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RESEARCH

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Investigating the potential of growing crops hydroponically utilizing feed and draw solutions from fertilizer drawn forward osmosis

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Abstract

This study investigated the potential of utilizing both the draw and feed solutions resulting from fertilizer drawn forward osmosis for hydroponic crop cultivation. Synthetic brackish groundwater of 2500 ppm was used as the feed solution, whereas commercial hydroponic nutrients, sourced from a local supplier, were utilized as a draw solution. This study also investigated the potential of integrating nanofiltration with forward osmosis, but supplementing the water necessary for further dilution of draw solutions through nanofiltration. Two crops were selected, i.e., cherry tomatoes and spinach grown at different water salinities, for their economic values. The cherry tomatoes were grown in Deep Water Culture hydroponic systems, while the spinach was grown in Nutrient Film Technique systems. If this application is deemed feasible, it allows for providing a method to grow two different crops in areas associated with non-arable land and brackish groundwater. During desalination, it was observed that there were two groups of flux readings, the first with an average flux of 7 to 9 l/m^2/h, and the other with an average flux of 4 to 6 l/m^2/h. This was due to using the same draw solution twice; once to concentrate the feed solution to 5000 ppm, and then once more to concentrate the feed solution to 3500 ppm. It was found that while the 3500 ppm cherry tomatoes tables had the highest yield and highest number of tomatoes throughout the plants lifetime, tomatoes from freshwater tables on average weighed more by about 19%, while, on average, 5000 ppm tomatoes weighed less than 3500 ppm tomatoes by 10%. The results of the spinach demonstrated that while both control and experiment groups yielded similar number of leaves, the average yield per plant for the experiment group was higher than the control group (by 25%).

Keywords Desalination, Fertilizer drawn forward osmosis, Forward osmosis, Draw solution, Feed solution, Hydroponics, Tomatoes, Spinach

Background

Agricultural production consumed 85% of world water in the last decade, and it is expected to double by 2050. By 2050, the irrigated area is predicted to increase by a factor of 1.9, while climate change is exacerbating water stress in many regions of the world by altering water supply patterns. Water scarcity and land clearance are key environmental challenges as a result of these pressures around the world. Water use and stress have a wide range of environmental consequences. Water abstraction has both direct and indirect consequences on aquatic and water-dependent creatures.

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For example, diminished natural water availability and groundwater decline may cause water stress in terrestrial ecosystems downstream of water usage locations. Agricultural land conversion and settlement have direct ecological consequences for both the sites and the surrounding landscape. Crop production, in general, deprives land of much of its ecological value, for example, by degrading biodiversity and disrupting ecosystem functioning. Feeding humanity in the future will be a huge challenge due to population expansion and increased per-capita food demand [17].

Researches have been investigating alternative sources of water for decades, one of which is brackish groundwater. The U.S. Geological Survey Organization defines brackish water as having salinities between 1000 and 10,000 mg/l. There are six major brackish groundwater aquifers in Egypt, and more than half of Egypt's area can access brackish groundwater. Moreover, approximately half of Egypt's groundwater aquifers are renewable through rainwater seepage, irrigation water, sanitary drainage water and industrial effluents. Desalination research efforts have been directed towards investigating the potential of desalting brackish groundwater.

FO is a naturally occurring process in which a solvent passes through a FO membrane from a solution with a greater water chemical potential, feed solution (FS), to a solution with a lower water chemical potential, draw solution (DS). Because of the semipermeable nature of a FO membrane, solute molecules or ions are rejected during the process. After a FO procedure, a concentrated feed solution and a diluted draw solution are obtained. The FO driving force is the differential in osmotic pressure between feed and draw solutions. As a result, the two most important components of FO processes are the FO membrane and the draw solution. The FO process is new and can achieve separation at the molecular level. FO is an osmotically driven membrane process that operates at no/low hydraulic pressure, unlike pressure-driven membrane processes. FO methods recover more water, have less membrane fouling, and use less energy than pressure-driven membrane processes [23]. However, FO can only be considered to use less energy if the draw solution does not need to be regenerated or if further treatment of the draw solution is not necessary, as is the case in dewatering processes when using seawater or the desalination brine as a low-cost draw solution and in fertilizer dilution applications when using seawater as the feed solution and the concentrated fertilizer as the draw solution Mohammadifakhr et al. [13]. FO is used in a variety of applications, including food processing, pharmaceutical intermediate enrichment, and osmotic power generation, in addition to its huge potential in saltwater desalination and wastewater reclamation [23].

