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Using Desalination to Improve Agricultural Yields: Success Cases in Mexico

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Abstract

Water scarcity is a global problem, motivating growth and development of new technologies for water treatment, reuse and desalination. For many arid regions in Mexico, especially in the northwest, agriculture is an important economic activity. The Yaqui Valley in Sonora, Mexico, faces problems related to aquifer overexploitation and saline intrusion, which have increased salt concentration in well water to 2000–9000 mg/L total dissolved solids (TDS) and led to soil salinization and low crop yields. This work evaluates the effect of TDS in irrigation water on crop yield. A 150 m³/d desalination plant was used, consisting of 12 SWC4B-MAX membrane modules, with 98% rejection and 75% recovery. Two crops were irrigated with control (4000 mg/L) and desalinated water (200 mg/L). Sorghum (*Sorghum*) had yields of 7.9 and 8.8 ton/ha, whereas tomatillo (*Physalis philadelphica*) had yields of 30.82 and 35.88 ton/ha, respectively. Evidently, the desalination process influences agricultural yields.

Keywords: reverse osmosis, irrigation, crop yields, desalination

1. Introduction

Constant population growth, soil erosion, scarcity and excessive consumption of fresh water represent the most important reasons for the constant development and innovation of new technologies to provide water in large quantities and good quality [1]. Water scarcity exists

when demand exceeds freshwater supply in a given area [2]. The three main features that characterize water scarcity are: the physical shortage of available water to meet demand; the level of infrastructure development that controls storage, distribution and access; and the institutional capacity to provide the required water services [3]. In Mexico, there is a chronic shortage of water, especially in the northern part of the country, where precipitation volumes are notably lower than the potential evapotranspiration [4].

Considering that 97% of the water available on Earth has a salinity level exceeding 35 g/L, the desalination process is a viable option in the short term, which has had a significant growth in the recent past [2]. At the beginning of the modern development of desalination, before the 1970s, desalination methods consisted of thermal processes and their operation was such that they evaporated the fluid and collected the condensate. Known thermal processes include thermal vapor compression (TVC), multi-stage flash (MSF) and multi-effect distillation (MED) [5]. However, because evaporation processes require large amounts of energy for their operation, the use of semi-permeable membranes through reverse osmosis (RO) has become the main technology in use, accounting for 65% of the installed capacity of desalination plants. This installed RO capacity grows at a rate of 4 million m³/d each year [4].

The use of desalination to produce clean water as well as industrial and agricultural water has gained popularity among the sectors that require this resource [3]. The agricultural sector is the most important consumer of water resources, so RO desalination technology for crop irrigation has been successfully implemented in several countries, mainly in arid regions such as Israel [6] and Spain, where more desalinated water is currently provided for agricultural use than for domestic use [7, 8]. Likewise, several nations such as China, Chile and Australia offer specialized advice on the different techniques and technologies of desalination focused on agricultural crops [1], making the RO process the most used to tackle water scarcity in that sector [1, 2]. Therefore, desalination technologies enable the possibility to make optimal use of hydrological resources, both of the product (permeate) water and the retentate (brine).

The characteristics of irrigation water are directly linked to the quality of the crops harvested, as high salinity is intolerable for most crops established for food production. The agricultural sector benefits from the supply of higher volumes of better quality water [7]. However, the volume of global desalinated water currently accounts for only 1% of the world's supply. Of this value, only 2% of desalinated water is used for agricultural purposes [9, 10].

The state of Sonora, located in northwestern Mexico, ranks second in irrigation crops in the country. About 95% of the state is considered semi-arid and is characterized by a climate of high temperatures and low rainfall per year. Those conditions, combined with the overexploitation and lack of recharge into aquifers, have led to a decrease in the levels of available water [3], especially for agriculture. Several regions in the state present high salinity in well water, ranging from 2000 to 9000 mg/L of total dissolved solids (TDS), which are attributed to saline intrusion effects, causing soil salinization and decreasing the yields of vegetable and grain crops [8]. In this context, the objective of this study is to evaluate the performance of two typical crops (Sorghum and Tomatillo) under brackish water irrigation, by comparing their yield using water with different salinity levels, in order to determine the salinity-yield effect.

