005). The total global water demand is dominated by agricultural use (70%) followed by industrial use (21%) and domestic use (9%). Limited water resources have enforced the use of low-quality irrigation water. Using low-quality irrigation water may reduce crop yields and damage the environment, soils, and aquifers. Therefore, with increasing water scarcity, development of efficient water sources for agricultural use is the major challenge that the growing population is currently facing.

Seawater, brackish water or wastewater desalination are the only alternatives to increase water supply beyond what is available from the hydrological cycle (Shannon *et al.* 2008). The climate changes due to global warming are constantly increasing the salinity level of both land and seawater, reducing the availability of existing fresh water for households, agriculture and industry. A study from Diaz *et al.* (2013) demonstrated that irrigation with desalinated seawater led to a significant increase in salinity and boron in the soils that could affect the yield of moderately tolerant crops. This has made it urgent to invent an appropriate water treatment technology that not only removes macro, micro and nano-pollutants but also desalinates water to a

doi: 10.2166/ws.2017.229

significant extent. Continued research and development of new treatment technologies are essential to improve the availability and quality of water supplies for agricultural use (Shannon *et al.* 2008). Consequently, thermal and membrane based desalination technologies are playing an important role in solving global water scarcity problems.

Desalination not only separates the undesirable salts from the water, but also removes ions which are essential to plant growth. The desalinated water when applied to agriculture has added advantages as it contains sufficient levels of nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) (Yermiyahu *et al.* 2007). According to Domingo *et al.* (2013) the important features of desalination for agriculture are: (a) no requirement for post-treatment since the water produced will be rich in nutrients, (b) the presence of boron above 0.5 ppm is toxic to crops, (c) reduced labor requirements, (d) reduced energy costs and (e) reduced requirements for civil works. There are two desalination technologies which are dominant in the production of water for agriculture and these are brackish water reverse osmosis (RO) and seawater reverse osmosis (SWRO). SWRO has emerged as the more advanced and leading technology due to better product water quality, lower energy requirements and hence lower cost of water compared to thermal desalination technologies (Shaffer *et al.* 2012; Domingo *et al.* 2013).

Treated wastewater is the other source of water for agriculture and the technology most commonly employed for this treatment is desalination. However, the efficiency of desalination technologies in terms of costs and energy requirements is considered as a barrier to its implementation in agricultural use (Greenlee *et al.* 2009; Shaffer *et al.* 2012). A proper balance between crop value and the total desalination cost is essential to make use of the technology on a large scale. This paper discusses the issues, benefits, and features of desalination technologies in agriculture. It covers the chemistry of plant nutrients, irrigation systems, the desired quality of water for agriculture, the available water resources and existing desalination technologies to fulfil the water demand in agriculture. Further, the features, cost factors, opportunities and challenges of desalination technologies in a number of different countries are discussed.

FEATURES OF DESALINATION FOR AGRICULTURE

One of the important features of desalination for agriculture is the feed water quality. The use of saline water for irrigation increases the salinity of soil if sufficient care is not taken to leach the attached salts from the plant roots. The additional amount of water required for leaching depends on the salinity of the irrigation water and the specific salt tolerance of the crop to be irrigated. Generally, seawater is most promising resource for desalination in the future due to its enormous availability. Also, the production of desalinated water for agricultural purposes can be augmented if the production cost of the process is optimized.

Water quality and plant chemistry

The selection of a suitable desalination technology for agricultural use depends upon the type of crop and its water quality requirement. According to Birnhack *et al.* (2010) the recommended quality parameters to be considered when using desalinated water for combined agricultural and municipal uses are: electrical conductivity (EC), concentration ranges of Cl^-, Na^+, B, Ca^{2+}, Mg^{2+} and SO_4^{2-}, alkalinity, the water stability index in terms of calcium carbonate precipitation potential (CCPP), and pH. Based on Israeli experience in desalination for agriculture, Yermiyahu *et al.* (2007) proposed values of water quality parameters recommended for agricultural use (Table 1). Further, they concluded that the presence of certain minerals such as Ca^{2+}, Mg^{2+} and SO_4^{2-} in the desalinated water acted as additional external fertilizer in the product water. The salinity of the desalinated water, especially the NaCl concentration, will decide the EC value.

Effect of salinity

The high salinity of the irrigation water is one of the causes of low productivity of the crops. The use of highly saline water for agricultural use (>100 ppm) commonly leads to deposition of sodium ions at the plant roots which act as an inhibition layer for the uptake of nutrients. This will cause water stress for the plant and it will no longer be able to extract water from salty soil. If water uptake is

Table 1 | Recommended qualities of desalinated water for agriculture based on Israeli agricultural experience (Greenlee *et al.* 2009)

Parameter	Standard seawater composition (at 3.5% salinity)	Recommendation for domestic and agricultural usage
Electrical conductivity (dS/m)	47.7 (Gros *et al.* 2008)	<0.3
$[Cl^-]$ (mg/l)	19,345 (Gros *et al.* 2008)	<20
$[Na^+]$ (mg/l)	10,752 (Abdel-Satar *et al.* 2017)	<20
$[Ca^{2+}]$ (mg/l)	416 (Rahmawati *et al.* 2012)	32–48
$[Mg^{2+}]$ (mg/l)	1,295 (Abdel-Satar *et al.* 2017)	12–18
$[So_4^{2-}$-S] (mg/l)	2,701 (Abdel-Satar *et al.* 2017)	>30
[B] (mg/l)	4.0–5.0 (Hasson *et al.* 2011)	≤ 0.4
Alkalinity (mg/l as $CaCO_3$)	1,697 (Abdel-Satar *et al.* 2017)	>80
pH	7.5–8.4 (Abdel-Satar *et al.* 2017)	<8.5

