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IN-SITU DESALINATION FOR CLIMATE-RESILIENT IRRIGATION

PERFORMANCE OF TWO COMMERCIALLY AVAILABLE MEMBRANES TO CONFIGURE A MEMBRANE-BASED SUBSURFACE IRRIGATION SYSTEM FOR THE GERMINATION OF BEAN SEEDS

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ABSTRACT

A study was conducted to compare the performance of two commercially available membranes, BW30 reverse osmosis (RO) and CTA-ES forward osmosis (FO), used to configure a membrane-based subsurface irrigation system, expected to respond to changes in the soil matrix suction potential and plant demand.

The system was used for the germination of bean seeds in a silty clay loam soil on saline solutions of 0.21, 1.4 and 3.1 dS/m. The system performance was evaluated in terms of final germination, seedling growth parameters and soil quality.

Plants grown under the proposed irrigation system presented germination similar to hand-watered plants, while salt accumulating in the soil was minimised.

INTRODUCTION

The use of water with a high presence of total dissolved solids (TDS) can cause deleterious effects on both plant growth and soil quality.

The effects of salinity on plant development are mainly derived from the energy diverted from growth to overcome the osmotic gradient of the soil water solution (Kolay, 2008) and to the excessive accumulation of salts on the vacuoles, which may limit the transport of carbohydrates to growing cells (Munns, 2002). An over-proportional presence of sodium to other salts in water for irrigation adversely affects soil structure by disrupting the force binding clay particles, causing swelling and dispersion and leading to a loss of soil structure, porosity and, consequently, a reduction on water infiltration rate (Lamm *et al*., 2006; Warrence *et al*., 2003). In order to mitigate these impacts, the removal of salts from water prior to irrigation is required, which can be achieved through conventional desalination processes. However, due to their complexity and high costs, their full-scale application for irrigation is not feasible.

Power consumption associated with the extraction of fresh water can range from 0.05 to 0.4 kWh/m^3, compared with 0.7 to 2.0 kWh/m^3 for extraction and desalination of brackish water containing 1000 to 5000 mg/L TDS, which would result in an average six-fold cost increase (National Water Commission, 2008).

A novel membrane-based subsurface irrigation system aims to alleviate desalination costs for irrigation, as desalination is approached in a different configuration. Semi-permeable membranes form the pipes required to deliver water directly to plant roots as a response to the negative water potential provided by both soil matrix potential and plant water demand, which also minimises water loss by mismatched estimation of crop water requirements.

This study focused on evaluating the performance of a forward and reverse osmosis membrane under the proposed subsurface irrigation mode, in terms of plant growth and soil quality, in comparison to plants conventionally irrigated.

METHODOLOGY

Two types of commercial available membrane, BW30 reverse osmosis (RO) membrane (Dow-Filmtec, USA) and CTA-ES forward osmosis (FO) (Hydration Technology Incorporated, USA) were tested in triplicate during the germination of common bean (*Phaseolus vulgaris* cv. Jade, Sunland Seeds Pty Ltd, NSW).

The seeds were germinated in shallow tubes (20 seeds per tube) at a depth of 1cm on a 2cm base of a silty clay loam soil. The TDS of irrigation water corresponded to salinity levels of 0.21, 1.4 and 3.1 dS/m. The base of each tube was designed to house a semi-permeable membrane separating the water reservoir from the soil. Water uptake by the plant was determined daily by measuring the volume required to replenish the reservoir to a calibrated level. The daily reference evapotranspiration (ETc), equivalent to crop water demand, was estimated from continually monitoring the evaporation rate from a white plastic pan of 9.7cm of diameter kept on a balance connected to a computer with a data-logging program. The evaporation rate was later used to estimate the evapotranspiration, according to Equation 1 (FAO 2006).

$$ET_c = ET_o \times K_c \qquad (1)$$

where: ET_c is the crop evapotranspiration under standard conditions (mm/d); ET_o is the reference crop evapotranspiration, (mm/d); and K_c is the crop coefficient that varies by crop and stage of development (unitless). Leaf area was measured by scanning leaves on a desktop scanner (HP Scanjet G3110) and posterior image processing using the software Image J (Schneider *et al*., 2012). The conductivity of the soil saturation extract (EC_e) was measured at the end of the experiment (15 days) by diluting soil samples in deionised water to the proportion of 1:5 (Slavich and Petterson, 1993).