One of the shortcomings of FO is that the resultant is not freshwater, as opposed to RO, but rather a diluted draw solution (DS). However, this shortcoming can be taken advantage of by utilizing a concentrated fertilizer solution as the DS, in a process known as fertilizer drawn forward osmosis (FDFO). Hence, by diluting the concentrated fertilizer solution DS through FO, the resultant DS can be used directly in fertigation. Fertigation is the application of diluted fertilizers to agricultural farmlands via an irrigation system. Thus, making it an ideal concept to recover water from feed water resources to dilute a fertilizer solution which can then be used to fertigate farmland [10]. This means that water can be reclaimed to dilute fertilizer solutions from otherwise unusable sources of water, such as brackish groundwater, seawater, or wastewater. Moody and Kessler were the first to report on the prospect of using fertilizer as a DS [14]. However, more recent studies conducted by Phuntsho et al. [18], Chekli et al. [5, 6] and El Zayat et al. [7] investigated several inorganic fertilizers to determine their potential as DSs for direct fertigation.

Nanofiltration (NF) is a specialty membrane that is used in water softening by separating mono and divalent ions. NF is better used with brackish water than seawater, because of its capability of removing bacteria, viruses and other harmful compounds that can be found in brackish water, Also NF membrane has high salt rejection with divalent ions with molecular weight above 300, while lower salt rejection for monovalent ions with molecular weight less than 150 and it is capable of removing color, odor, water hardness and sulfate from well water and the cost of NF stations is almost the same as brackish water and reverse osmosis but the energy consumption is much less [8].

Water and energy savings can be realized by combining FDFO technology with modern agriculture technologies, such as hydroponics [1, 2]. Hydroponics is defined as the practice of growing plants without the use of soil, either using an inert medium such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, and rice hulls, or other substrates to which a nutrient solution containing all the essential elements required by the plant is applied [20]. By utilizing a concentrated hydroponic nutrient solution as DS in FDFO, the resultant diluted DS can either be used directly for hydroponic agriculture, is further diluted to the appropriate concentration. This application has been conducted successfully by several researchers, including Chekli et al. [5, 6], who utilized wastewater as FS and a concentrated commercial hydroponic nutrient solution as a DS. The resultant diluted DS from FDFO was used to grow hydroponic lettuce. Moreover, environmental and economic impacts can be further realized by combining FDFO technology

