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Brackish water desalination for greenhouse agriculture: comparing the costs of RO, CCRO, EDR, and monovalent-selective EDR

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Abstract

Greenhouses are a rapidly growing agricultural sector that uses desalination systems. However, the desalination requirements of the greenhouse industry and an economic evaluation of desalination technologies for greenhouses have not been reported previously. Several greenhouse operators in North America using desalination systems were interviewed to identify key design specifications. A detailed cost comparison was conducted for key technologies: reverse osmosis (RO), closed circuit RO (CCRO), electrodialysis reversal (EDR) and monovalent selective EDR (MS-EDR). Capital, energy and membrane replacement costs, savings in feedwater costs from operating at higher recovery, and potential savings in fertilizer from using MS-EDR, were calculated. For <10-hectare greenhouses, RO was the most cost-effective technology. For >10-hectare greenhouses, alternatives can be considered. MS-EDR is economically competitive if it can retain at least 20% of the calcium and magnesium needed for growing and if membranes last 7 years. CCRO is competitive if the sum of feedwater and brine disposal costs are >\$0.24/m^3. If this cost was \$0.32/m^3, additional investment over RO for CCRO, EDR and MS-EDR, could pay itself back in 2.4, 3.4 and 2.1 years. In Ventura county where municipal water costs \$1.05/m^3, RO, CCRO, EDR and MS-EDR had payback periods of 7.1, 8.4, 7.8 and 8.2 months.

Keywords: Groundwater, desalination, agriculture, electrodialysis, reverse osmosis, cost

Nomenclature

Acronyms

CapEx	capital expense, \$
Cap$_{fac}$	capacity factor, -
Cap$_{m3/day}$	capacity, m^3/day
Cost$_{elec}$	electricity cost, \$/kWh$_e$
Cost$_{fert}$	fertilization cost, \$/m^2
EDR	electrodialysis reversal
MS-EDR	monovalent selective EDR
OpEx	operating expense, \$
RO	reverse osmosis
RPP	relative payback period
RR	recovery ratio
Sav	savings, \$
SpCapEx	specific capital cost, \$-day/m^3
SpE	specific energy, kWh$_e$/m^3
SPP	simple payback period
TDS	total dissolved solids

Roman

$r_{\mathrm{Ca,Mg}}$	ratio of divalent ions
t_{memb}	membrane life, yr.

Subscripts

feed	feedwater
fert	fertilizer
gw	groundwater
ha	hectare
ns	nutrient solution
pw	product water
w	pure water

1. Introduction

1.1 Background and motivation

By 2050, based on current consumption patterns and farming practices, projected water availability will be insufficient to feed the world's population from current croplands [1]. Part of the solution may rely on shifting from conventional open-air soil-based farming to more water efficient and higher yielding greenhouse based hydroponic agriculture (see Fig. 1), where plants are grown in a growing media with nutrients delivered using nutrient solutions and the climate around the plants controlled.

As an example, for growing the same amount of lettuce, hydroponic greenhouse agriculture (referred in the paper henceforth as "greenhouse agriculture") consumed 12.5 times less water and used 10.5 times less area than conventional farming [2]. The high yields and low water usage has resulted in a high adoption rate of greenhouse based agriculture, with the \$22.9 billion dollar greenhouse industry growing annually at a rate of 8.9 % [3].

Desalination is very important for the greenhouse industry. Greenhouses, depending on their scale of operations, can generate a significant amount of revenue per m^3 of water used. Zarzo et al. [4] had reported the average value per m^3 of water generated by greenhouses in Spain was 5.79 €/m^3 (6.72 \$/m^3). While exact revenue numbers are confidential, we were able to estimate the revenue and net profits from publicly available data on greenhouses in Alberta, Canada [5] and water consumed by tomatoes in greenhouses [6]. Revenue of 108 \$/m^2 and net profit of 13 \$/m^2 [5] translated per m^3 of water used as 109 \$/m^3 and 14 \$/m^3 respectively.

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Figure 1. Tomatoes growing in a hydroponic greenhouse owned by CEICKOR in Queretaro, Mexico.

Since greenhouses replace soil with nutrient solutions, the quality of water is of central importance to greenhouse producers. Greenhouses regularly monitor the pH and the salinity or total dissolved solids (TDS) of their waters to ensure the water is of the desired quality. Many greenhouses use municipal water to meet their water needs; however, municipal water is expensive in several parts of the world and may not be readily available. These reasons have driven a number of greenhouses to use groundwater to meet their water needs. About half the groundwater resources in the world are too brackish ($0.5 \leq S \leq 5$ g/kg) for food production [7], requiring desalination before use. These reasons have led the greenhouse industry to be early adopters of desalination within the agriculture industry. New desalination technologies designed to serve the needs of 21st century agriculture are likely to first serve the greenhouse industry sub-sector before being adopted for conventional field farming.

1.2 Desalination systems

Today, the most widely used and lowest cost brackish water desalination system is reverse osmosis (RO) [8], which is a membrane based pressure driven system that can produce a very pure product water [9]. Water produced from RO systems provides a clean slate for producers to add nutrients such as nitrates, phosphates, potassium, calcium, and magnesium.

For brackish water desalination, alternatives to conventional RO include: a novel variant of RO that operates in a semi-batch fashion called closed circuit reverse osmosis (CCRO) [10–13]; a membrane based electricity driven process called electrodialysis reversal (EDR) [14–17]; and a variant of EDR called monovalent-selective electrodialysis reversal (MS-EDR) [18–22] which uses MS-EDR membranes to selectively remove monovalent ions (see Fig. 2). CCRO systems have been commercially deployed over the last 10 years. EDR systems have been commercially deployed for brackish water desalination since the late 1970s [14] with variants designed for city-scale desalination [15,23], village-scale desalination [17,24,25], and even for in-home water treatment [26–28]. MS-EDR systems and its variants have been commercially deployed since the early 1960s for concentrating seawater to produce table salt in Japan [20,29]. MS-EDR membranes were originally designed to selectively concentrate sodium chloride from seawater and have not been commercially deployed yet for brackish desalination applications.

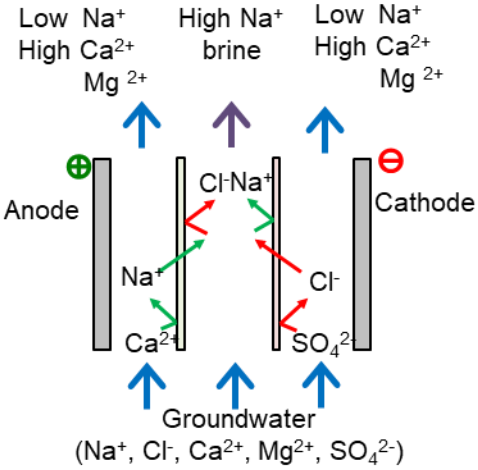

Figure 2. Diagram showing MS-EDR membranes selectively separating monovalent ions

More recently, Cohen et al. [19] had proposed the idea of using MS-EDR systems to "partially desalinate" irrigation water reducing the need for adding calcium, magnesium and sulfate fertilizers. RO and its variants produce water that is too pure for agricultural use [30] with conventional farmers in Israel having to pay an additional 0.5 $\$/m^3$ to put back in the required fertilizers [19,31]. For perspective, the cost of desalinated RO product water typically ranges from 0.39-1.5 $/m^3 [8]. Effectively, agricultural users pay to remove some of the nutrients and pay to add them back in. In principle, MS-EDR systems could retain a significant amount of the calcium, magnesium and the sulfates leading to potential fertilizer savings.