2. Methodology

2.1. Location of the study area

This study took place near Cd. Obregon, Sonora, Mexico, in field 1814 (**Figure 1**), located in the Yaqui Valley, with geographic coordinates $27^{\circ} 11' 21.7''$ N, $109^{\circ} 52' 15.6''$ W [8].

2.2. Configuration of the desalination process

A $150 \text{ m}^3/\text{d}$ capacity RO desalination plant was used, consisting of 12 Hydranautics $8 \times 40''$ SWC4 membrane modules with a permeate flow rate of $27.3 \text{ m}^3/\text{d}$, 99.8% salt rejection, spiral wound configuration, polyamide composite membrane and 440 ft^2 active membrane area. The plant uses a 40 hp high pressure pump (Grundfos). The pressure levels in the membrane modules and cartridge filters, as well as the process flow rates, were all monitored. In determining the water production cost of the RO process, the costs of electricity, labor, chemicals and maintenance were considered.

2.3. Brackish well pump

The water supplied to the desalination process was sourced from a brackish well adjacent to the study area, with an average salinity of 4000 mg/L TDS. The brackish water was pumped from the well by a 3 hp triphasic pump (Grundfos).

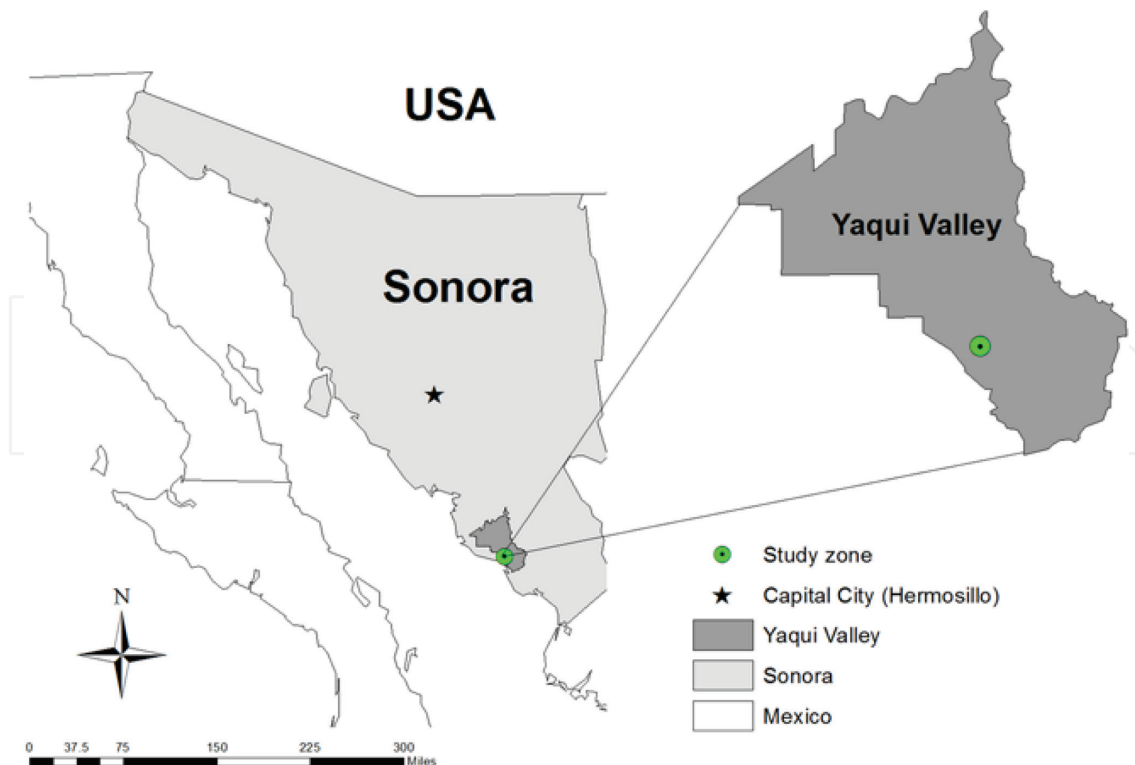


Figure 1. Study area, Sonora, Mexico.