appreciably reduced, the plant slows its rate of growth. The lack of nutrients makes the crops very susceptible to disease and low yields. High sodium concentrations in soil can cause deterioration of the physical condition of the soil; for example, by waterlogging, the formation of crusts, and reduced soil permeability (Nable *et al.* 1997). It is necessary to adjust the sodium adsorption ratio (SAR), related to modification of soil structure and impermeabilization. The optimum salinity for many crops (almond, orange, pepper, lettuce, cucumber, tomato, broccoli and celery) is below 2 mS/cm. Any increase reduces productivity, which becomes almost zero at 4.5–5 mS/cm. The ions such as chlorides, boron, nitrates and ammonium will contribute to the salinity of irrigation water. Table 2 represents the damage caused to crops by varying the salinity of agricultural water. Oxygen demand is an important parameter for assessing the concentration of organic contaminants in treated waste water. Biochemical oxygen demand (BOD) is a measure of the amount of oxygen that bacteria will consume while decomposing organic matter under aerobic conditions. BOD is expressed in milligrams per liter (mg/l) and measured by the incubation of a water sample over a specified period (usually five days) at a constant temperature of 20 °C in the dark. BOD is an important water quality parameter because it provides an index to assess the effect discharged wastewater will have on the receiving environment. The higher the BOD value, the greater the amount of organic matter available for oxygen consuming bacteria. Chemical oxygen demand is the amount of oxygen consumed in the oxidation of organic compounds by strong oxidizing agents. Though there are several methods, because of the influence of the salts, the alkaline potassium permanganate method is widely used in seawater monitoring and investigation. The amount of dissolved oxygen in streams is dependent on the water temperature, the quantity of sediment in the stream, the amount of oxygen taken out of the system by respiring and decaying organisms, and the amount of oxygen put back into the system by photosynthesizing plants, stream flow, and aeration.

Table 2 | The damage caused by irrigation water by varying the salinity (Yermiyahu *et al.* 2007)

Parameters	No damage	Increasing damage	Serious damage
TDS (mg/l)	<375	375–1,500	$>1,500$
SAR	<6.0	6.0–9.0	>9.0
Root absorption: sodium (mg/l)	<70	70–210	>210
Root absorption: chloride (mg/l)	<142	142–355	>355
Root absorption: boron (mg/l)	<0.5	0.5–2.0	>2.0
Leaf absorption: sodium (mg/l)	<70	>70	–
Leaf absorption: chloride (mg/l)	<106	>106	–
Sprayer: nitrates (mg/l)	<90	90–520	>520
Ammonium for sensitive species (mg/l)	<5	5–30	>30
pH	6.5	6.5–8.4	–

The high nitrogen concentrations in the water supply nitrogen to the crop and may cause excessive vegetative growth, lodging, and delayed crop maturity. The unsightly deposits on fruit or leaves is due to overhead sprinkler irrigation with water high in bicarbonate, water containing gypsum, or water high in iron. There are various abnormalities often associated with an unusual pH of the water. The suspended organic and inorganic sediments cause problems in irrigation systems through clogging of gates, sprinkler heads and drippers. A special problem faced by some farmers practicing irrigation is deterioration of equipment due to water-induced corrosion or encrustation (Ben-Gal & Shani 2002).

Water infiltration rate

The variation of the water infiltration rate in soil is one of the major factors affecting plant growth. It depends on the structure of the soil and a low infiltration rate causes water to remain on the soil surface for a long time leading to a slow supply of water to the internal parts of the plants. Water salinity is mainly due to sodium, calcium and magnesium, and ionic concentrations decide the infiltration rate. High salinity water will increase infiltration by weakening the soil structure due to the accumulation of sodium at the surface. This leads to further deterioration of the soil particles, mainly due to calcium ions which lead to the clogging of soil pores with time.

Toxic effect of boron

The concentration of ions in soil or water can have a major toxic effect on plants. Toxicity is mainly due to toxic ions present in water or soil and their uptake into plants above a certain concentration lead to crop damage or yield reduction (Stamatis *et al.* 2011). The ions of primary concern are boron, chloride and sodium. Generally, the boron concentration in seawater is between 4 and 6 mg/l and its concentration varies in groundwaters. Boron is toxic (Ben-Gal & Shani 2002) and the boron concentration in irrigation water should be $\leq$0.4 mg/l. The boron tolerance of different crops based on its concentration in water is summarized in Table 3. The removal of boron by RO is highly affected by its charge since boron is neutral in its boric acid form at seawater pH. However, the net boron rejection by a selected RO membrane is highly dependent on the boric acid/borate ion ratio in the seawater (Hilal *et al.* 2011).

Table 3 | Boron tolerance of different crops based on its concentration in water (Glueckstern *et al.* 2005; Zarzo *et al.* 2013)

Crop type	Crops	Boron content (mg/l)
Sensitive	Apple, cherry, lemon, oranges, peach, grapefruit, avocado, elm, apricot, fig, grapes, plum, beans, garlic, walnut, onion, sesame, lupin, strawberry, peanut	0.30–1.0
Semi-tolerant	Barley, broccoli, red pepper, radish, potato, turnip, barley, oats, corn, tobacco, cauliflower, squash, cabbage, carrot, lettuce, onion, potato, pumpkin, spinach, olive, roses, wheat	1.0–4.0
Tolerant	Asparagus, cranberry, cotton, cucumber, gladiolus, sesame, tulip, beet, tomato, bean, grass, peppermint, rye, parsley	4–10.5

Types of irrigation systems

Irrigation is the artificial application of water to plants in controlled amounts at desired intervals. There are different methods of irrigation based on the techniques used to supply water to the plants. In the first type, surface irrigation, water is applied and distributed over the soil surface by gravity. It is the most common form of irrigation throughout the world. Surface irrigation is often referred to as flood irrigation, implying that the water distribution is uncontrolled and therefore, inherently inefficient. Surface irrigation comes in three major types; level basin, furrow and border strip.

A second type, sprinkler irrigation, consists of devices used to irrigate agricultural crops, lawns, landscapes, golf courses, and other areas. Sprinkler irrigation is a method of applying irrigation water which is similar to natural rainfall. Water is distributed through a system of pipes usually by pumping. It is then sprayed into the air through sprinklers so that it breaks up into small water drops which uniformly fall to the ground.

The third type, drip irrigation, is the system where water is spread directly onto the root system of the plant and is a water sensible irrigation system. Drip irrigation needs to run for 30 min for it to take effect. Pipes with perforated holes are buried just below the surface, a blocker only lets the droplets out one at a time. Drip irrigation can be classified into surface drip irrigation and subsurface drip irrigation (SDI) systems. A surface drip irrigation system uses close emitter spacing (300–450 mm) and a thin wall (0.2–0.25 mm) drip-line placed 25–150 mm below the surface. Surface drip irrigation is widely used to irrigate perennial crops and annual row crops. A drip irrigation system can often work well even with high salinity water (Oron *et al.* 1999). Advantages of surface drip irrigation include improved water management, potential energy saving, improved crop establishment, and fertilizer application can be done conveniently and efficiently through a surface drip irrigation system. SDI is the irrigation of crops through buried plastic tubes containing embedded emitters located at regular spacings. The SDI system uses 500–685 mm emitter spacing and a slightly thicker wall (0.33–0.38 mm) dripline placed 200–350 mm below the surface. The use of SDI offers many other advantages for crop production, including reduced nitrate leaching compared to surface irrigation, higher yields, a dry soil surface for improved weed control and crop health, the ability to apply water and nutrients to the most active part of the root zone, protection of drip lines from damage due to cultivation and other operations, and the ability to safely irrigate with wastewater while preventing human contact.