The selectivity of MS-EDR membranes towards monovalent ions have been studied in the literature for seawater and concentrated seawater salinities [32,33]. Cohen et al. [19] investigated the selectivity for salinities of commercially available MS-EDR membranes: Selemion CSO/ASV from Asahi Glass and Chemicals Co., Neosepta CMS/ACS from Astom Co., and MVK/MVA from PCA Gmbh. Cohen et al. [19] found that only the CSO membranes maintained the desired selectivity at groundwater salinities, with further improvements when polyethyleneimine was coated on the membranes leading to average removal ratios of 72%, 58% and 43% for sodium, calcium and magnesium respectively. Selectivity was observed to drop significantly with time for unknown reasons, requiring frequent restoration, with the need for further research into the problem. It must be noted that currently available commercial MS-EDR membranes were all designed for treating water with a salinity greater than that of seawater. More recently, the manufacturer Fujifilm [34] had been developing MS-EDR membranes designed for brackish desalination applications.

The differences in the quality of the product water produced by RO, CCRO, EDR and MS-EDR systems must also be noted. While CCRO produces a pure product water stream like RO, EDR and MS-EDR do not produce pure product water streams. Commercial brackish EDR systems were designed for producing drinking water and are not typically operated to produce product streams with salinities lower than 250 ppm. MS-EDR systems are expected to operate in similar salinity ranges but producing product water streams with much lower sodium concentrations than EDR systems.

1.3 Literature gaps and objectives

Significant gaps in the literature exist on RO, CCRO, EDR and MS-EDR systems, especially about how they compare in terms of costs. Furthermore, the desalination treatment needs and priorities within the greenhouse industry have not been published in the literature. While several works have compared the performance of RO and EDR [35–37], to the best of our knowledge, the only one that compared CCRO with RO and ED was a previous study that by the present authors [12]. However, the previous analysis was restricted to just energy consumption for treating groundwater at 3000 ppm and did not compare capital or membrane replacement costs. No study in the literature has compared the costs of RO, CCRO, EDR and MS-EDR systems.

Separate from the costs of these systems, to the best of our knowledge, no study has compared the savings generated by these systems in terms of savings in feedwater costs from operating at different recoveries and potential fertilizer savings that are possible from MS-EDR. Another important question concerning MS-EDR technology, is whether it is worth investing significant research and development efforts to enable the technology for agricultural applications. A preliminary techno-economic analysis is needed to assess the value provided by MS-EDR and to assess if the technology could be affordably produced for the agriculture market.

The objective of this paper is to first present the desalination needs for the greenhouse industry, and then the results of a techno-economic analysis and comparison of the technologies of RO, CCRO, EDR, and MS-EDR. The methods used for our analysis are presented along with the key findings. The benefits and drawbacks of the technologies are presented with recommendations on which technology to use. The capital costs, energy costs and membrane replacement costs of each technology was calculated. The savings in water and fertilizer used were quantified for each technology. A payback period was estimated for each technology based on market prices of water in select areas. A relative payback period for CCRO, EDR, and MS-EDR (relative to RO) was also calculated. Areas where future desalination research and development efforts should focus on are also highlighted.

2. Greenhouse industry needs

2.1 Methods

To effectively compare desalination technologies for use in greenhouses, the metrics for comparison and the requirements for greenhouses need to be characterized. To identify the desalination needs and priorities of the greenhouse industries, and evaluate the savings possible, we carried out a detailed review of the literature, and phone and in-person interviews of greenhouse growers and operators.

We focused on greenhouses in North America that currently used desalination technologies. Within North America, we determined that desalination systems were currently being used in parts of California and Florida in the USA and in the state of Queretaro in Mexico. A total of 34 in-person interviews were conducted in these states: 5 in Florida, 10 in California, and 19 in Queretaro. The in-person interviews conducted in the USA covered 206 hectares or 26% of the area under greenhouse cultivation in the USA [38]. The in-person interviews conducted in Mexico covered a cultivation area of 484 hectares or approximately 14 % of the area under cultivation in large greenhouses (> 5 ha.) that is reported in the literature [38]. Thus, the findings are representative of the industry's desalination needs.

2.2 Desalination system configuration and design specifications

Figure 3 shows the typical water flow configuration in greenhouses that use groundwater. Groundwater is pumped from an aquifer to a desalination system, which produces a brine stream and a treated water stream. Nutrients are added to the treated water to obtain a nutrient solution, which is sent to the greenhouse. Several greenhouses recirculate the water leaving a greenhouse after disinfecting the water using ultraviolet radiation. In the greenhouses we interviewed, both the desalination brine and the discharge water from the greenhouse were used to irrigate field crops and trees such as avocados that were more salt tolerant.

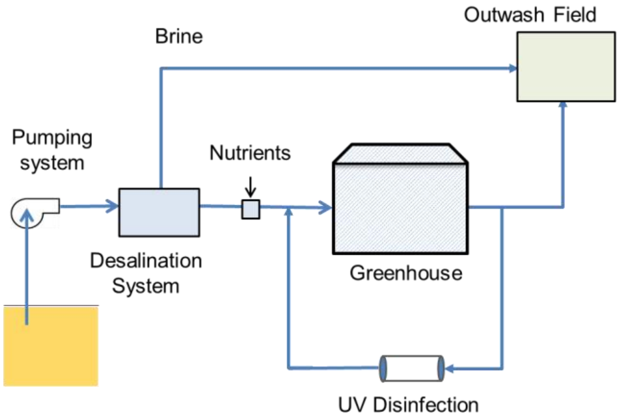

Figure 3. Diagram showing typical water flow in a greenhouse

Table 1 summarizes the desired desalination system specifications. For each parameter, both the range of values encountered in our interviews and the final design value chosen for our analysis is shown. The chosen values represented the most commonly found values at greenhouses that used desalination systems. For the calculations reported in this paper, each hectare under greenhouse cultivation needed a desalination system with a capacity of 60 m^3/day operated without supervision for 12 hours a day, year-round at a 90% capacity factor. The feed water was assumed to have 850 ppm of total dissolved solids. Greenhouses typically wanted a payback period of 2 years on their investments. Within our sample of greenhouses, the average cost of fertilization was \$3/m^2. The sodium level desired in nutrient water was 23 ppm (~1 mM/L). The levels of calcium and magnesium varied with the type of vegetable cultivated. For our calculations, we assumed a representative desired value of 175 ppm of calcium ions (~4.4 mM/L) and 40 ppm (~1.7 mM/L) of magnesium ions.

Table 1. Desired desalination system specifications

Parameter	**Units**	**Range**	**Value**
System			
Capacity per hectare	m^3/day-ha	50-100	60
Feed water TDS	ppm	320-1100	850
Operation time	hours	8-12	12
Type of operation		Auto.	Auto.
Desired payback	(yr.)	2-4	2
Fertilizer cost	\$/m^2	2.5-4.1	3
Desired nutrient water composition			
Na^+	ppm	23-115	23
Ca^{2+}	ppm	120-200	175
Mg^{2+}	ppm	40-80	40

2.3 Discussion on greenhouse priorities and market learnings

The key learnings related to the greenhouse industry and their desalination needs and priorities are discussed below.

2.3.1 Two different types of greenhouse end-users with different priorities

From interviewing greenhouse growers, we realized that within the greenhouse industry, there were two very different types of end-users: greenhouses with areas less than 5 hectares under cultivation, and those with areas greater than 5 hectares. Greenhouses with less than 5 hectares under cultivation generally tended to be small family-owned operations with limited capital budgets and a strong preference to buy technology that has already been proven to be reliable. These greenhouses were less interested in obtaining fertilizer savings using partial desalination technologies. They were far more interested in achieving higher water recoveries from their desalination systems to reduce their groundwater usage and be prepared for potential future regulations on groundwater use.

Greenhouses with more than 5 hectares under cultivation had a more corporate ownership model with a greater focus on delivery return on investments to stockholders. These greenhouses were interested in cost savings wherever possible and were interested in new desalination technologies that could increase both water savings and fertilizer savings. We also observed significant economies of scale at work in the greenhouse industry, with profit margins generally increasing with acreage under cultivation. Larger greenhouses were interested in investing in new technologies but generally required payback periods less than 2 years.