2.4. Physical and chemical pretreatment system

The desalination plant has a physical pretreatment system consisting of a multimedia filter and 6 cartridge filters. The multimedia filter (63" × 90") has a capacity of 100 ft³ and consists of anthracite, turbidex, zeolite, and gravel. This filter removes suspended particles up to 50 μm in diameter. Subsequently, the cartridge filters remove particles of up to 5 μm in size.

For chemical pretreatment, a 0.25 hp diaphragm pump was used for the supply of antiscalant. In order to prevent salt precipitation on the surface of the membranes and, thus, prevent an increase in operating pressure. A 0.20 hp diaphragm pump was also used for the supply of H₂SO₄ at 30%, to regulate pH at the inlet of the RO membrane modules, maintaining a value of 7.0 ± 0.1.

2.5. Water and soil quality

Water quality was measured using a multiparametric measuring device (YSI 556 MPS). The concentration of salts in the feed, product and retentate of the RO process were determined. In addition, electrical conductivity (μS/cm), TDS (mg/L), pH and temperature (°C) were also measured. A visible spectrophotometer (SPECTRUM PROVE 300) was used to determine the concentration of different minerals in the water.

Soil quality was determined via pH and electrical conductivity (μS/cm) measurements. The damage caused by salinity in the agricultural soil was assessed at the beginning, during and at the end of the project, by determining parameters such as Sodium Adsorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP). These parameters measure soil damage caused by sodium buildup.

2.6. Experimental design

To assess the effect of salt concentration in irrigation water on crop yield, two different experiments were conducted with sorghum and tomatillo (*Physalis philadelphica*). The experiments occurred in different agricultural cycles and different years (2014 and 2016). The first crop was chosen because it has a high tolerance to salt concentration in water. The second crop was chosen because it is not very tolerant to salinity in water. An experimental planting area of 1 ha was used. The field was divided into two sections of 0.5 ha each (**Figure 2**). The first section was irrigated with well water containing 4000 mg/L TDS on average. The second section was irrigated with treated water from the desalination process, with an average of 200 mg/L TDS.

A drip irrigation system was used with a flow rate of 1 L/h, using 16 mm diameter irrigation belts. The treated water for irrigation was generated by mixing the permeate from the RO plant with raw well water, in order to reach an average salinity of 200–285 mg/L TDS. The following formula was used to calculate the mixtures:

$$C_1 V_1 + C_2 V_2 = C_3 V_3 \quad (1)$$



Figure 2. Satellite photograph of the study area and experimental sections.

where:

C_1 = salt concentration in the feed water from the well, in mg/L of TDS.

V_1 = volume of well feed water, in liters (L).

C_2 = salt concentration in the permeate water, in mg/L of TDS.

V_2 = volume of permeate water, in liters (L).

C_3 = required salt concentration for irrigation, in mg/L of TDS.

V_3 = volume of required irrigation water in liters (L).

The water mixtures were stored in three tanks, each being 5000 L in size. The water was homogenized by an electric stirrer that was placed in the tank hatch.

2.7. Irrigation control sensors

Electronic sensors (Watermak 200) and manual tensiometers were installed to monitor soil moisture (matric potential), in order to determine the optimal moment to water the soil. The matric potential is a measure of the force or tension of soil moisture with which water is retained. It is the product of adhesion or attraction between the surface of soil particles and water; and cohesion or attraction between water molecules. The water retention process, which depends on the surface tension characteristics of the water in the soil, as well as on the

contact angle between water and soil particles, is the main mechanism of water retention in light and middle soils within certain moisture intervals, and in heavy soils. In this context, a matric potential between 30 and 40 kPa indicates that the soil needs irrigation, whereas a matric potential between 0 and 10 kPa indicates that the soil is saturated [11].