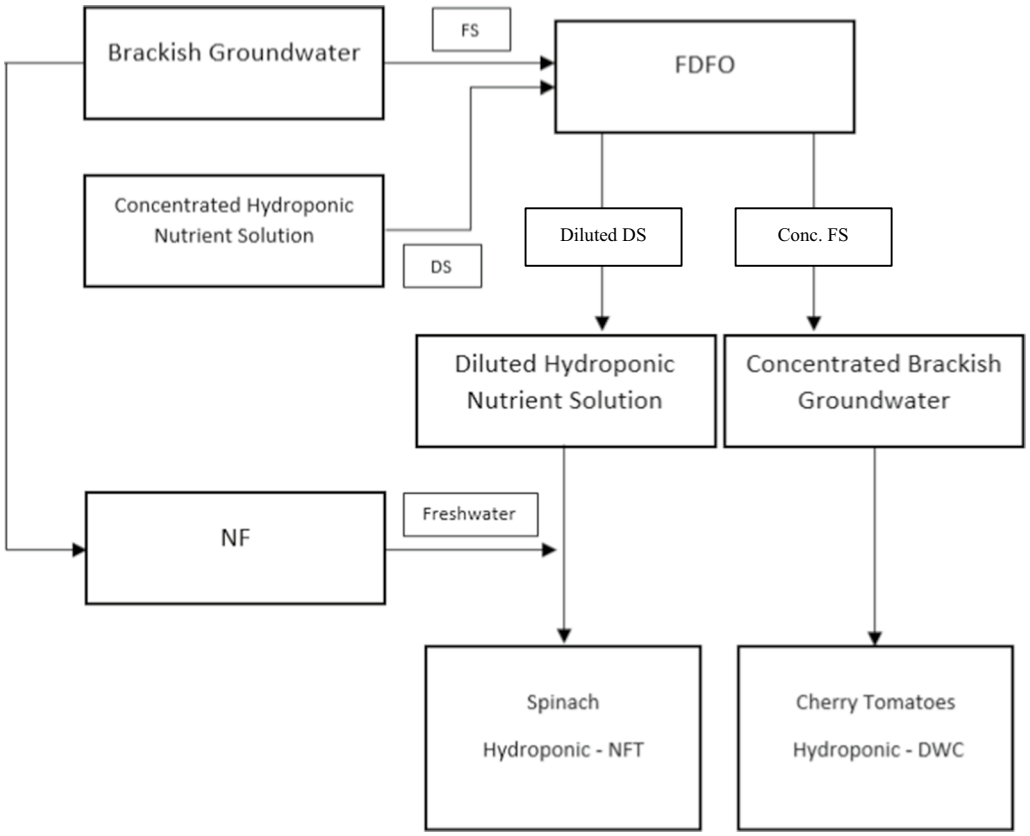

Fig. 1 Experiment flow chart

with NF technology; Kim et al. concluded that an FDFO-NF hybrid system consumed less energy when compared to other hybrid desalination technologies, where the FDFO-NF system consumed 13.6% lower energy than an MF-RO system and 21% lower than a UF-RO hybrid system [9].

This study investigates the potential of utilizing both the draw and feed solutions resulting from fertilizer drawn forward osmosis for hydroponic production of two crops with different salinity tolerance levels. This expands on previous research efforts by investigating a method to utilize the concentrated feed solution in agriculture, and investigating the salinity tolerance of crops grown hydroponically.

Table 1 PFO-100 element specifications [19]

Membrane area per element	7.0 m^2
Operational pH limits	2–11
Temp operating range (°C)	> 0–60
Free Chlorine tolerance (ppm)	< 0.1
Transmembrane operating pressure range (Feed–Draw)	0–3 psig (0–0.21 bar)
Max pressure at any port	10 psig (0.68 bar)
Physical dimensions L x W x H [mm]	502 × 350 × 460
Housing materials	Plastic, Carbon Fiber, Aluminum
Membrane materials	Active layer material: polyamide Support layer material: porous hydrophilic polymer
Shipping/Storage solution	Glycerin & 1% Sodium Bisulfite Solution