2.3.2 Technologies used in the field

All the desalination systems used within the sample of greenhouses we interviewed in the USA used RO systems. In comparison, in the sample of greenhouses interviewed around Querétaro, Mexico, only one greenhouse used an RO system while the other greenhouses used ion-exchange resin-based systems. The technology choice was largely a reflection of the salinity of the groundwater in both regions.

The groundwater salinity in the greenhouse clusters around Querétaro, Mexico was generally less than 400 ppm. In comparison, greenhouses that we sampled in the USA that used RO, had groundwater salinities ranging from 575 to 1300 ppm, with a salinity of 850 ppm being representative. Ion-exchange resin-based water treatment systems typically operate well only up to a salinity of 400 ppm. All the greenhouses we interviewed in the USA had groundwater salinities higher than the range of operation of ion-exchange resin-based systems. Furthermore, the budgets for equipment for greenhouses in Mexico was much lower than for greenhouses in the USA, and the Mexican operators overwhelmingly preferred the lower cost ion-exchange resin-based systems (which were reportedly 70% the capital cost of RO and 40% the operating cost).

In view of their low salinity range of operation, ion-exchange resin-based systems are considered as water softening systems and not desalination systems per se. For this paper, in order to make a fair comparison, we focused our analysis to desalination technologies for treating water with salinities greater than 500 ppm.

2.3.3 Low desired payback periods

Greenhouse operators in general wanted the payback periods on capital to be 2-4 years, with the most common response in our interviews being 2 years. Despite the high revenues per m^3 of water enabled by desalination technologies, capital cost for RO equipment is only a fraction of the revenue enabled by RO. Due to widespread production of RO systems for industrial and municipal applications around the world and high competition between RO companies, RO systems are now a commodity product. Thus, newer desalination technologies, in order to compete with RO, must have capital costs comparable to RO or at the maximum a capital cost that can be paid off by the relative savings incurred over RO within a 2-year period:

$$\mathrm{CapEx}_{\mathrm{max,desal}} = \mathrm{CapEx}_{\mathrm{RO}} + 2 \times \mathrm{Sav}_{\mathrm{desal,yr}} \qquad (1)$$

2.3.4 Price of water

To estimate the value provided by increased water recovery from a desalination system, a price needs to be set on ground water (feed water to the desalination system), product water and brine discharge. During our interviews, we realized that there were several different water prices to consider and that there was a mismatch between the true value of the water and its current market price. Before selecting a price for groundwater, product water and brine discharge for our analysis, a deeper discussion on water prices is needed.

Table 2 shows current water prices depending on the type of water. Water is typically heavily subsidized for agricultural use with the average cost of water for a farm in the USA being 0.027 $/$m^3$ [41]. Municipal water costs can be significantly higher, with agricultural users in Ventura County in Southern California paying 1.05 $/$m^3$ [43]. The high cost of municipal water has led several greenhouses to invest in wells to source groundwater at significantly lower costs.

Table 2. Range of water prices

Water source	Ref.	Water price ($/acre-foot)	($/$m^3$)
Groundwater tariff in Texas	[39]	1	0.0008
Cost of pumping per 100 feet	[40]	20.5	0.017
Average cost of farm water in USA	[41]	33	0.027
Median cost of recharging groundwater in California	[42]	390	0.32
Cost of surface water for agricultural use in Ventura County. California	[43]	1294	1.05

True value of groundwater:

Historically, in the USA and other parts of the world, groundwater withdrawals were not heavily regulated with withdrawal tariffs being non-existent or very low (e.g. groundwater tariffs are only $0.0008/$m^3$ in Texas [39]). The current cost of groundwater for a greenhouse largely consists of capital cost for well construction and energy costs for lifting water. For every 100 feet of aquifer depth, the operating cost of pumping water is reported to be $0.017/$m^3$ [40]. After amortization, the capital costs for a well are expected to add a few US cents per m^3. However, these costs do not represent the true value of groundwater.

Due to increased withdrawals, greenhouses are increasingly concerned about regulatory tariffs being imposed on groundwater and about the long-term availability of groundwater for operations. Greenhouses are increasingly becoming more environmentally conscious, with some greenhouses we interviewed considering an "accounting cost" of water to make business decisions. They are increasingly recognizing that the current costs for groundwater may not be applicable in the future, especially given that greenhouses are often in operation for more than 20 years. We felt that a fair "accounting cost" of water should be representative of the true value of the water and looking at the cost of recharging groundwater can be a good measure of the true value of groundwater. Several projects currently operate in California to recharge groundwater, with the median costs of recharging groundwater being 0.32 $/$m^3$ [42]. For this paper, we assumed that a fair "accounting cost" for groundwater is the median cost of recharging groundwater: 0.32 $/$m^3$.

True value of product water:

To calculate payback periods on desalination systems and compare desalination systems, we must also quantify the value of product water produced from a desalination system. One method of valuing desalination product water is by looking at the pricing of the alternative currently used by greenhouses: municipal groundwater. Thus, for this paper, we assumed that value of the product water is the market price of municipal water for agricultural users in Ventura County, California: 1.05 $/$m^3$ [43]. More discussion around the value of product water can be found in Section 4.3.

Costs associated with brine discharge:

Most greenhouses we interviewed did not incur significant brine disposal costs. Desalination brine was typically mixed with nutrient rich greenhouse discharge water and used to irrigate salt resistant crops and trees such as avocados grown outside the greenhouse. Only one greenhouse we interviewed used an evaporation pond. However, a few greenhouses incurred indirect brine disposal costs due to the need to buy land for growing salt resistant crops outside the greenhouse. We could not accurately estimate what these indirect costs were. Since these indirect costs were difficult to compute and even more difficult to generalize, for the general analysis presented in the paper we assumed that brine disposal costs were 0 $/$m^3$ (i.e. no costs associated with brine). However, results presented in later sections are presented in such a way that greenhouses can easily understand how brine disposal costs may affect desalination technology selection.

To summarize, for calculations presented in this paper, we used an “accounting cost” of groundwater of 0.32 $\$/m^3$, a price for the product water of 1.05 $\$/m^3$ and no costs for brine disposal.

3. Desalination system costs

For our analysis we focused on the desalination technologies of RO, CCRO, EDR and MS-EDR. The design specifications for the systems were reported in Table 1. All systems treated feed water of salinity 850 ppm. While RO and CCRO systems delivered water with almost no salt, EDR and MS-EDR systems were designed to produce water at 250 ppm.

3.1 Methods

3.1.1 Capital costs

Specific capital costs (SpCapEx) for RO, CCRO, EDR and MS-EDR were calculated based on data in the literature, conversations with greenhouses who bought desalination systems and conversations with desalination system manufacturers. For RO, cost data was obtained from publicly available data from Forever Pure [44], from conversations with RO manufacturers [45–48], and from data provided by the greenhouses themselves. For CCRO, cost data was obtained from the manufacturer Desalitech [49], with CCRO systems typically costing twice that of RO for capacities 54.5-272.5 m^3/day (10-50 gpm), 1.25 times that of RO for capacities 272.5-817.6 m^3/day (50-150 gpm) and 1.1 times that of RO for capacities larger than 817.6 m^3/day (150 gpm). For EDR, costs were obtained from the literature [17,25,35,50,51] and from conversations with a manufacturer [34]. MS-EDR for brackish desalination has not yet been widely deployed to the best of our knowledge, however, systems are expected to be commercially available by the end of 2020. Since greenhouse water treatment only required selective removal of sodium, we assumed in our capital cost model for MS-EDR stacks in greenhouses that only the cation exchange membranes were monovalent selective (i.e. anion exchange membranes in these stacks are conventional EDR membranes that are not monovalent selective). From manufacturer conversations, we assumed that using cation selective MS-EDR membranes will lead to a 10% premium in capital costs for an MS-EDR stack over an EDR stack.