3. Results and discussion

3.1. Desalination process operating parameters

The results obtained during the operation of the desalination process are shown in **Table 1**.

The pumping equipment pressure is within the desired range as it averages 37.33 psi, very close to the acceptable minimum of 30 psi. This indicates that the water level of the well is adequate, as well as the power and flow rate of the pump used to draw fluid from the well. With respect to the multimedia filter, an average pressure drop of 7.33 psi is observed, which is acceptable for operation. This suggests that the multimedia filter is removing 50 μm particles without clogging in its filter media. On the other hand, the cartridge filter had an average pressure drop of 6.33 psi, which suggests that the removal of 5 μm suspended particles is occurring without any problem, and that the membrane system should be operating as intended. The flow rate supplied from the desalination process to irrigation, for both study years was in the range of 1.5–1.7 L/s.

3.2. Process water field parameters

Measurements at the desalination plant show that when the feed water presents about 3900 mg/L TDS, the permeate and retentate currents have 285 and 11,200 mg/L TDS, respectively. There is an increase in temperature of 0.32 and 1.2°C in the permeate and retentate respectively, considering that the temperature in the feed water is 24.69°C (**Table 2**).

Parameter	Units	Min	Max	Sample			Mean
				1	2	3	
Well discharge pressure	psi	30	80	40	36	36	37.33
Multimedia filter inlet pressure	psi	30	70	38	33	33	34.66
Multimedia filter outlet pressure	psi	20	60	30	26	26	27.33
Multimedia filter pressure drop	psi	8	12	8	7	7	7.33
Cartridge filter inlet pressure	psi	20	40	33	29	28	30.00
Cartridge filter outlet pressure	psi	20	40	32	28	28	29.33
Cartridge filter pressure drop	psi	5	10	6	6	7	6.33

Table 1. Operation of the desalination process.

Sample	pH	Temperature (°C)	Electrical conductivity (µS/cm)	Total dissolved solids (mg/L)
Feed	7.68	24.69	6096.00	3901.40 ± 222.55
Permeate	6.16	25.01	446.00	285.00 ± 51.20
Retentate	8.08	25.89	17,496.00	11,197.44 ± 1389.01

Table 2. Water characterization at the 150 m³/d desalination plant.

The analysis of the RO desalination plant shows that it works as intended, since the concentration of salts in the produced water decreased significantly with respect to the feed water. Observed salt rejection was 92% compared to the salinity level of the brackish well, this through the action of semi-permeable membranes. On the other hand, the temperature of the retentate and permeate flows was always higher than the feed rate, due to the friction that occurs during pumping in RO, as well as the friction within the membrane modules. Care should be taken to ensure that the temperature does not exceed 45°C in the feed water, as this can shorten the working life of the equipment. Operating at high temperatures would increase permeate flow and decrease rejection (increased salt passage) as the diffusivity of both water and salt in the membrane increases with temperature. However, if temperature is increased significantly, changes in the polymer structure of the membrane can also occur, which could cause irreversible damage to the membrane.

3.3. Physical-chemical parameters of process water

The results of physical-chemical analysis of the water in the feed, permeate and retentate, are presented (**Table 3**). These were obtained using standard analytical techniques and a PROVE-300-Merck spectrophotometer.

These data are consistent with the data characterized by field parameters for both experimentation years [8, 11]. It can be observed that the presence of sodium in the permeate is 80.06 mg/L, which does not interfere with the adsorption of the nutrients in the irrigation water when adding fertilizers to the crop. However, special care must be taken in the dosage of nutrients by means of fertilizers in the irrigation water, since fertilizers can present high acidity and salinity, which inhibits the adsorption of nutrients.

3.4. Soil parameters of the agricultural field

The reduction of pH in RO permeate water is caused by the removal of carbonates and bicarbonates from the feed. Brackish well water usually contains bicarbonates (calcium, sodium, magnesium) and carbonates (calcium), which raise the pH of the water. Soil measurements of all physical-chemical parameters, SAR and ESP, at the beginning and end of the experiment are shown in **Figure 3**.