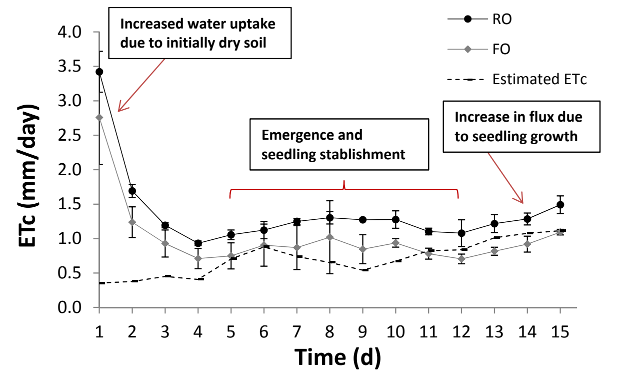
A second experiment was carried out to evaluate the effects of direct application of brackish water on both plant growth and soil quality. Tubes were weighed daily and water loss was directly measured by mass change, which corresponded to the evapotranspiration.

RESULTS AND DISCUSSION

Experiments for membrane-based and direct irrigation were carried out under ambient conditions at an average temperature of 19.2 and 20.8°C, and relative humidity of 57 and 48.4%, resulting in an average evaporation of 1.56 and 1.79 mm/d, respectively (Table 1). A general water flux trend throughout the experiment (15 d) for both RO and FO membranes, when tap water (0.21 dS/m) was used as feed water, is depicted in Figure 1.

Table 1. Climatological data observed during the experiments of membrane-based and direct irrigation.

Value	Temperature (°C)	Relative humidity (%)	Evaporation (mm/d)
Membrane-based			
Minimum	14.7	29.8	0.89
Average	19.2	57.0	1.56
Maximum	24.9	86.9	2.20
Direct irrigation			
Minimum	9.3	15.3	1.22
Average	18.3	48.4	1.79
Maximum	32.4	79.5	2.33



Increased water uptake due to initially dry soil

Emergence and seedling stablishment

Increase in flux due to seedling growth

Figure 1. Water flux for the RO and FO membranes under the subsurface irrigation mode.

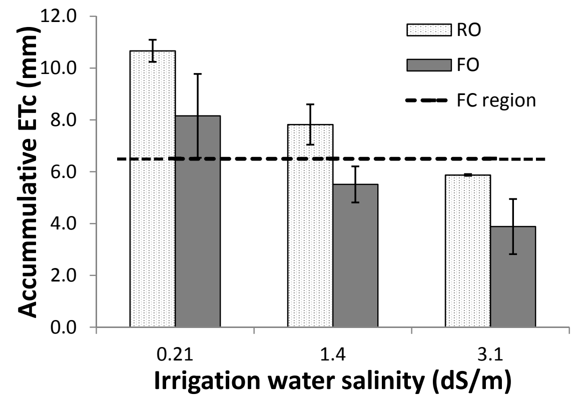


Figure 2. Accumulative evapotranspiration (water flux) for the RO and FO membranes at different salinity levels for the period of germination (0–7th day).

The water flux delivered by the RO membrane was found to closely respond to the theoretical ETc value, which demonstrates the capacity of the system to respond to the crop water demand variation. The water flux for both membranes decreased as the water salinity increased over the experiment duration (Figures 2 and 4). This was attributed to the higher osmotic resistance arising from higher salt concentrations present in the feed water.