3.1.2 Energy consumption and costs

The specific energy consumption (SpE) for RO, CCRO, EDR and MS-EDR were obtained using process models in the literature that were adapted for the conditions relevant to greenhouse use. RO specific energy consumption was estimated using a model reported by Nayar et al. [12] and Warsinger et al. [13]. The RO systems were assumed to operate at a recovery of 70% like systems currently used in the field with the pumps assumed to be 70% efficient. CCRO specific energy consumption was estimated using a model reported previously by Warsinger et al. [13]. For the paper, CCRO systems were assumed to operate at a recovery of 90%. EDR and MS-EDR specific energy consumption was calculated using an adaptation of process models previously developed and validated by Nayar et al. [20,52] for treating seawater and concentrated seawater. The membrane transport model for the EDR process model was previously used by McGovern et al. to simulate the performance of brackish ED systems [35]. The energy consumption predicted from these models were verified against data from the literature [25] with our values matching the reported values in the literature to within 4%.

For the MS-EDR process model, sodium chloride transport properties for the MS-EDR membranes Neosepta CMS and ACS were used [53]. It must be noted that brackish MS-EDR systems in the field are expected to be using newer membranes from FujiFilm designed for brackish water desalination. These membranes are expected to be more selective at brackish salinities than the Neosepta membranes; however, we have assumed that the resistance characteristics and sodium transport will be similar to Neosepta CMS and ACS membranes. The EDR and MS-EDR systems were assumed to be operating at a recovery of 80%. It must be noted that all the energy consumption process models assumed groundwater to be an aqueous solution of sodium chloride—an assumption shown to be accurate for predicting energy consumption [17,25].

To calculate energy costs, we assumed an electricity price ($\mathrm{Cost_{elec}}$) of 0.1 $/kWh$_e$, a daily system operation time of 12 hours, and a capacity factor ($\mathrm{Cap_{fac}}$) of 90%:

$$\mathrm{OpEx_{energy,yr}} = \mathrm{SpE} \times \mathrm{Cost_{elec}} \times \mathrm{Cap}_{\frac{\mathrm{m^3}}{\mathrm{day}}} \times \left(\frac{12}{24}\right) \times 365 \times \mathrm{Cap_{fac}} \tag{2}$$

3.1.3 Membrane replacement costs

Membrane replacement costs ($\mathrm{Cost_{memb}}$) were calculated for a 600 m^3/day system corresponding to the desalination needs of a 10-hectare greenhouse. RO membrane replacement costs were estimated using an online calculator from Suez Water [54]. CCRO systems were assumed to have the same membrane replacement cost as an RO system. EDR and MS-EDR membrane areas were estimated using the process model developed by Nayar et al. described in Section 3.1.2. The process models were validated previously [20,52] for accurately calculating membrane area for seawater brine concentration applications. For this study, we further validated the model against data reported by Wright et al. [25] for a commercial EDR stack, with our model predicting membrane area within 18% of experimental values.

Brackish RO membrane elements were assumed to cost $550 per element [54]. EDR membranes were assumed to have a cost of 160 $\$/m^2$ [17]. MS-EDR membranes for high salinity applications cost 222 $\$/m^2$ [20]. For brackish applications, newer MS-EDR membranes can cost between 150-250 $\$/m^2$ [34]. For the purpose of this study, we assumed an average MS-EDR membrane cost of 200 $\$/m^2$.

From our interviews, RO membranes are replaced on average every 4 years. CCRO membranes in the field were reported to last longer than RO membranes because the recirculation of water in CCRO generally led to lower scaling and fouling risks and reduced cleaning requirements compared to RO [49]. From manufacturer conversations [49], we conservatively assumed that CCRO membranes need replacement every 5 years. From the literature, EDR membranes are expected to be replaced every 10 years [17,50]. MS-EDR membranes developed for high salinity applications have a membrane life of 7 years [20,52]. We assumed conservatively that MS-EDR membranes designed for brackish desalination, will also have a membrane life of 7 years.

For this paper, membrane replacement costs were annualized over the membrane lifetime (t_{memb}) without assuming an interest rate to obtain a simple annualized membrane replacement cost:

$$\mathrm{OpEx}_{\mathrm{memb,yr}} = \frac{\mathrm{Cost}_{\mathrm{memb}}}{t_{\mathrm{memb}}} \tag{3}$$

3.1.4 Other operating costs

Greenhouses have annual maintenance contracts related to their desalination equipment. These costs cover the cost of annual inspection by an experienced technician and the cost of using chemicals and anti-scalants. Due to the variability in pricing of maintenance contracts with location, we could not accurately estimate the operating costs. Since, these costs are not expected to vary much between technologies, RO, CCRO, EDR and MS-EDR systems can be effectively compared without including these operating costs.

3.2 Capital costs

Figure 4 shows a comparison of the specific capital costs of RO, CCRO, EDR and MS-EDR as a function of system capacity up to a capacity of 3750 m^3/day, enough for 62 hectares of greenhouse cultivation. The raw data and the equations of best fit are shown. Table 3 lists the equations of best fit with the R^2 values and the average absolute percentage deviation (AAPD) of the data from the equation of best fit.

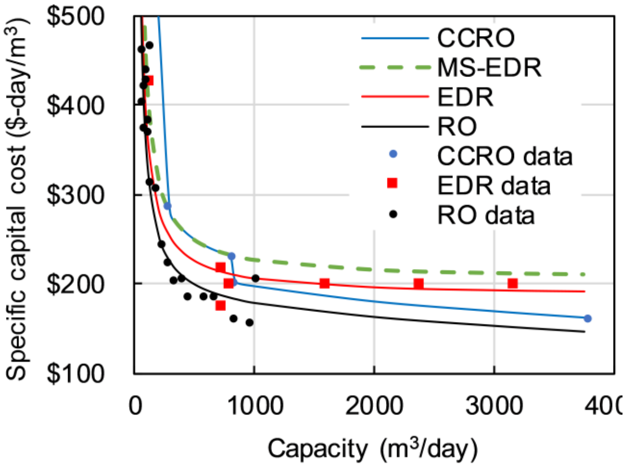

Figure 4. Specific capital cost of RO, CCRO, EDR and MS-EDR varying with capacity, with the raw data and equations of best fit shown.

Table 3. Specific capital costs of RO, CCRO, EDR and MS-EDR.

	Equation		R^2	AAPD
RO	$\mathrm{SpCapEx}_{\mathrm{RO}} = -0.007085 \times \mathrm{Cap}_{\mathrm{m^3/day}} + 169 + {}^{17{,}005}\!/_{\mathrm{Cap}_{\mathrm{m^3/day}}}$	(4)	0.86	9%
CCRO	$\mathrm{SpCapEx}_{\mathrm{CCRO}} = \begin{cases} 2 \times \mathrm{SpCapEx}_{\mathrm{RO}}, & 54.5 \le \mathrm{Cap}_{\mathrm{m^3/day}} < 272.5 \\ 1.25 \times \mathrm{SpCapEx}_{\mathrm{RO}}, & 272.5 \le \mathrm{Cap}_{\mathrm{m^3/day}} < 817.6 \\ 1.1 \times \mathrm{SpCapEx}_{\mathrm{RO}}, & \mathrm{Cap}_{\mathrm{m^3/day}} \ge 817.6 \end{cases}$	(5)	n/a	n/a
EDR	$\mathrm{SpCapEx}_{\mathrm{EDR}} = 185 + {}^{20{,}000}\!/_{\mathrm{Cap}_{\mathrm{m^3/day}}}$	(6)	0.95	9%
MS-EDR	$\mathrm{SpCapEx}_{\mathrm{MS-EDR}} = 1.10.\times \mathrm{SpCapEx}_{\mathrm{EDR}}$	(7)	n/a	n/a

It can be seen that the specific capital cost of all desalination systems were very sensitive to the capacity at the ranges we considered. The specific capital cost of desalination increased significantly at capacities less than 600 m^3/day, i.e., for greenhouses with less than 10 hectares under cultivation. The specific capital cost of a 60 m^3/day RO system for a one-hectare greenhouse cost 452 \$-day/m^3, while a 600 m^3/day system for a 10-hectare greenhouse cost only 193 \$-day/m^3 — a reduction of 57 % in specific capital costs.