Taking chlorine and sodium ions as reference, as they are the major indicators of salts present in a sample, there is an evident increase in salinity (greater than 600 and 610% on average) attributed to brackish water irrigation for sorghum and tomatillo (*Physalis philadelphica*) in the

Water type	Ca	Mg	Na	K	NO ₃	HCO ₃	Cl	SO ₄	TDS
Feed	65.55	146.32	1079.66	72.74	28.76	33.83	1969.45	445.74	3842.05
Permeate	4.86	10.85	80.06	5.39	2.13	2.51	146.04	33.05	284.91
Retentate	190.70	425.90	3143.70	211.70	83.60	98.50	5733.80	1297.60	11,185.90

Table 3. Water quality assessment via physical-chemical parameters, in mg/L.

study area. On the other hand, under desalinated irrigation, the concentration of the sodium ion is reduced to 96%, which can be directly attributed to the salt removal by the RO process [11, 12].

Moreover, the SAR and ESP at the beginning and end of the experiment did not show significant changes in the samples irrigated with desalinated water, mainly due to the ease of internal soil drainage [13]. However, brackish irrigation samples show an average increase of 230% in SARs and 610% in ESP.

3.5. Desalinated water production cost

The economic data of the desalination process are shown in **Table 4**.

The economic evaluation of the process shows that the cost of producing desalinated water is \$0.338 USD/m³ very similar to that reported by the International Desalination Association [11, 14, 15], which is \$0.368 USD/m³, both for brackish water. To determine the viability of this desalination technology applied to agriculture, farmers should look for high-yield crops so that the cost-benefit effect is profitable, such as vegetables (e.g., tomatoes, chiles), and using drip irrigation systems [16].

3.6. Crop yields

3.6.1. Sorghum (2014)

There was a notable difference in the height of the plants, with the part irrigated with desalinated water being 10–15 cm higher on average. In addition, the plants irrigated with brackish water showed what appeared to be burned tips on the leaves of the plants: This is due to the excess of salts that are concentrated in the crop by the effect of brackish water from the well and possibly the addition of fertilizers. Although the latter was not reflected in burnt tips on the leaves of the plants irrigated with desalinated (**Figure 4**).

In all cases, the average height observed for the sorghum irrigated with desalinated water was higher compared to the average height of the crop irrigated with brackish water. This is directly attributed to soil management and the concentration of salts in the water, and therefore in the soil. These results in salt increase coincide with those reported by other authors [17, 18], who state that high salinity directly affects nutrient assimilation and germination in sorghum crops.