DESALINATION FOR AGRICULTURE: RESOURCES AND CHARACTERISTICS

Similar to potable water the demand for agricultural water is common in most countries. It is directly linked to providing good quality food in sufficient quantity. Water scarcity and continuous reduction in its quality continue to be one of the major threats to agricultural production, especially in the Mediterranean basin, arid and semi-arid regions (Oron *et al.* 2008). The recent advancements in RO research have enabled the development of suitable membranes and efficient modules to fulfil cost effective quality water production for agriculture (Lee *et al.* 2003; Quist-Jensen *et al.* 2015). The alternative water resources for agriculture are discussed below.

Seawater desalination for agriculture

Seawater is the largest source of water and it contributes 97% of the total water on earth. The salinity of seawater is generally in the range of 35,000 ppm total dissolved solids (TDS). The concentrations of other ions in seawater linked to agriculture are presented in Table 1. Though usage of saline water is common in agriculture, it should fulfil three important criteria. First, it must be desalted using a cost-effective technology, secondly, yields should be high enough to balance the ratio between the yield to expense ratio and thirdly, suitable research should be carried out to nullify the effect of desalinated water irrigation on the environment (Glenn *et al.* 1998; Zarzo *et al.* 2013). However, the issue of effective removal of boron using RO technology adds a high cost to the process (Glueckstern *et al.* 2005).

Brackish water desalination for agriculture

Direct irrigation with brackish waters is limited to very few salt tolerant crops. Generally, the TDS (~5,000 ppm) and sodium (~1,500 ppm) contents of brackish water are much above the tolerance level of many crops. Brackish water desalination is an interesting option considering the lower cost of desalinating than seawater desalination (Zhou & Tol 2005; Glueckstern & Priel 2007; Shaffer *et al.* 2012). A membrane based treatment process comprises three steps: pretreatment, membrane treatment and post-treatment. Pretreatment is essential to increase the efficiency of separation processes, to reduce the cost and to increase the life of the membrane and prevent it from fouling. Post-treatment is necessary to maintain the proper concentrations of fertilizer ions in the product water (Birnhack *et al.* 2010).

Treated wastewater for agriculture

Treated wastewater and primarily domestic treated wastes can be reused for agricultural irrigation (Asano *et al.* 1992; Lee *et al.* 2003; Taylor *et al.* 2006). However, the former has drawbacks such as: high system or equipment costs, additional costs of effluent quality control, and the need to minimize health and environmental risks (Stamatis *et al.* 2011). The treated wastewater can provide a considerable amount of necessary nutrients for plants. The main factors that determine the suitability of recycled water for agricultural irrigation are salinity, heavy metals, and pathogens, which cause adverse effects on humans, plants and soils. The nutrients contained in the treated water are, however, up to a certain level, beneficial for agricultural use (Oron *et al.* 1991). If not, extra investments are required to add extra nutrients to the product water. Further, Oron *et al.* (2008) concluded that the main problems associated with the reuse of domestic wastewater for irrigation are as follows. (a) The suspended material associated with effluent water might clog the water distribution systems, primarily the drippers. This problem can be solved by installing filters at the control heads of the irrigation systems. (b) The pathogens contained in the applied effluent. The health and environmental risks can be minimized by disinfection and by using SDI (Gantzer *et al.* 2001; Oron *et al.* 2001). (c) Applying treated domestic wastewater is associated with adding dissolved solids to the soil media and the groundwater. This is due to the extra dissolved solids added to the wastewater from households, and during water evaporation from open-surface reservoirs. The wastewater generated from desalination can be reused for agricultural irrigation, after proper treatment. However, advanced technology like membrane based desalination may lead to higher quality water and minimal health and environmental risks.

DESALINATION TECHNOLOGIES FOR AGRICULTURAL USE

Generally, desalination of saline water is a multi-step process. Pretreatment and post-treatment are the main steps influencing the quality of the product water. In post-treatment, the desired amount of nutrient ions will be added to maintain the quality of the product water. Thermal and membrane desalination technologies are commonly used for agricultural requirements.

Thermal distillation was the first desalination technology in which saline water is distilled into steam, and then into pure water by condensation. Thermal distillation is the most common technology with ~21% of the total desalinating facilities in the world. The other technologies currently in use for agriculture are electrodialysis (ED) and RO. However, thermal based distillation technologies consume more energy than RO while ED is effective only when the feed water is brackish water. Currently, RO desalination is the accepted technology for irrigation world-wide due to drastically reduced process costs and high quality of the product water.

RO desalination for agriculture

As discussed above, RO is considered as the future for agricultural water production. The energy requirement always remains a crucial constraint for desalination since energy constitutes up to 75% of the total operational cost of a seawater RO desalination plant (Semiat 2008; Gude 2011; Phuntsho *et al.* 2013). Three decades ago the energy required for seawater desalination was 5–10 kW h/m^3, modern state-of-the-art RO systems need only around 3.0 kW h/m^3 (Schiermeier 2008; Elimelech & Phillip 2011; Phuntsho *et al.* 2013). Spain is a suitable example in the field of brackish water desalination for an agricultural area, with more than 300 treatment plants and 22.4% of the total desalinated water is used for agriculture. Multsch *et al.* (2015) made an important conclusion on cost analysis using RO desalinated water for agriculture. The study revealed that the cost needs to be reduced below 0.2 $\$ \text{ m}^{-3}$ for sprinkler and drip irrigation and even below 0.1 $\$ \text{ m}^{-3}$ for widespread used surface irrigation systems.