Among the desalination systems we compared, RO capital costs were the least. CCRO systems had the highest specific capital costs up to a capacity of 272.5 m^3/day (50 gpm) after which MS-EDR systems had the highest specific capital costs.

3.3 Energy consumption

Figure 5 shows a comparison of the specific energy consumption of RO, CCRO, EDR and MS-EDR for treating feed water with a salinity of 850 ppm. While the RO and CCRO systems were assumed to produce a product of salinity 25 ppm, the ED and MS-EDR systems were assumed to deliver a product salinity of 250 ppm. CCRO consumed the lowest specific energy at 0.49 kWh$_e$/m^3 followed by EDR at 0.51 kWh$_e$/m^3. MS-EDR consumed slightly more energy due to the higher resistance of MS-EDR membranes over conventional EDR membranes. RO consumed the most specific energy at 0.60 $\mathrm{kWh_e/m^3}$ as they had the lowest recovery ratio among the four systems of only 70%.

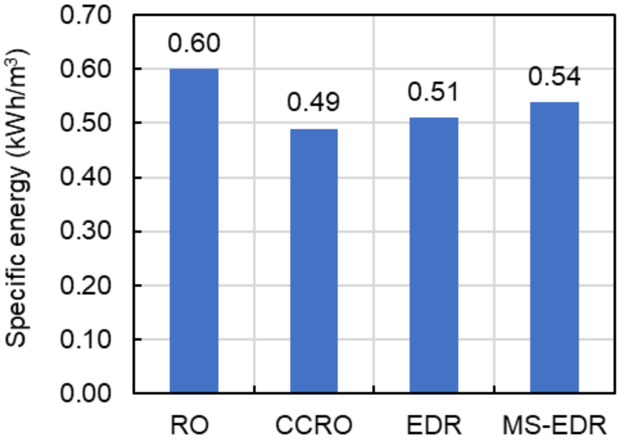

Figure 5. Specific energy consumption for RO, CCRO, EDR and MS-EDR for treating 850 ppm feed water

3.4 Operating costs: Membrane replacement and energy

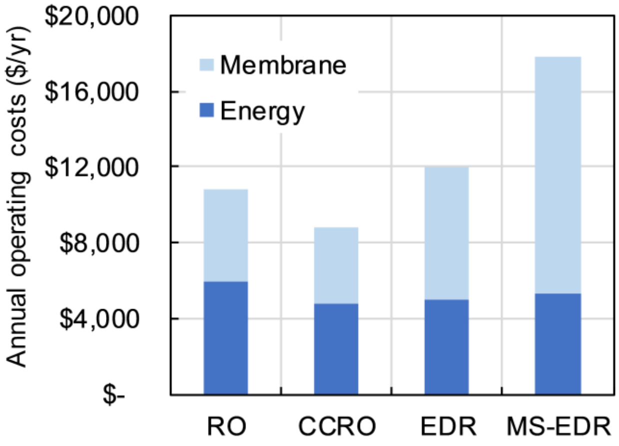

Figure 6. Annual costs for energy and membrane replacement for RO, CCRO, EDR and MS-EDR for treating 850 ppm feed water

Figure 6 shows a comparison of annual energy and membrane replacement costs for RO, CCRO, EDR and MS-EDR systems treating feed water of salinity 850 ppm at a capacity of 600 $\mathrm{m^3}$/day of product water (i.e., for a 10-hectare greenhouse). The sum of the annual energy and membrane replacement costs for RO, CCRO, EDR and MS-EDR systems were $10,863, $8789, $11,992 and $17,799 respectively.

For RO systems, on average, to achieve 70% recovery at a flow rate of 600 $\mathrm{m^3}$/day, 36 brackish RO elements were needed [54], with the total RO membrane replacement cost being $19,800—17% of the capital cost of an RO system. The RO membrane replacement cost as a proportion of total capital costs was corroborated in our interviews. CCRO systems were assumed to have the same membrane replacement costs but with the membranes assumed to last 5 years instead of 4 years based on manufacturer conversations [49]. EDR membrane replacement cost significantly more at $69,650 with MS-EDR membrane replacement costing even more at $87,400. EDR and MS-EDR membranes amounted to 53% and 58% of their respective capital costs.

Currently, the active brackish RO plants in the world outnumber brackish ED/EDR plants at least 10-fold [55] with EDR seen more as a niche technology [23]. Consequently, RO membranes are currently produced in much higher volumes than EDR and MS-EDR membranes, leading to much lower costs for the RO membranes. While EDR and MS-EDR systems consumed less energy than a conventional RO system, the energy savings were superseded by the higher membrane replacement costs. However, the savings from operating at a higher desalination system recovery and potential fertilizer savings must be considered to see if the higher operating and capital costs are justified.

4. Value provided

To effectively compare desalination systems, the value provided by systems in terms of water savings from increased recovery and fertilizer savings from partial desalination need to be quantified. Since both water and fertilizer savings vary between greenhouses, we characterized these savings to help greenhouse industry end-users make their purchasing decisions.

4.1 Water savings from increased desalination system recovery

Conventional brackish RO systems operated at a recovery ratio (RR) of 70% with EDR, MS-EDR and CCRO systems capable of operating at higher recoveries. Operating at higher recoveries can lead to savings in both feedwater costs and brine disposal costs.

The annual feedwater savings per hectare from operating at a higher recovery than 70% was captured using the following equation:

$$\mathrm{Sav}_{\mathrm{RR,feed,ha}} = \mathrm{Cap}_{\mathrm{ha}} \times \left(\frac{\mathrm{Op.hr.}}{24}\right) \times \left(\frac{1}{0.7} - \frac{1}{\mathrm{RR}}\right) \times 365 \times \mathrm{Cap}_{\mathrm{fac}} \times \mathrm{Cost}_{\mathrm{feed,w}} \qquad (8)$$

where, the values for product water capacity per hectare ($\mathrm{Cap}_{\mathrm{ha}}$) and daily hours of operation ($\mathrm{Op.hr.}$) were sourced from Table 1 as 60 $\mathrm{m^3}$/ha and 12 hours per day respectively. The capacity factor ($\mathrm{Cap}_{\mathrm{fac}}$) for the greenhouse was assumed to be 0.9.

Figure 7 shows the annual savings in feedwater costs, calculated from Eq. (8), varying with recovery ratio and feedwater costs.