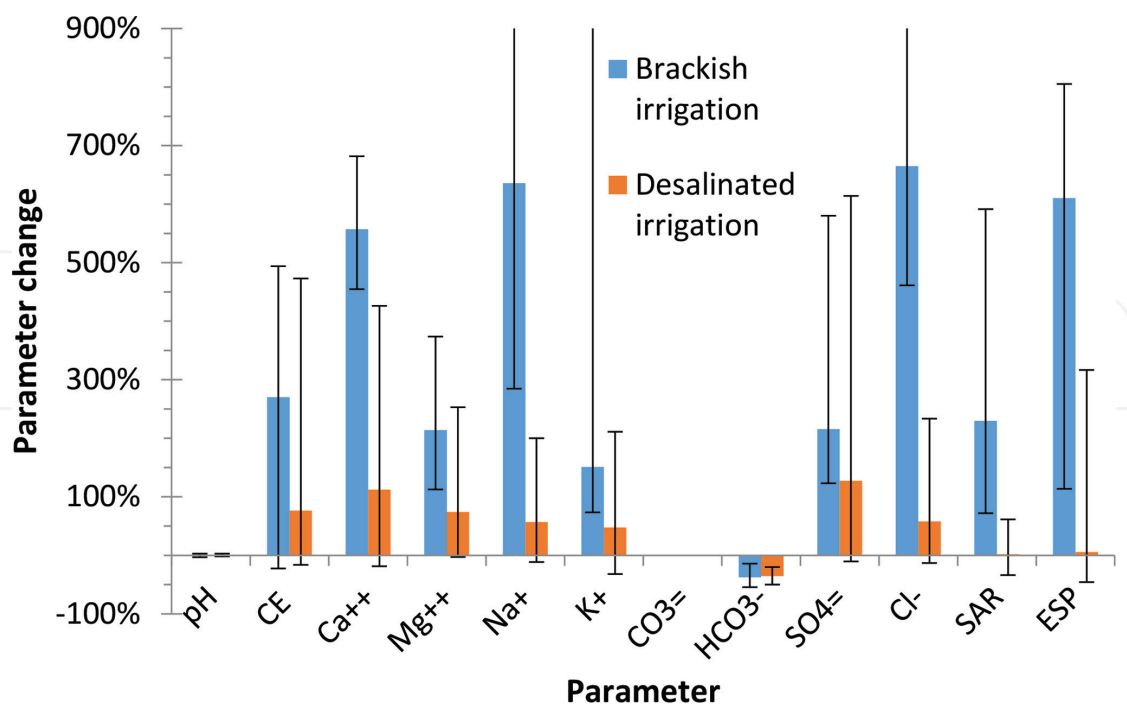


Figure 3. Physical-chemical parameters in the agricultural field soil.

Concept	Cost (USD \$/m ³)
Energy cost	0.207
High pressure pumps	
Dosage pumps	
General energy	
Labor costs	0.095
Operating personnel	
Technical assistance	
Chemical costs	0.0043
Antiscalant	
RO Clean	
Sulfuric acid	
Maintenance costs	0.031
Piping and accessories	
Soldering	
Total	0.338

Table 4. Operating costs.

At the time of harvest, it was verified that parameters such as the height (m), the number of panicles per m² and weight per panicle (g) were higher in all cases when using water with lower salt concentration. This led to an increase of 1 ton/ha (10.2%) of sorghum for the desalinated irrigation compared to irrigation with brackish water (Table 5). ANOVA analyses show a direct relationship in height and number of fruits, with respect to the salinity of water irrigated, with a 95% reliability.

Sorghum harvesting had a single cut, producing 7.9 ton/ha for the area irrigated with brackish water (4000 mg/L TDS), while the area irrigated with desalinated water (200–285 mg/L) yielded 8.8 ton/ha. Yield in tons shows a difference of 10.2%, demonstrating a higher profit margin when using desalinated water (Figure 5).

The results in Figure 5 are similar to those of a previous study [17, 18] where the effect of saltwater irrigation on sorghum cultivation was verified. That study determined a direct relationship between seedling weight, stem diameter, delayed germination effect, and crop yield.

3.6.2. Tomatillo (*Physalis philadelphica*) (2016)

A difference in plant height was observed as a result of a lower salt concentration in the irrigation water. The plants irrigated with desalinated water were 5–6 cm smaller on average than those irrigated with brackish water. This decrease in height was due to greater weight and diameter in the products. These results coincide with other investigations that use water with different concentrations of salts to observe significant differences [16].

Some of the parameters found were similar, such as stem diameter, plant height, germination and yield per cut. Nonetheless, there was an improvement when irrigating with lower salinity water [16, 18]. In addition, the tomatillo (*Physalis philadelphica*) crop was harvested in three