RO has proved to be a good technology for brackish water desalination with the moderately lower pressure requirement of 10–20 bar due to fewer ionic constituents present in brackish water. It has the potential to remove up to 90–98% of TDS. Still, there are several issues related to the implementation of RO in agricultural use which need to be addressed, such as the high purity of RO desalinated water with lack of nutrients in the product for direct fertigation. RO membrane fouling due to the presence of inorganic salts, colloidal and particulate matter, organic compounds and microorganisms present in the feed water reduces membrane efficiency and lifespan. Therefore, various foulants present in seawater should be reduced prior to feeding of seawater into the RO system. An efficient pretreatment technique is essential to reduce the concentration of scaling ions and to achieve the high-water recovery in the RO process. The conventional pretreatment is chemical dosing with coagulants, acids, disinfectants, antiscalants and sodium bisulphite for oxidant removal all of which increase the cost of treatment. Recently, RO desalination was integrated with low energy filtration technologies such as forward osmosis (FO), microfiltration (MF) and nanofiltration (NF) and emerged as a promising technology for large-scale implementations. The integrated technologies prior to RO served to effectively remove hardness ions to reduce the seawater salinity, and to improve the efficiency of the RO process. The desalinated water needs to be followed by blending with appropriate nutrients to maintain the nutrient levels for plant and vegetable growth. The adverse effect of desalinated water on plants and soils is the relatively low alkalinity and Ca^{2+} values, as well as the negligible Mg^{2+} concentration. The ions essential for plant growth such as K^{+} and SO$_4^{2-}$ will be removed almost completely by RO membranes. The major concern related to the reuse of desalinated water in irrigation is the high value of the parameter Sodium Adsorption Ratio (SAR), which can potentially develop in the water. SAR values can be lowered by adding either Ca^{2+} or Mg^{2+} to desalinated water. Adding Mg^{2+} is preferable from both health and agriculture (inexpensive Mg fertilization) aspects (Lahav *et al.* 2010). Thus, not only the cost of pretreatment, but the incorporation of lost nutrients in the desalinated RO water for irrigation by proper post-treatment technologies will increase the operational expenses.

Integrated RO desalination for agriculture

Researchers are currently working on different ways to integrate RO with other processes. One process is called Zero Discharge Desalination (ZDD). The ZDD concept utilizes the energy-saving feature of ED to remove the monovalent salts (primarily NaCl and KBr) from the RO reject and concentrate them about threefold before the evaporation step. FO is the other emerging technology that can be operated without any pressure requirements (McCutcheon *et al.* 2006; Ling *et al.* 2010; Chung *et al.* 2012). Unlike RO, FO separates water from saline water by making use of the osmotic pressure gradient across the membrane as the driving force of the process. The quality of desalinated water by FO technology again depends on the feed solution (FS), and a higher ionic strength draw solution (DS) that is used for the process. However, subsequent integration of FO with low pressure RO as part of an FO-LPRO hybrid process is essential to obtain quality water for agriculture (Linares *et al.* 2014).

Shaffer *et al.* (2012) demonstrated that the integrated FO and RO process has the potential to achieve stringent product water quality requirements while consuming less energy than a conventional seawater RO facility. The schematic presentation of a typical FO/RO integrated system is presented in Figure 1, where FO acts as a pretreatment step for the subsequent RO process. Linares *et al.* (2014) demonstrated that this process has the potential to achieve low boron and chloride concentrations without requiring additional, post-treatment, RO passes since seawater will pass through two semipermeable membranes in the integrated process. FO has a much lower organic fouling propensity than RO, a better understanding of FO biofouling and scaling behavior can further improve the performance of the integrated desalination process. The development of fouling resistant FO membranes and improved design of FO membrane modules are important areas of continued research to control and mitigate fouling in the FO process (Shaffer *et al.* 2012). The development of boron selective FO membranes and optimization of efficient DS are the current challenges in FO technology.

Fertilizer drawn FO (FDFO) desalination can be directly used for fertigation (fertilized irrigation) as it contains essential nutrients for plant growth. This process utilizes fertilizer solutions in high concentration as DS for the process and FS as seawater. Hence, pure water from seawater will pass into the DS to dilute it and this water can be used for the fertigation. The high concentrations of nitrogen, phosphorous and potassium (NPK) obtained in the DS is considered as one of the drawbacks of this process. However, the TDS of the feed water

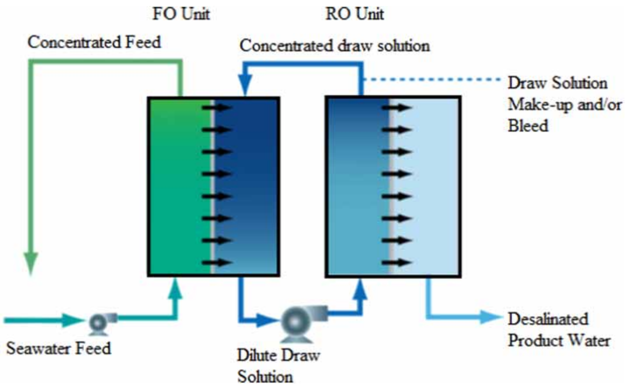

Figure 1 | Schematic representation of an integrated FO and RO desalination process (Yangali-Quintanilla *et al.* 2011).

(usually seawater) will determine the final fertilizer concentration (Phuntsho *et al.* 2011; Phuntsho *et al.* 2012). The schematic diagram used by Phuntsho *et al.* (2011) for their bench scale FDFO experiment is presented in Figure 2. In their experiments, most of the fertilizers were able to achieve nutrient concentrations lower than acceptable nutrient concentrations for direct fertigation. However, if the nutrient concentration was found to be high in DS, the authors suggested NF post-treatment as being more advantageous to attain reduced nutrient concentrations in the final product water with less energy consumption.

Thermal solar desalination for agriculture

Renewable solar energy may be used to desalinate seawater in arid regions using the principle of vapour transport. The vaporized water molecules are then condensed to obtain quality water. This technology is generally known as membrane distillation where the membrane acts as a barrier layer for the separation of water from saline water driven by solar irradiation (Tiwari *et al.* 1992). Toufik *et al.* (2015) demonstrated that the quantity of water produced from a solar still is less than the water requirement for a crop grown in an open irrigated field, and integration of solar desalination with the greenhouse concept may be more efficient.

Solar desalination in combination with water efficient greenhouses is more suitable for cultivation using saline water or brackish water (Tinaut *et al.* 1978; Sodha *et al.* 1980; Mashalya *et al.* 2015). Trombe & Foex (1961) demonstrated the first system combining a solar still with a greenhouse. Chaibi & Jilar (2004) developed roof light transmission by a concept of reduced solar radiation absorbed by a layer of flowing water in a glass container covered by a top glass. As shown in Figure 3, the fresh water evaporated, condensed on the top glass and was collected at the roof eaves. The system demonstrated an efficient option for the support of small scale agricultural production, in places where only saline water is available. Further, Chaibi (2013) and Jones *et al.* (2016) have demonstrated the greenhouse integrated system using solar and photovoltaic (PV systems), which were found to be reliable and valid technologies with low investment and water cost compared to solar collector based desalination technologies, for vegetables and flowers grown in greenhouses.