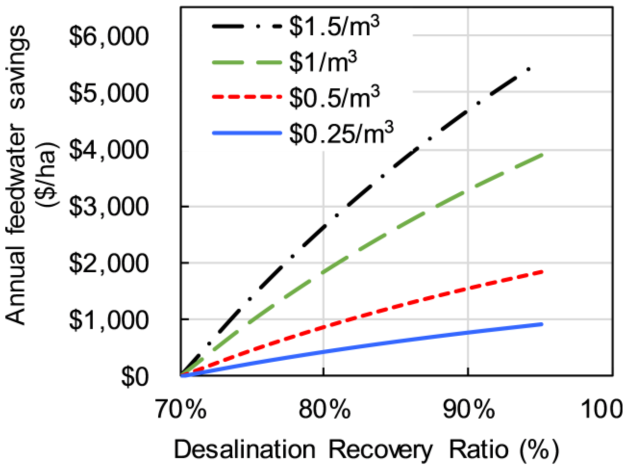

Figure 7. Annual water savings for desalination recovery ratios greater than 70% for various effective feed water prices

Figure 7 can also be used to separately calculate the annual savings in brine disposal costs from operating desalination systems at higher recoveries. Since, the product water required is fixed, the mass flow rate of feedwater reduced at higher recovery is numerically equal to the mass flow rate of brine reduced. Thus, the labels shown for feedwater costs can also be read as the "sum of feedwater costs and brine disposal costs". Greenhouses that do incur brine disposal costs can use Fig. 7 to calculate the savings in brine disposal costs which must be added to the savings in feedwater costs. As an example, if we assume zero brine disposal costs and a feedwater cost of 0.32 $\$/m^3$ equivalent to the median cost of recharging groundwater in California, the annual savings per hectare at recoveries of 80% and 90% was \$563 and \$1001, respectively. If the brine disposal costs were instead 0.18 $\$/m^3$ bringing the sum of feedwater and brine disposal costs to 0.5 $\$/m^3$, from Fig. 7, the annual savings per hectare at recoveries of 80% and 90% will be \$880 and \$1564, respectively.

4.2 Fertilizer savings from MS-EDR

The ability of MS-EDR systems to preferentially remove sodium over calcium and magnesium ions can lead to fertilizer savings for greenhouses. Currently, greenhouses using RO need to add significant amounts of calcium and magnesium to the obtain the desired composition of nutrient water. Calcium and magnesium salts contribute approximately to 1/3rd of annual fertilizer costs:

$$\mathrm{Cost}_{\mathrm{Ca,Mg,ha}} = {}^{\mathrm{Cost}_{\mathrm{fert,ha}}}\!/_{3} \tag{9}$$

where, $\mathrm{Cost}_{\mathrm{fert,ha}}$, from Table 1 varied from 2.5-4.1 $\$/m^2$ within the sample of greenhouses we interviewed. Greenhouses growing flowers incurred much lower fertilization costs than those growing vegetables. Furthermore, the degree to which greenhouses recirculated their nutrient solutions affected their overall fertilization costs.

The ratio of calcium and magnesium salts saved using MS-EDR systems ($r_{\mathrm{Ca,Mg,saved}}$) depends on both the amount of calcium and magnesium within groundwater and the amount of selectivity of the MS-EDR membranes towards calcium and magnesium ions:

$$r_{\mathrm{Ca,Mg,saved}} = r_{\mathrm{Ca,Mg,gw}} \times r_{\mathrm{Ca,Mg,selec}} \tag{10}$$

where, $r_{\mathrm{Ca,Mg,gw}}$ is the ratio of the concentration of calcium and magnesium ions in ground water to that in the nutrient solution (from Table 1):

$$r_{\mathrm{Ca,Mg,gw}} = \frac{[\mathrm{Ca}^{2+}]_{\mathrm{gw}} + [\mathrm{Mg}^{2+}]_{\mathrm{gw}}}{[\mathrm{Ca}^{2+}]_{\mathrm{ns}} + [\mathrm{Mg}^{2+}]_{\mathrm{ns}}} \tag{11}$$

and, $r_{\mathrm{Ca,Mg,selec}}$ is the ratio of the concentration of calcium and magnesium ions in the product water of an MS-EDR system to that in the feed.

$$r_{\mathrm{Ca,Mg,selec}} = \frac{[\mathrm{Ca}^{2+}]_{\mathrm{p,MS-EDR}} + [\mathrm{Mg}^{2+}]_{\mathrm{p,MS-EDR}}}{[\mathrm{Ca}^{2+}]_{\mathrm{f,MS-EDR}} + [\mathrm{Mg}^{2+}]_{\mathrm{f,MS-EDR}}} \tag{12}$$

Since MS-EDR systems have yet to be piloted in greenhouses, the exact selectivity is uncertain. Furthermore, the amount of calcium and magnesium in groundwater varies significantly by location. Thus, we felt it best to estimate the potential cost savings across a wide range of calcium and magnesium savings:

$$\mathrm{Sav}_{\mathrm{Ca,Mg,ha}} = \mathrm{Cost}_{\mathrm{Ca,Mg,ha}} \times r_{\mathrm{Ca,Mg,saved}} \tag{13}$$

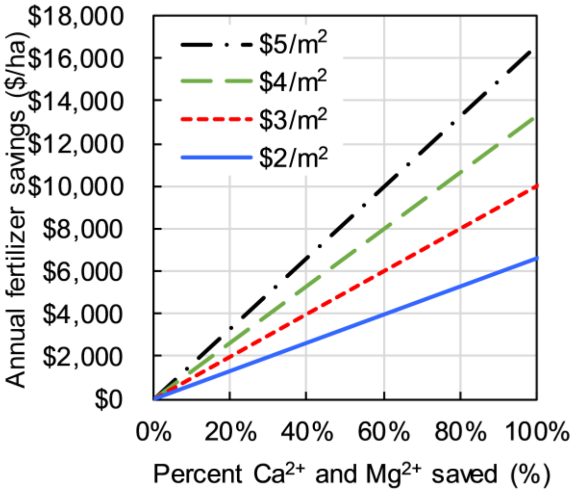

Figure 8. Variation of annual savings in fertilizer from reduced addition of calcium and magnesium expressed as a function of percent of calcium and magnesium saved at different rates of fertilizer use

Figure 8 shows the annual fertilizer savings per hectare of greenhouse cultivation, calculated using Eq. (13), varying with the percentage of calcium and magnesium salts saved and the annual fertilization costs for a greenhouse.

From our interviews, the average annual cost of fertilization was 3 $\$/m^2$. Thus, on average, the annual cost of calcium and magnesium salts per hectare ($\mathrm{Cost}_{\mathrm{Ca,Mg}}$) was approximately 1 $\$/m^2$. Within the available sample of greenhouses where the groundwater salinity was greater than 500 ppm, the value for $r_{\mathrm{Ca,Mg,gw}}$ varied from 21-86 % with an average value of 53%. If we assume that $r_{\mathrm{Ca,Mg,selec}}$ for MS-EDR systems was 33 %, we get a range of potential savings in calcium and magnesium salts of 7-29 %. From, Fig. 8 for an annual fertilizer cost of 3 $/m^2, the fertilizer savings would thus be in the range of 700-5800 $/m^2.

4.3 Value of product water

Greenhouse operators we interviewed were interested in short payback periods, preferably less than 2 years. However, to calculate a payback period, a value must also be assigned to the product water. The value of product water is different from that of groundwater. Greenhouses currently drill wells and use groundwater largely because municipal water is either not available or is too expensive. For quantifying the value of product water, we chose the cost of the alternative to desalinated groundwater which is, commercially available municipal water.

From Section 2.3.4, the price of municipal water for agricultural use in Ventura County, California was 1.05 $/m^3 [43]. The annual value of the product water (Value_{pw}) as a function of capacity, daily hours of operation and capacity factor was thus:

$$\text{Value}_{\text{pw}} = \text{Cap}_{\text{m}^3/\text{day}} \times \left(\frac{\text{Op.hr.}}{24}\right) \times 365 \times \text{Cap}_{\text{fac}} \times 1.05\ [\$/\text{m}^3] \qquad (14)$$

For a 10-hectare greenhouse operating a 600 m^3/day desalination system for 12 hours a day at a 90% capacity factor, the annual value of the product water was $206,955.