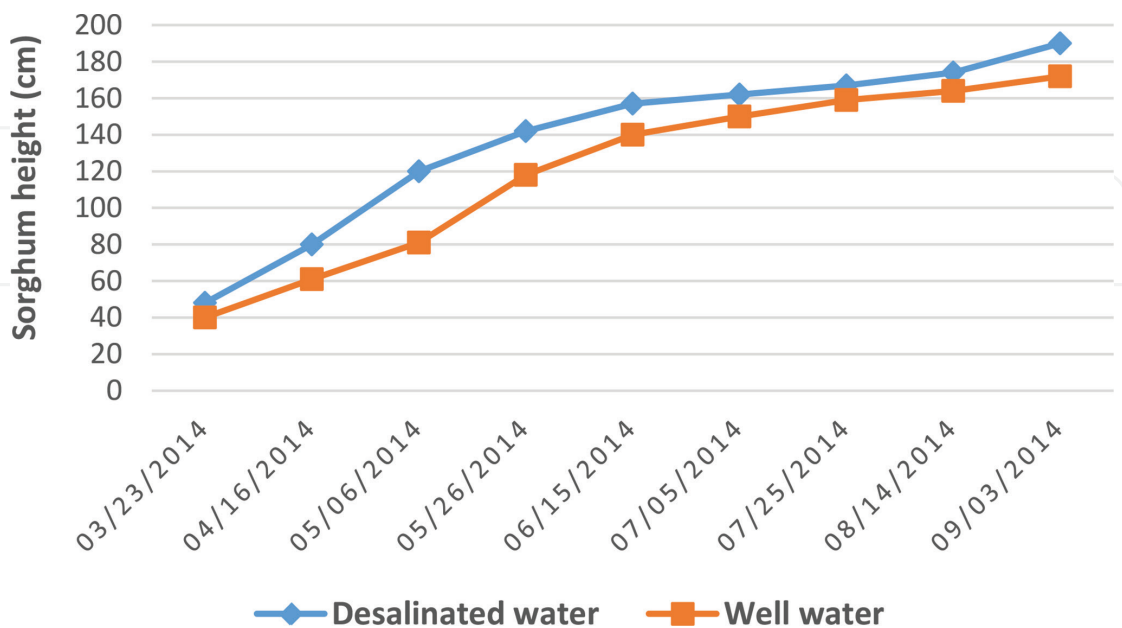


Figure 4. Behavior of the mean height of the sorghum crop.

Parameter	Desalinated irrigation	Brackish water irrigation	α 95%
Height (m)	1.7	1.5	X
Number of panicles per m ²	29.0	28.0	
Weight per panicle (g)	30.0	29.0	
Yield (Ton/ha)	8.8	7.9	

Table 5. Behavior of the sorghum crop parameters.

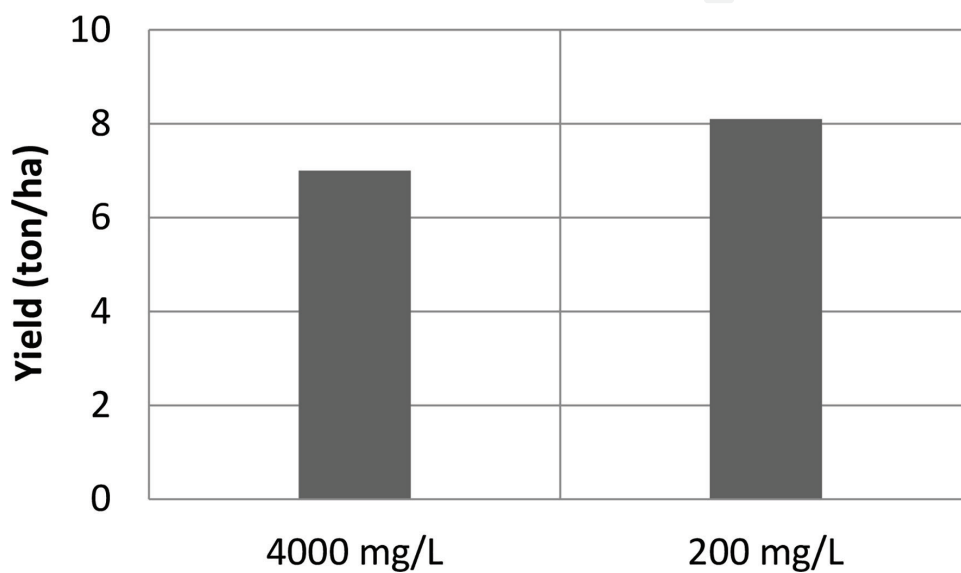


Figure 5. Dependence of sorghum crop yield with salinity in irrigation water.