During germination, soil water content is one of the limiting factors to determine success, especially during the phase of seed imbibition. Soil moisture content at field capacity (FC), i.e. the maximum water holding capacity for a specific soil against gravity, is recommended for bean germination (Yusuf *et al.*, 2011), generally assumed to be between 0.1 and 0.33 bar of water potential (Kirkham, 2014; Ritchie, 1998). For the soil considered in this study, a water potential of 0.33 bar is equal to 0.26 g/g of gravimetric water content (Lindsay, 1988). In Figure 2, the accumulative water flux for the germination period (seven days) is reported in terms of ETc (mm); the dashed line represents the total ETc value required to raise an initial soil water content of 0.083 g/g to FC, estimated to be equal to 6.5mm.

Evaporation impact on soil water storage was observed only for treatments with water flux above the FC region; for the rest of the treatments, the soil surface remained dry during germination. Considering the estimated FC demand (Figure 2), the total water flux observed for the RO was found to be 65% and 20% higher than that for salinities of 0.21 and 1.4 dS/m respectively, and 9.2% lower for 3.1 dS/m. For the FO membrane, the water flux was 26% above the estimated FC at the salinity level of 0.21 dS/m; for salinities of 1.4 and 3.1 dS/m, the water flux was 15 and 40% lower than the estimated requirement. As expected, the water uptake by soil was affected by salinity, which also directly affected the final germination percentage (Figure 3). Although a flux decrease as salinity increased was observed for both RO and FO membranes, the difference in germination percentage between the highest and lowest salinity level was only 10% for the RO, while for FO the difference was equal to 44%. The results indicate a better performance for RO membrane to sustain water flux as salinity of irrigation water increased, which resulted in a germination percentage similar to seeds germinated at conditions of FC for direct irrigation.

A similar effect of salinity on water flux was also observed for fluxes posterior to germination during seedling establishment (Figure 4).

At this phase, plants were found to uptake water from direct contact to the membrane as the root system develops towards the water source, suggesting that water absorption due to soil capillary forces would be more critical during germination than during seedling establishment. The average theoretical demand (ETc) for this period was lower or equal to the flux observed for the RO membrane at all salinity levels. However, for the FO membrane, the water flux at salinitiy levels of 1.4 and 3.1 dS/m were lower than the estimated demand. Water flux trend followed that observed during germination, which also reflects the water demand per treatment based on plant density result from germinating.

The growth of plants irrigated by the membrane-based system was compared to plants that received direct (conventional) irrigation for similar salinity levels (Figure 5 and 6). It could be observed that plants that received direct irrigation were shorter than plants irrigated through both RO and FO membranes for all salinity levels, as depicted in Figure 5. According to Kaymakanova (2009), the reduction on the growth of plants irrigated with water rich in salts could be related to the effect of salinity on the inhibition of both cell division and enlargement, which could also be related to the observed reduced total leaf area for plants directly irrigated than those which received irrigation through the RO membrane (Figure 6 and 7). The lowest total leaf area was observed for the FO membrane and highest salinity level, which agrees to the lowest germination percentage. Soil water conductivity was measured at the end of the experiment (Figure 8) to investigate the capacity of the membranes to prevent salts from reaching soil and plants.

A sharp increase for the concentration of salts in the saturation solution extract (reported as electrical conductivity, ECe) was observed only for the direct water application over 15 days compared to membrane treatments. This demonstrates that both membranes could effectively attenuate salt movement across when salinity was increased within the studied range.