5. Overall technology comparison

The desalination technologies RO, CCRO, EDR and MS-EDR can be effectively compared in terms of the payback periods on the technologies. The capital costs, energy costs and membrane replacement costs calculated from Section 3 and the savings from increased desalination system recoveries and fertilizer savings calculated from Section 4 are combined together in this section to calculate a simple payback period (SPP):

$$\text{SPP} = \frac{\text{CapEx}}{\text{Value}_{\text{pw}} + \text{Sav} - \text{OpEx}} \qquad (15)$$

To effectively compare against RO, we also calculated a relative payback period (RPP_{tech}) for CCRO, EDR and MS-EDR:

$$\text{RPP}_{\text{tech}} = \frac{\text{CapEx}_{\text{tech}} - \text{CapEx}_{\text{RO}}}{\text{Sav}_{\text{tech}} - (\text{OpEx}_{\text{tech}} - \text{OpEx}_{\text{RO}})} \qquad (16)$$

The relative payback period removed the value of the product water from the calculation, and estimated whether the additional capital cost in a technology alternative to RO was justified by the savings the technology produced over RO.

Table 4 shows the capital costs, energy costs, membrane replacement costs, the value from water savings and fertilizer savings and the simple and relative payback periods for RO, CCRO, EDR and MS-EDR systems for a 10-hectare greenhouse. The systems had a capacity of 600 m^3/day assuming 12 hours a day of operation with a 90% capacity factor, treating 850 ppm of feedwater. The recovery ratios of the RO, CCRO, EDR and MS-EDR systems were 70%, 90%, 80% and 80% respectively. Feedwater savings were calculated assuming a feedwater cost of 0.32 $/m^3 while product water was valued at 1.05 $/m^3. It was assumed conservatively that 15% of the calcium and magnesium needed in the nutrient solution could be saved by using the MS-EDR system. The results on simple and relative payback periods can be extended to greenhouses greater than 10 hectares.

5.1 Simple payback periods can be less than 9 months

Figure 9 shows the simple payback periods for the RO, CCRO, EDR and MS-EDR systems. When compared against municipal water priced at 1.05 $/m^3, the payback periods for all the systems were less than 12 months. Considering that these systems are expected to have a life of 15 years, greenhouses obtain significant value from desalination. Conventional RO, at 7.1 months, had the shortest simple payback period. CCRO, EDR and MS-EDR systems were estimated to have a payback period of 8.4, 7.8 and 8.2 months respectively.

Table 4. Capital costs, operating costs, savings created, simple payback period and relative payback period for RO, CCRO, EDR and MS-EDR systems for a 10-hectare greenhouse with treatment capacity of 600 m^3/day.

Parameters	Units	RO	CCRO	EDR	MS-EDR
CapEx	$	115,898	144,873	131,000	144,100
$\text{OpEx}_{\text{energy,yr}}$	$	5913	4829	5028	5312
$\text{OpEx}_{\text{memb,yr}}$	$	4950	3960	6964	12,487
$\text{Savings}_{\text{Ca,Mg}}$ at 15% Ca^{2+} and Mg^{2+} ions saved	$	-	-	-	15,000
$\text{Savings}_{\text{RR,feed}}$ at 0.32 $/m^3	$	-	10,011	5631	5631
Net annual operating costs	$	10,863	-1222	6361	-2833
Value_{pw}	$	206,955	206,955	206,955	206,955
SPP	months	7.1	8.4	7.8	8.2
RPP	years		2.4	3.4	2.1

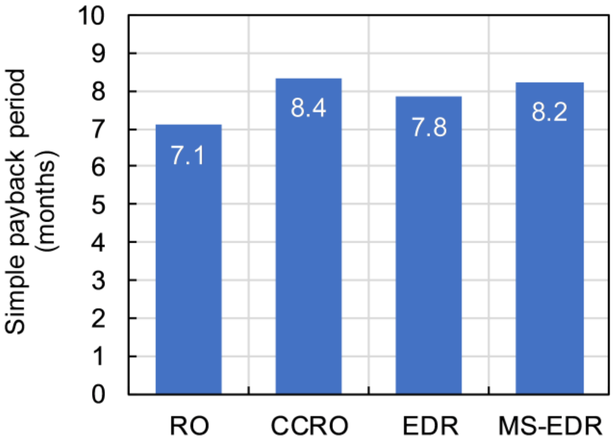

Figure 9. Simple payback period for RO, CCRO, EDR and MS-EDR for a 10-hectare greenhouse treating feedwater of salinity 850 ppm, assuming product water value of 1.05 $/m³, feedwater cost of 0.32 $/m³ and 15% savings in calcium and magnesium ions.

5.2 Variation of relative payback periods with feedwater costs and degree of calcium and magnesium saved

Table 4 also showed the relative payback periods of CCRO, EDR and MS-EDR systems when compared against RO without accounting for the value of product water. When the sum of feedwater and brine disposal costs was 0.32 $/m³, the relative payback periods for CCRO was 2.4 years while that of EDR was 3.4 years. If MS-EDR systems can save at least 15% of the calcium and magnesium needed for nutrient solutions, the relative payback period of MS-EDR will be less than 2.1 years—justifying the higher membrane costs.

However, in practice, the cost of feedwater, brine disposal, the value of product water and the amount of calcium and magnesium in groundwater and the practical selectivity of newer MS-EDR membranes may be different from our assumptions. To reduce the uncertainty on the relative payback period, we varied feedwater costs and the percentage of calcium and magnesium needed for nutrient solutions that was saved and calculated the relative payback periods for each system.

Figure 10 shows the variation of the relative payback period of MS-EDR with the percent of calcium and magnesium saved and the sum of the feedwater and brine disposal costs. The relative payback period was very sensitive to the percent of calcium and magnesium saved, especially for values lower than 30%. Regardless of feedwater costs, if MS-EDR systems can save 20% of the calcium and magnesium needed for nutrient solutions, the relative payback period will be less than 2.5 years, enough for the technology to be adopted. This number can be used to inform MS-EDR membrane designers of the target values for $r_{\mathrm{Ca,Mg,selec}}$ for the MS-EDR membranes.

In Section 4.2, we reported that the greenhouses we sampled where the TDS was greater than 500 ppm on average had groundwater that already contained 53% of the calcium and magnesium needed for typical nutrient solutions. Thus, if MS-EDR membranes could retain at least 38% of the calcium and magnesium in the feedwater in the product water (i.e., $r_{\mathrm{Ca,Mg,selec}}$ = 38%), MS-EDR can be adopted by several greenhouses. For comparison, Cohen et al. [19] had reported experiments on Selemion CSO MS-EDR membranes that showed the membranes saving 42 % of the calcium and 57 % of the magnesium in feedwater. Thus, MS-EDR systems show considerable promise for application in greenhouses with sizes greater than 10 hectares, justifying further research and development on the technology.

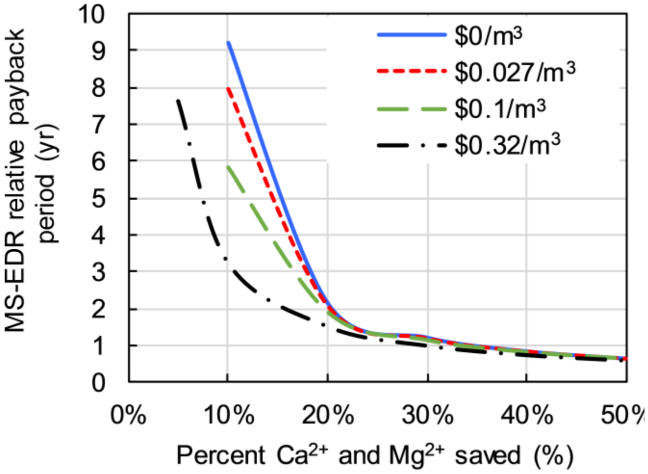

Figure 10. Variation of relative payback period for an MS-EDR system with percent of calcium and magnesium saved at different feedwater costs for a 10-hectare greenhouse assuming 3 $/m² fertilization costs