DESALINATION FOR AGRICULTURE IN DIFFERENT COUNTRIES

The total production of desalinated water is increasing across the world. However, for agricultural purposes the volume of desalted water is low (only 2–3%) compared to world water

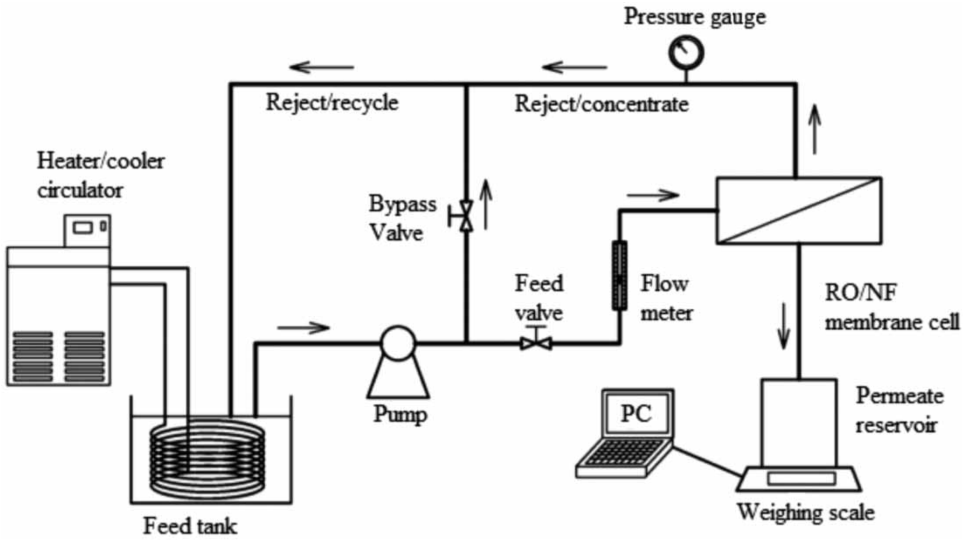

Figure 2 | Schematic diagram of the bench scale cross-flow nanofiltration unit used in this study. For all the experiments, the unit was operated at different applied pressures (10–30 bar), a crossflow rate of 500 mL/min and a temperature of 25°C (Phuntsho *et al.* 2013).

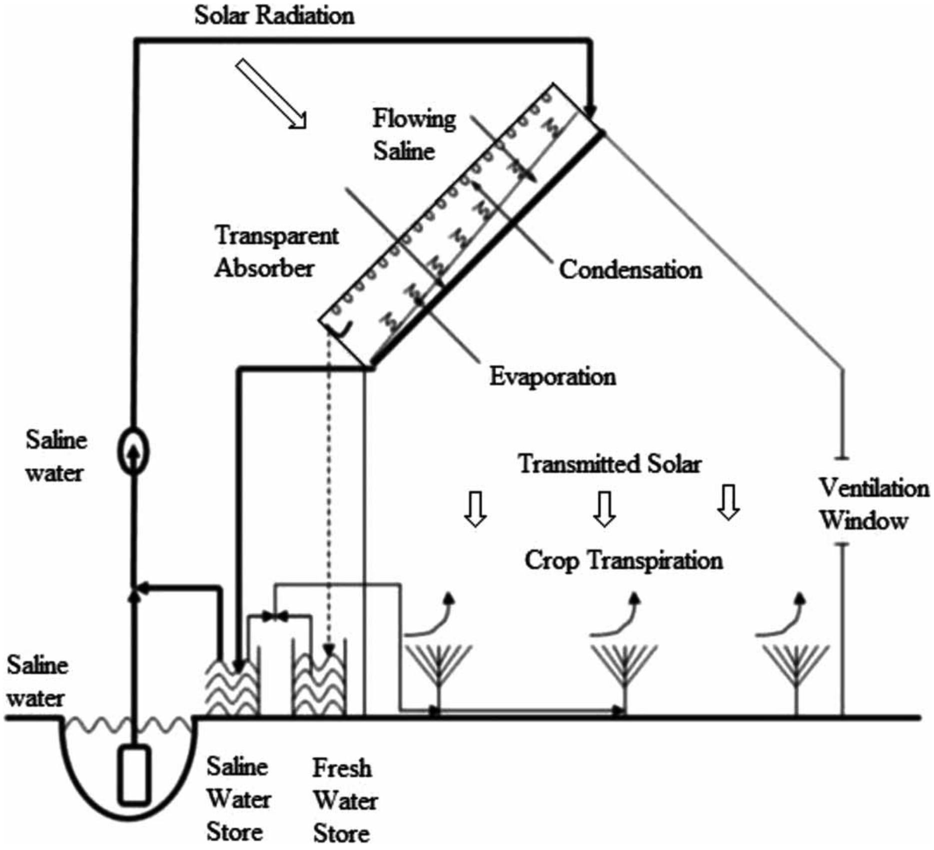

Figure 3 | Schematic presentation of water desalination integrated in greenhouse roof (Jones *et al.* 2016).

production. The countries which produce the most desalinated water are the Gulf countries, the USA and Spain. Spain uses the most desalinated water for agriculture with 22% (Díaz *et al.* 2013). Water produced through desalination is the only major source of potable water for the Gulf Cooperation Council (GCC) countries. Kuwait is reported to have around 13% utilization of desalinated water for agriculture.

In Israel, a new seawater desalination plant has been opened in Ashkelon, on the southern Mediterranean coast, with a capacity to produce 100,000,000 m^3/year making it the largest RO desalination plant in the world (Yermiyahu *et al.* 2007). Other countries like Australia, Algeria, Libya, Chile, etc. are using desalination plants for agricultural use. According to the report by Miller (1991), most arid and semi-arid countries, where 40% of the world's population live, have serious periodic droughts. Asian countries are suffering from fresh water shortage and the quality of available water sources is also declining. It is worth noting that agriculture occupies a major role in the economic activity of all the countries and the majority of arid region countries use 80% of their water for agricultural purposes. An Australian survey found that nearly 53% of the population envisioned desalinated water usage for irrigation with a cheaper potable water price of $ 0.55/m^3 (Kudish & Gale 1986). An Egyptian survey estimates the expected water demand to reach a level of 130 billion m^3/year, with more than 80% used for agriculture, compared to its current water supply of 73 billion m^3/year. Countries like China and India with large populations are also planning towards the implementation of a desalination program due to water scarcity generated during recent decades (Hadid *et al.* 2004).