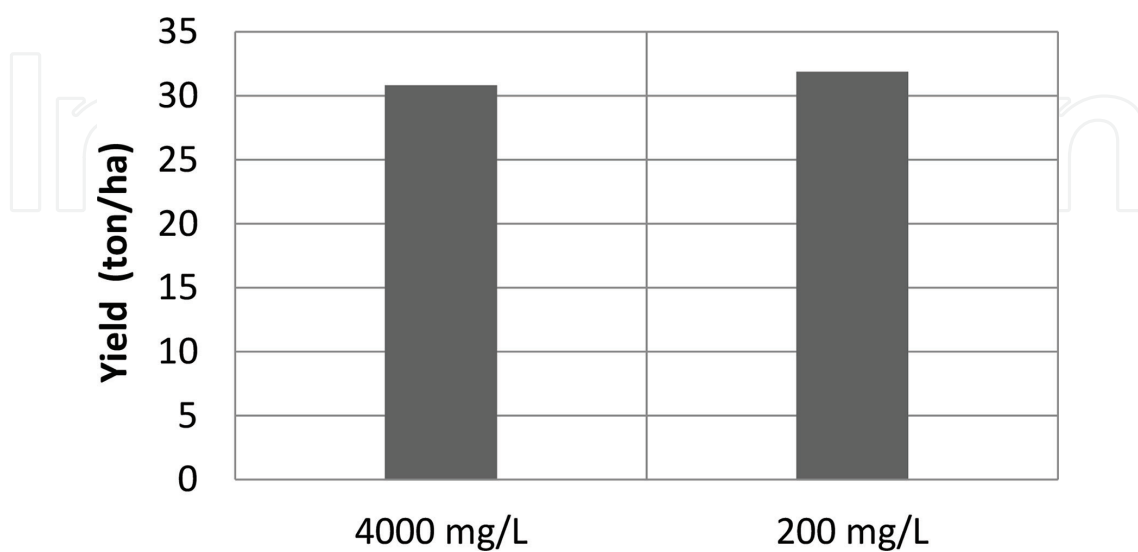


Figure 6. Dependence of tomatillo crop yield with salinity in irrigation water.

cuts. The average yield for the area irrigated with brackish water was 30.82 ton/ha, while the section irrigated with desalinated water yielded 35.88 ton/ha (**Figure 6**).

4. Conclusions

The use of desalinated water for agricultural irrigation increased the productivity of sorghum and tomatillo (*Physalis philadelphica*) crops. This means that wells with high salinity in the region can be utilized for irrigation through the use of desalination systems. In this sense, public and private investments in desalination in the rural sector are viable in the short term.

Cations and anions from the well water were successfully removed by the use of SWC4 membranes in an RO system. The operating parameters of the desalination process, such as pressure drop through the membrane modules, multimedia filter and cartridge filters, were below the limits and within the correct operating standards, which ensured a flow rate of 1.5–1.7 L/s of permeate, as well as a high rejection above 92%.

The total cost of producing the desalinated water was 0.338 USD $\$/\text{m}^3$. The cost of using electrical energy to operate the high pressure pump represented 70% of the total cost. Clearly, desalination processes need to incorporate renewable energy generation processes to reduce their environmental impact. In this energetic context, it is concluded that vegetables such as tomatillo have a higher profit in the market, compared to the sale of grains such as sorghum. This research project and other authors reaffirm that for the economic viability of desalination applied to agriculture, there must be a coupling of desalinated water using irrigation tapes for crops of high commercial value, with renewable energy such as solar photovoltaic.

The performance of the *Physalis philadelphica* and Sorghum are greatly improved by using tapes and sensory equipment, to apply irrigation as required and to decrease the concentration of salts in the irrigation water. It is concluded that the objective of the project has been satisfactorily achieved. Finally, it is concluded that with the use of desalination, producers will not need to worry about planting crops that support or tolerate the concentration of salts from their wells, since they will be able to establish high yield and high commercial value crops. Notably, the cost of production is a success factor in places where desalination is applied, such as agriculture and others. It is also necessary to continue investigating the incorporation of electric energy from renewable sources.

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