Figure 11 shows the variation of the relative payback period of CCRO and EDR systems with the sum of the feedwater and brine disposal costs for a 10-hectare greenhouse. Shifting to CCRO from conventional RO is economical when the sum of the feedwater and brine disposal cost is greater than 0.24 $/m³ when the relative payback period becomes 3 years. Similarly, shifting to EDR from conventional RO is economical when the sum of feedwater and brine disposal cost is greater than 0.35 $/m³. At the capacity we considered, CCRO systems were slightly more expensive than EDR systems. However, CCRO had a lower operating cost than EDR and also operated at a higher recovery ratio of 90% compared to 80% for the EDR system creating significant water savings allowing CCRO to quickly make up for the higher capital costs. Thus, CCRO relative payback periods were lower than that for EDR for the same sum of feedwater and brine disposal costs. CCRO relative payback periods are expected to be even better at higher capacities since specific capital cost of CCRO decreases significantly

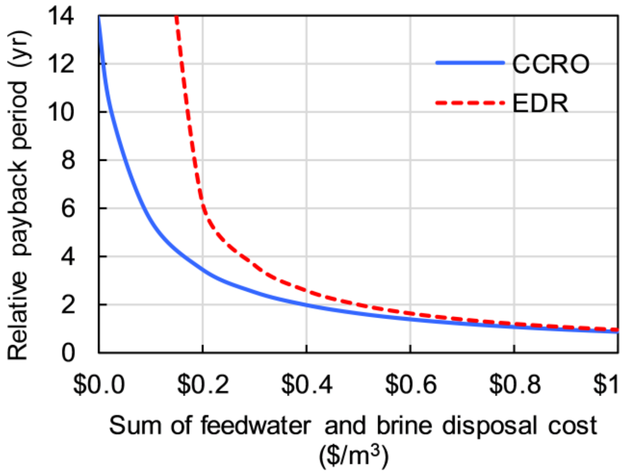

Figure 11. Variation of relative payback period for a CCRO and EDR system with the sum of feedwater and brine disposal costs for a 10-hectare greenhouse

It must be noted that EDR may not be viable in several greenhouses and that the results for EDR shown in Fig. 11 are applicable only for some greenhouses. While CCRO product water is very similar to RO product water, EDR product water in our simulations was more saline at 250 ppm. EDR system costs increase significantly if the product salinity is reduced further. These systems can be used in greenhouses only if the amount of sodium in EDR product water is less than or equal to the 23 ppm greenhouses need. Since EDR is not selective to sodium, the proportion of sodium relative to total salinity will not change between the feed and product streams even as the total salinity is reduced. Thus, for an 850 ppm EDR feed stream, the sodium concentration in the feed must be less than 78 ppm to result in a 250 ppm EDR product stream with a sodium concentrations less than 23 ppm. . Furthermore, pilot tests need to be conducted in greenhouses with EDR systems to further confirm their applicability in greenhouses. Since, CCRO systems have been commercially deployed widely and have product water qualities similar to that of RO, CCRO can be deployed in greenhouses without the need for pilot testing. Thus, from an adoption point of view, CCRO systems can be more easily adopted by greenhouses compared to EDR and MS-EDR systems.

6. Limitations of the study and areas for future research

- Simulations and results shown for desalination systems assumed a feedwater salinity of 850 ppm. Our general findings on the economic performance of RO, CCRO, EDR and MS-EDR systems may be valid for feedwaters with salinities up to 1000 ppm. However, beyond 1000 ppm, the results may vary significantly. Future work can compare these technologies at higher salinities.

- We assumed a range of selectivity for MS-EDR membranes while carrying out an analysis on the potential of MS-EDR. Our analysis shows that future research and development efforts on the MS-EDR technology are commercially justified. However, significant uncertainties remain on the MS-EDR technology when applied to brackish water conditions, especially on the selectivity of these membranes towards sodium and the membrane life. Lab-scale tests and pilot tests at greenhouses are needed to fully validate the potential of MS-EDR systems.

- Future work can include more performance comparisons with ion-exchange resins systems for feedwater salinities lower than 500 ppm, and with nanofiltration. Comparing these additional technologies in a detailed manner was beyond the scope of this work.

- A framework and approach for comparing RO, CCRO, EDR and MS-EDR was presented. While the overall approach and broad trends may be valid across geographies, specific values of payback periods and relative payback periods are sensitive to the cost of groundwater and the value of product water. For several calculations presented in this paper, the payback periods were calculated using an “accounting cost” of ground water of 0.32 $/m^3 and a value of the product water of 1.05 $/m^3. These numbers were sourced from Southern California and are what we believe are the best representative numbers on the real costs and value of ground water and product water. To make decisions on technology investments in other geographies, the same framework can be used but the groundwater costs and the value of product water must be selected appropriately with the evaluation done on a case-by-case basis.

7. Conclusions

The key conclusions of the paper are discussed below.

7.1 Greenhouse sector commercial and technical needs

- Greenhouses need desalination systems to produce water with less than 23 ppm of sodium at an as-high-as-possible recovery ratio to minimize groundwater usage.
- Greenhouse operators desire simple payback periods less than 2 years for their desalination systems.
- Greenhouses with areas under cultivation greater than 5 hectares had more corporate ownership structures and were generally early-adopters of new technology. Thus, desalination system developers especially those focusing on developing new technologies should partner with larger greenhouses (> 5 hectare) for piloting their technologies.
- Greenhouses with areas under cultivation greater than 5 hectares and with source water (typically groundwater) salinities greater than 500 ppm currently use RO systems to desalinate the source water. When the source salinities are lower than 500 ppm, greenhouses typically used ion-exchange resin-based systems to treat the source water (used widely in Queretaro, Mexico). If the source water salinity is low enough, greenhouses directly use the source water after media filtration.

7.2 Desalination system costs

- Between the technologies RO, CCRO, EDR and MS-EDR, RO had the lowest capital cost.
- Specific capital costs of all desalination systems were found to increase several-fold at capacities less than 600

m^3/day (i.e. for greenhouses with less than 10 hectare greenhouses).

- For greenhouses with areas less than 10 hectares with groundwater salinities greater than 500 ppm, RO was the most cost-effective technology when compared to CCRO, EDR and MS-EDR. RO system component and membranes at these small capacities are more widely available and cost lesser. RO systems are likely to be also much easier to maintain for greenhouses with a size less than 10 hectares.
- For greenhouses with areas greater than 10 hectares:
    - Both CCRO and MS-EDR systems show great promise under the right conditions of feedwater costs and calcium and magnesium savings possible.
    - MS-EDR systems are economically viable, irrespective of feedwater and brine disposal costs, if they can save at least 20% of the calcium and magnesium needed for nutrient solutions and have a membrane life of 7 years. Further research and development on brackish MS-EDR systems, especially related to membrane life and monovalent selectivity is justified.
    - CCRO systems are economically viable if the sum of feedwater and brine disposal costs are greater than 0.24 $/$m^3$.
    - EDR systems show promise if the sum of feedwater and brine disposal costs are greater than 0.35 $/$m^3$ and if the groundwater has a low enough sodium concentration (≤ 78 ppm) such that the sodium concentrations in EDR product water is less than or equal to 23 ppm.
    - CCRO systems can be commercially deployed without pilot testing. However, EDR and MS-EDR systems need to be pilot tested at greenhouses with the system costs, reliability and product water quality validated further before commercial deployment.
- For greenhouses with areas greater than 10 hectares, a feedwater salinity of 850 ppm, a feedwater cost of 0.32 $/$m^3$, product water value of 1.05 $/$m^3$ and an annual fertilization cost of 3 $/$m^2$:
    - RO, CCRO, EDR and MS-EDR systems had simple payback periods of 7.1, 8.4, 7.8 and 8.2 months respectively.
    - Relative to RO, the additional investment on CCRO, EDR and MS-EDR would pay itself back in 2.4, 3.4 and 2.1 years respectively.

8. Acknowledgments

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