DESALINATION FOR AGRICULTURE: OPPORTUNITIES AND CHALLENGES

Desalination was only used to provide domestic and industrial supplies during its early stage of invention. Once this technology had been improved, its application was extended to other sectors, especially to agriculture. Desalination for agriculture has advantages as it utilizes non-conventional and unlimited water resources which do not depend on the weather, increases agricultural productivity and product quality, reduces water consumption and has a less negative impact on soils and crops in comparison with direct use of seawater or brackish water.

Cost factor

The cost of desalinated water is still too high compared to conventional water resources for the full use of this resource in irrigated agriculture. The net cost of desalinated water for agriculture is the sum of energy, labor, chemicals, payback costs, membrane replacement, operation and management, and maintenance. For desalination via seawater RO, the operational costs are around 0.35–0.5 €/m^3 (without payback), depending on plant size, intake, distance between intake and RO plant and product pumping. Water costs are between 5% and 25% of overall crop production. Desalination processes require large amounts of energy and this is considered the major constraint to large-scale production of freshwater from saline waters. Apart from energy, operation and management, as well as payback are the most significant costs as presented in Table 4, while manpower, chemicals and maintenance comprise a smaller portion of the total cost.

Table 4 | Costs of seawater and brackish RO desalination for agriculture (Beltran & Koo-Oshima 2004)

	Seawater ($/acre/foot)*	Brackish water
Energy	327–401	119–178
Labor	27–120	30–104
Chemicals	27–80	30–45
Membrane replacement	1–54	22–33
Chemical cleaning	1–3	2–4
Maintenance	27–48	18–27
Operation and management	461–728	223–401
Payback costs	223–327	104–134
Total costs	669–1,055	312–535

* 1 acre/foot = 1233.48 m^3.

To make desalinated water sustainable for agriculture, water has to be ionically balanced (SAR). The other costs influencing desalination for agriculture are the costs of maintaining proper salt concentrations in the feed and permeate during desalination. Specifically, the cost of removal of boron and addition of SO_4^{2-}, Ca^{2+}, and alkalinity by means of a calcite-dissolution post-treatment process. Additional enrichment of the desalinated water with Mg^{2+} would raise the price further. According to new recommendations for desalinated water in Israel (Jones *et al.* 2016), dissolved Ca^{2+} concentrations should not be increased beyond 48 mg/l. To meet agricultural needs, missing nutrients might be added to desalinized water in the form of fertilizers. Supplying Ca^{2+} and Mg^{2+} at 24 and 12 mg/l, respectively, costs ~\$0.09/m^3. Direct chemical dosage at the desalination plant to increase Mg^{2+} is also a relatively expensive alternative (adding ~\$0.045/m^3 to the overall post-treatment cost when 10 mg/l Mg^{2+} is supplied as $MgCl_2$). It also results in the addition of unwanted counter anions. Therefore, a cost-effective alternative method was developed, where excess Ca^{2+} ions (generated in the common H_2SO_4-based calcite dissolution post-treatment process) are replaced with Mg^{2+} ions originating from seawater (extracted using specific ion-exchange resins). This alternative was able to balance $SO_4{}^{2-}$, Ca^{2+}, Mg^{2+}, alkalinity, and pH composition in desalinated water at a cost-effective price (Birnhack & Lahav 2007). The post-treatment cost of purchasing and injecting Ca^{2+}, Mg^{2+}, and S as chemical fertilizers into the water at the farm is expected to be high – up to \$0.5/m^3 in Israel at current prices. Blending re-introduces desirable, as well as undesirable, dissolved salts and therefore must be evaluated in terms of cost to potential yields as well as in terms of the economic and environmental costs of leaching. The additional cost of the removal of boron will be in the range of 0.05–0.07\$/m^3 in a large system and 50% or more in small systems (Hilal *et al.* 2011).

Environmental impacts

Although desalination is the only additional source of fresh water in the future, it has significant environmental impacts. The problem of brine management and its discharge are considered as environmental effects of desalination for agriculture. The high salinity of brine from seawater desalination plants is typically not suitable for any use. However the brine from brackish water or surface water desalination plants may be suitable for irrigating some crops.

The brine which is a byproduct of RO desalination generally has a great impact on environmental pollution. It must be diluted before injecting back into the sea. The water recovery of the RO process for seawater will be in the range of 30–40%. That means the remaining 60–70% brine will be treated or discharged back into the natural resources like the sea. Such a discharge has a significant effect on the seawater habitat, flora and fauna. The other chemicals that are used during the RO desalination process should be treated to remove environmental impacts (Sadhwani *et al.* 2005). The other unfavorable impact on the environment is the production of CO_2 during the desalination process since these processes are run by the consumption of energy from fossil fuel.

CONCLUSIONS

The sources of desalinated water for agriculture, such as seawater and brackish water are abundant resources on earth. However, direct implementation of these waters for agricultural use is not recommended due to the high salinity associated with these sources. The current desalination technologies in agriculture will continue to be researched, and innovations will become less expensive and hopefully lead to more desalination plants. The recent desalination trends show that RO costs are decreasing more rapidly compared to thermal technologies because of new innovations. The successful implementation of desalination technologies in agriculture will be improved by analyzing several aspects discussed below.

i. The agricultural suitability of land, its topography and soil geostructure, market for agricultural product, crop selection for the selected area, territorial scope, selection of greenhouses against open field, study on climate changes and their effect on crops.
ii. The improvements in efficiency of RO desalination for agriculture along with cost reduction are mainly attributed to effective modifications within the RO process. The RO integrated process was applied world-wide for agriculture, however, most of the studies are limited to laboratory-scale and need to be optimized on a large scale. The selection of a suitable desalination technology is crucial, based on agricultural area, crops selected and water resources quality.
iii. The cost reduction by large scale installation of desalination plants. This may minimize the labor costs, and allow the utilization of high efficiency mechanical equipment, etc.
iv. Research and development into implementation of advanced technologies like hydroponic crops and drip irrigation, biological pest control, etc., and finally the design of infrastructure and desalination plant.
v. To reduce CO_2 emissions, reducing energy consumption is the main issue. Thus, a low energy desalination process is highly favorable to the environment along with cost reduction. Though RO is the preferred option, there is large scope for further energy reduction in this process.
vi. Although solar energy for agricultural purposes has not yet gone beyond the experimental phase, its combination with water efficient greenhouses is an interesting possibility for the development of small scale cultivation in places where seawater and brackish water are the only available water resources.
vii. The treatment and environmentally safe disposal of brine and other toxic chemicals used for pre- and post-treatment. The maintenance of a minimum distance between the treatment plant and disposal area to minimize additional cost. For inland disposal, injection into deep wells of contaminated aquifers or discharge to large flow rivers could be the solution.