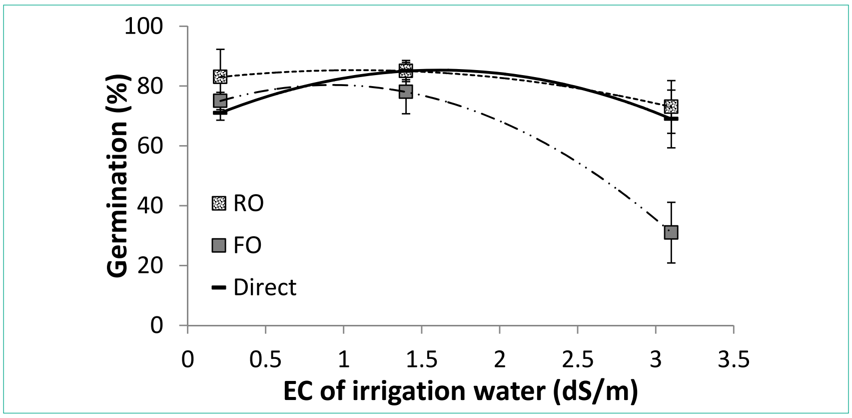


Figure 3. Percentage of germination for the RO and FO membranes and direct irrigation at different salinity levels.

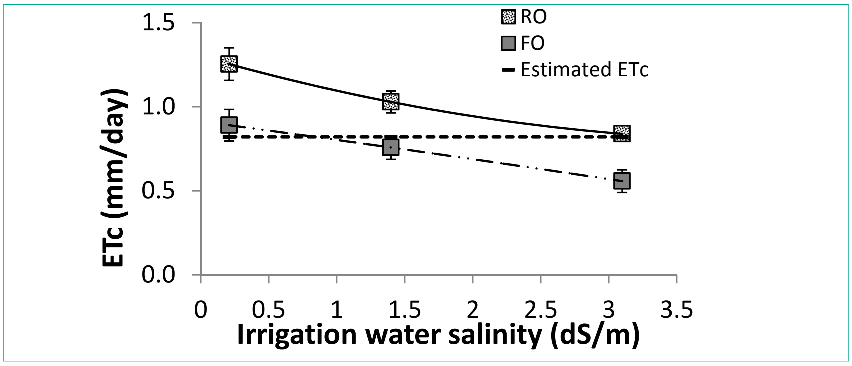


Figure 4. Average water flux for the RO and FO membranes at different salinity levels for the period of seedling establishment (8–15th day).

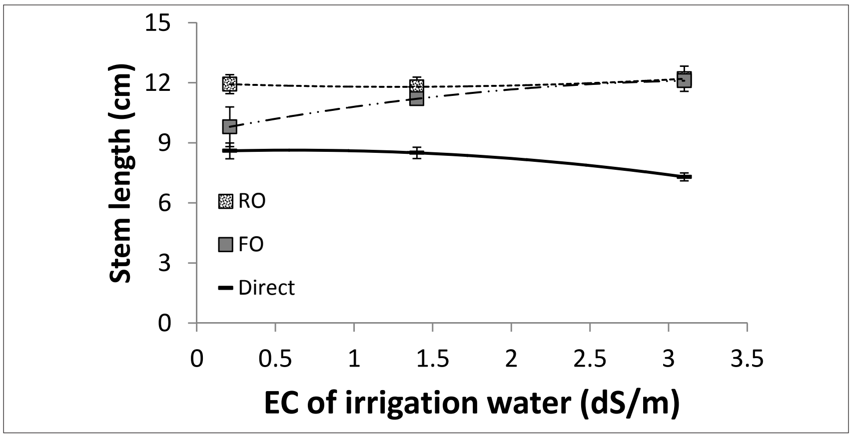


Figure 5. Final seedling height for the RO and FO membranes and direct irrigation at different salinity levels.

CONCLUSION

A better performance of water delivery was observed for the RO membrane as the flux remained higher than the estimated plant demand over the studied salinity range. Hence, the proposed irrigation method based on membrane technology has demonstrated the ability to respond to crop water demand during germination and mitigate soil salinisation when salinity of irrigation water increased from 0.21 to 3.1 dS/m. However, a future experiment considering the system's performance during the plant vegetative growth phase is required.