In the near future, fresh water scarcity will become a major threat for water rich countries too. Therefore, desalination for agriculture should be considered as an option for water supply only where no other resources are available at a reasonable cost. With continued research, wastewater desalination for agriculture may become less expensive, more environmentally friendly and hopefully lead to more desalination plants world-wide.

ACKNOWLEDGEMENT

Authors are grateful to the Kuwait Institute for Scientific Research (KISR) for supporting this review article, furthermore, we would like to acknowledge with much appreciation the crucial role played by the staff of the Doha Research Station of KISR, who gave fruitful comments and advice.

REFERENCES

Abdel-Satar, A. M., Al-Khabbas, M. H., Alahmad, W. R., Yousef, W. M., Alsomadi, R. H. & Iqbal, T. 2017 Quality assessment of groundwater and agricultural soil in Hail region. *Saudi Arabia Egyptian Journal of Aquatic Research* **43**, 55–64.

Asano, T., Richard, D., Crites, R. W. & Tchobanoglous, G. 1992 Evolution of tertiary treatment requirements in California. *Water Environment Technology* **3** (2), 37–41.

Beltran, J. M. & Koo-Oshima, S. 2004 Water desalination for agricultural applications. In: *Proceedings of the FAO Expert Consultation on Water Desalination for Agriculture Applications*, Land and Water discussion paper 5, Rome, Italy, p. 48.

Ben-Gal, A. & Shani, U. 2002 Yield, transpiration and growth of tomatoes under combined excess boron and salinity stress. *Plant and Soil* **247**, 211–221.

Birnhack, L. & Lahav, O. 2007 A new post-treatment process for attaining Ca^{2+}, Mg^{2+}, SO_4^{2-} and alkalinity criteria in desalinated water. *Water Research* **41**, 3989–3997.

Birnhack, L., Shlesinger, N. & Lahav, O. 2010 A cost-effective method for improving the quality of inland desalinated brackish water destined for agricultural irrigation. *Desalination* **262**, 152–160.

Chaibi, M. T. 2013 Thermal solar desalination technologies for small-scale irrigation. *American Journal of Energy Research* **1**, 25–32.

Chaibi, M. T. & Jilar, T. 2004 System design, operation and performance of roof integrated desalination in greenhouses. *Solar Energy Journal* **76** (5), 545–561.

Chung, T. S., Li, X., Ong, R. C., Ge, Q., Wang, H. & Han, G. 2012 Emerging forward osmosis (FO) technologies and challenges ahead for clean water and clean energy applications. *Current Opinion in Chemical Engineering* **1** (3), 246–257.

Díaz, F. J., Tejedor, M., Jiménez, C., Grattan, S. R., Dorta, M. & Hernández, J. M. 2013 The imprint of desalinated seawater on recycled wastewater: consequences for irrigation in Lanzarote Island, Spain. *Agricultural Water Management* **116**, 62–72.

Domingo, Z., Elena, C. & Patricia, T. 2013 Spanish experience in desalination for agriculture. *Desalination and Water Treatment* **51**, 53–66.

Elimelech, M. & Phillip, W. A. 2011 The future of seawater desalination: energy, technology, and the environment. *Science* **333**, 712–717.

Gantzer, C., Gillerman, L., Kuznetsov, M. & Oron, G. 2001 Adsorption and survival of fecal coliforms, somatic coliphages and F-specific RNA phages in soil irrigated with wastewater. *Water Science & Technology* **43** (12), 117–124.

Glenn, E. P., Brown, J. J. & O'Leary, J. W. 1998 Irrigating crops with seawater. *Scientific American* **279** (8), 56–61.

Glueckstern, P. & Priel, M. 2007 Boron removal in brackish water desalination systems. *Desalination* **205**, 178–184.

Glueckstern, P., Priel, M. & Kotzer, E. 2005 Blending brackish water with desalted seawater as an alternative to brackish water desalination. *Desalination* **178**, (1–3) 227–232.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B. & Moulin, P. 2009 Reverse osmosis desalination: water sources, technology, and today's challenges. *Water Research* **43**, 2317–2348.

Gros, N., Camoes, M. F., Oliveira, C. & Silva, M. C. R. 2008 Ionic composition of seawaters and derived saline solutions determined by ion chromatography and its relation to other water quality parameters. *Journal of Chromatography A* **1210**, 92–98.

Gude, V. G. 2011 Energy consumption and recovery in reverse osmosis. *Desalination and Water Treatment* **36**, 239–260.

Hadid, A. A., Batanouny, K. H., Jabarine, A. S. & Kader, A. A. 2004 *Proposal for Expanding the Crop Mandate of ICARDA to Include Horticultural Crops.* Report ICARDA 07/250. Beirut, Lebanon.

Hasson, D., Shemer, H., Brook, I., Zaslavschi, I., Semiat, R., Bartels, C. & Wilf, M. 2011 Scaling propensity of seawater in RO boron removal processes. *Journal of Membrane Science* **384**, 198–204.

Hilal, N., Kim, G. J. & Somerfield, C. 2011 Boron removal from saline water: a comprehensive review. *Desalination* **273**, 23–35.

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

Kudish, A. I. & Gale, J. 1986 Solar desalination in conjunction with controlled environmental agriculture in arid zones. *Energy Conversion Management* **26**, 201–207.

Lahav, O., Kochva, M. & Tarchitzky, J. 2010 Potential drawbacks associated with agricultural irrigation with treated wastewaters from desalinated water origin and possible remedies. *Water Science and Technology* **61** (10), 2451–2460.

Lee, R.-W., Glater, J., Cohen, Y., Martin, C., Kovac, K., Milobar, M. N. & Bartel, D. W. 2003 Low-pressure RO membrane desalination of agricultural drainage water. *Desalination* **155**, 109–120.

Linares, R. V., Li, Z., Sarp, S., Bucs, S. S., Amy, G. & Vrouwenvelder, J. S. 2014 Forward osmosis niches in seawater desalination and wastewater reuse. *Water Research* **66**, 122–139.

Ling, M. M., Wang, K. Y. & Chung, T. S. 2010 Highly water-soluble magnetic nanoparticles as novel draw solutes in forward osmosis for water reuse. *Industrial & Engineering Research* **49** (12), 5869–5876.

Mashalya, A. F., Alazba, A. A., Al-Awaadh, A. M. & Mattar, M. A. 2015 Area determination of solar desalination system for irrigating crops in greenhouses using different quality feed water. *Agricultural Water Management* **154**, 1–10.