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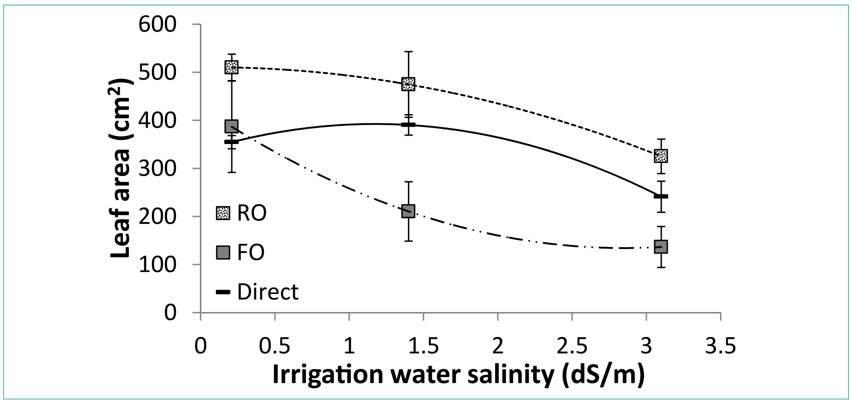

Figure 6. Final total leaf area for the RO and FO membranes and direct irrigation at different salinity levels.

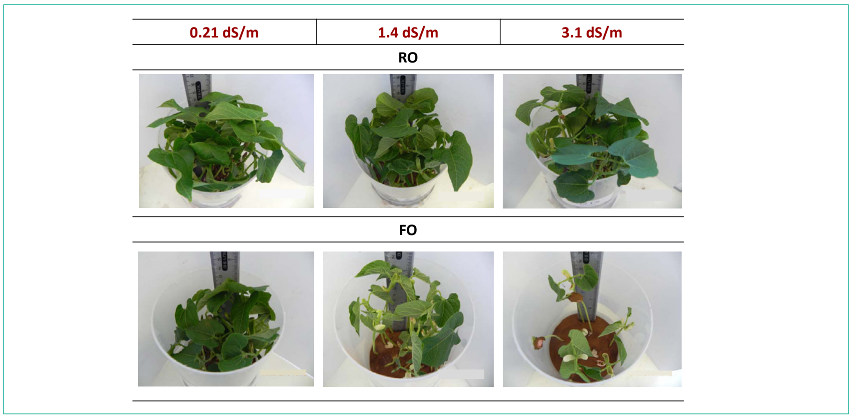

Figure 7. Visual appraisal of leaf area development for RO and FO treatments at different salinity levels of irrigation water.

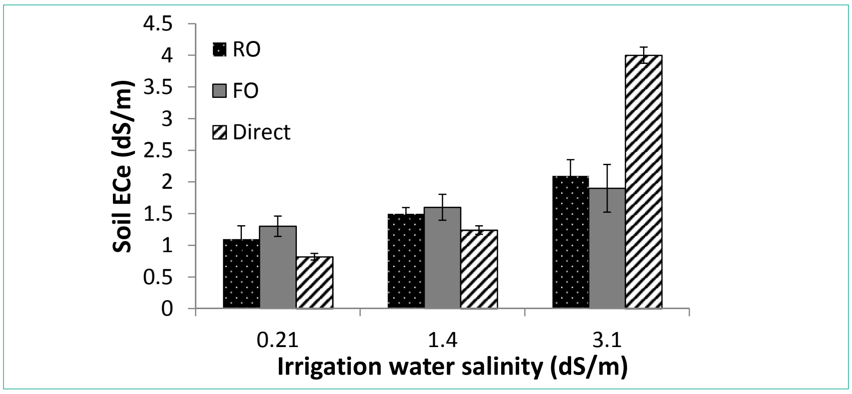

Figure 8. Electrical conductivity of the saturation extract of the soil (ECe) for the RO and FO membranes and direct irrigation at the end of experiment.

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