McCutcheon, J. R., McGinnis, R. L. & Elimelech, M. 2006 Desalination by ammonia-carbon dioxide forward osmosis: influence of draw and feed solution concentrations on process performance. *Journal of Membrane Science* **278**, 114–123.

Miller, G. T. 1991 *Environmental Science* (3rd edn). Wadsworth Publishing Co., California, USA, pp. 236–239.

Multsch, S., Alquwaizany, A. S., Lehnert, K.-H., Frede, H.-G. & Breuer, L. 2015 Is irrigation with partial desalinated seawater a policy option for saving freshwater in the Kingdom of Saudi Arabia. *Geophysical Research Abstracts* **17**, EGU2015–EGU6215.

Nable, R. O., Banuelos, G. S. & Paull, J. G. 1997 Boron toxicity. *Plant and Soil* **193**, 181–198.

Oron, G., DeMalach, Y., Hoffman, Z. & Cibotaru, R. 1991 Subsurface microirrigation with effluent. *Journal of Irrigation Drainage Engineering ASCE* **117** (1), 25–36.

Oron, G., Campos, C., Gillerman, I. & Salgot, M. 1999 Wastewater treatment, renovation and reuse for agricultural irrigation in small communities. *Agricultural Water Management* **38**, 223–234.

Oron, G., Armon, R., Mandelbaum, R., Manor, Y., Campos, C., Gillerman, L., Salgot, M., Gerba, C., Klein, I. & Enriquez, C. 2001 Secondary wastewater disposal for crop irrigation with minimal risks. *Water Science and Technology* **43** (10), 139–146.

Oron, G., Gillerman, L., Buriakovsky, N., Bickd, A., Gargir, M., Dolan, Y., Manor, Y., Katz, L. & Hagin, J. 2008 Membrane technology for advanced wastewater reclamation for sustainable agriculture production. *Desalination* **218**, 170–180.

Phuntsho, S., Shon, H. K., Hong, S. K., Lee, S. Y. & Vigneswaran, S. 2011 A novel low energy fertilizer driven forward osmosis desalination for direct fertigation: evaluating the performance of fertilizer draw solutions. *Journal of Membrane Science* **375**, 172–181.

Phuntsho, S., Shon, H. K., Hong, S. K., Lee, S. Y., Vigneswaran, S. & Kandasamy, J. 2012 Fertiliser drawn forward osmosis desalination: the concept, performance and limitations for fertigation. *Reviews in Environmental Science and Biotechnology* **11** (2), 147–168.

Phuntsho, S., Hong, S., Elimelech, M. & Shon, H. K. 2013 Forward osmosis desalination of brackish groundwater: meeting water quality requirements for fertigation by integrating nanofiltration. *Journal of Membrane Science* **436**, 1–15.

Quist-Jensen, C. A., Macedonio, F. & Drioli, E. 2015 Membrane technology for water production in agriculture: desalination and wastewater reuse. *Desalination* **364**, 17–32.

Rahmawati, K., Ghaffour, N., Aubry, C. & Amy, G. L. 2012 Boron removal efficiency from Red Sea water using different SWRO/BWRO membranes. *Journal of Membrane Science* **423–424**, 522–529.

Sadhwani, J. J., Veza, J. M. & Santana, C. 2005 Case studies on environmental impact of seawater desalination. *Desalination* **385**, 1–8.

Schiermeier, Q. 2008 Water: purification with a pinch of salt. *Nature* **452**, 260–261.

Semiat, R. 2008 Energy issues in desalination processes. *Environmental Science and Technology* **42** (22), 8193–8201.

Shaffer, L. D., Yip, N. Y., Gilron, J. & Elimelech, M. 2012 Seawater desalination for agriculture by integrated forward and reverse osmosis: improved product water quality for potentially less energy. *Journal of Membrane Science* **415–416**, 1–8.

Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Marinas, B. J. & Mayes, A. M. 2008 Science and technology for water purification in the coming decades. *Nature* **452**, 301–310.

Sodha, M. S., Kumar, A., Srivastava, A. & Tiwari, G. N. 1980 Thermal performance of solar still on roof system. *Energy Conversion and Management* **20**, 181–190.

Stamatis, G., Parpodis, K., Filintas, A., Stamatis, E. Z., Parpodis, G. & Filintas, K. 2011 Groundwater quality, nitrate pollution and irrigation environmental management in the Neogene sediments of an agricultural region in central Thessaly (Greece). *Environmental Earth Science* **64**, 1081.

Taylor, K. S., Anda, M., Sturman, J., Mathew, K. & Ho, G. 2006 Subsurface dripline tubing-an experimental design for assessing the effectiveness of using dripline to apply treated wastewater for turf irrigation in Western Australia. *Desalination* **187**, 375–385.

Tinaut, D., Echaniz, G. & Ramos, F. 1978 Materials for a solar still greenhouse. *Optica Pura Applicada* **11**, 59–61.

Tiwari, G. N., Sinha, S., Saxena, P. & Kumar, S. 1992 Review of solar distiller in other thermal applications. *International Journal Solar Energy* **13**, 135–144.

Toufik, T., Douani, M., Amoura, M. & Bettahar, A. 2015 Study of influence of operational parameters on the mass condensate flux in the condenser of seawater greenhouse at Muscat, Oman. *Desalination and Water Treatment* **57**, 13930–13937.

Trombe, F. & Foex, M. 1961 Utilisation of solar still energy for simultaneous distillation of brackish water and air conditioning of hot houses in arid regions. In: *UN Conf. on New Sources of Energy*, Paper 35/S/64 Revised, Rome, 1961.

Vorosmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. 2005 Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288.

Yangali-Quintanilla, V., Li, Z., Valladares, V., Li, Q. & Amy, G. 2011 Indirect desalination of Red Sea water with forward osmosis and low-pressure reverse osmosis for water reuse. *Desalination* **280**, 160–166.

Yermiyahu, U., Tal, A., Ben-Gal, A., Bar-Tal, A., Tarchitzky, J. & Lahav, O. 2007 Rethinking desalination water quality and agriculture. *Science* **318** (5852), 920–921.

Zarzo, D., Campos, E. & Terrero, P. 2013 Spanish experience in desalination for agriculture. *Desalination and Water Treatment* **51**, 53–66.

Zhou, Y. & Tol, R. S. J. 2005 Evaluating the costs of desalination and water transport. *Water Resources Research* **41**, W03003.

First received 25 July 2017; accepted in revised form 10 November 2017. Available online 24 November 2017