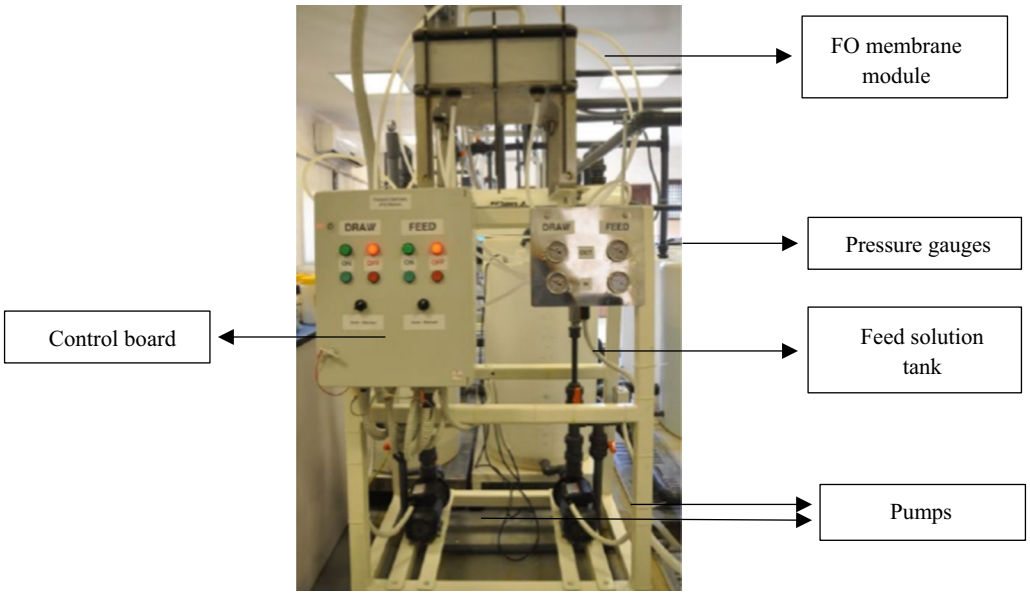

Fig. 2 Pilot-scale FO module

Theory

Forward osmosis

When a high osmotic pressure draw solution is separated from a lower osmotic pressure feed solution by semi-permeable membrane, force of the osmotic pressure differential (Δπ) causes the simultaneous dilution and concentration of the draw and feed solutions, respectively [11, 14]. The chemical potential difference in the solvent between the draw and feed solutions causes the osmotic potential difference [21]. Osmotic pressure (π) is defined as "the pressure necessary to prevent pure water from passing through a semi-permeable barrier and into a solution" [15].

The solution–diffusion model is the most commonly used model for mass transport over an FO membrane; in the FO process, the water flow (J_v) and solute flux (J_s) through the membrane can be calculated by the following equations [11]:

$$J_v = A(\sigma \Delta\pi - \Delta P) \tag{1}$$

$$J_s = B\Delta C \tag{2}$$

where A is the water permeability coefficient of the membrane, B is the solute permeability coefficient of the membrane; σ is the reflection coefficient, which is generally assumed to have a value of 1; ΔP is the applied hydraulic pressure; and ΔC is the solute concentration difference across the membrane. In FO process, ΔP is equal to zero, and water flux can be simplified as follows:

$$J_v = A(\pi_{draw} - \pi_{feed}) \tag{3}$$

where π_{draw} and π_{feed} are the osmotic pressures of the draw and feed solutions, respectively.

However, experimental water flux is usually less than what is projected in Eq. (3), due to the effects of external concentration polarization (ECP) and internal concentration polarization (ICP). While ECP can be mitigated by optimizing external hydraulic conditions, ICP is affected by the properties of the membrane, specifically its support layer; utilizing an efficient membrane that is especially designed for osmotically driven membrane processes is one of the key ways to solve the ICP problem [21]. The membrane utilized in this study is an FO membrane, and hence the effect of ICP on water flux was neglected.

Reverse solute flux (RSF) is among the most paramount properties to consider in FO processes. Due to the loss of draw solutes into the feed solution that cannot be recovered, the reverse flux of draw solutes into the feed solution results in an economic loss [4]. Reverse solute flux results in membrane fouling in addition to the loss of draw solutes, because complexes between feed and draw ions develop during this process [4]. The following equation can be used to calculate the FO reverse solute flux [22]:

$$J_s = \frac{B}{A.\beta R_g T} J_v \tag{4}$$

where β is the van't Hoff coefficient; R_g is the universal gas constant; T is the absolute temperature.

Fig. 3 Nanofiltration vessel in WEF NEXUS lab at AUC

Specific reverse solute flux (SRSF) is the mass of draw solutes lost due to reverse permeation per unit volume of water claimed from the FS, and is defined as the ratio between reverse solute flux and water flow [4]. SRSF can be calculated as follows:

$$SRSF = \frac{J_s}{J_v} \tag{5}$$

By combining Eqs. (4) and (5), SRSF can be expressed as

$$SRSF = \frac{B}{A.\beta R_g T} \tag{6}$$

Materials and methods

Figure 1 demonstrates the experimental plan. Brackish groundwater will be used as the feed for both FDFO and NF, and a concentrated hydroponic nutrient solution will be used as the draw for FDFO. The concentrated feed solution will then be utilized to grow cherry tomatoes in DWC hydroponic systems, while the diluted draw solution will be further diluted with the NF permeate, and utilized to grow spinach in NFT hydroponic systems.

Fig. 4 Spinach grown in NFT hydroponic systems

Fertilizer drawn forward osmosis

A pilot-scale crossflow filtration unit with a FO membrane module was employed in this investigation. Porifera provided the membrane module (PFO-100), which has a membrane area of 7 m^2 [19]. The Porifera PFO-100 is an 8-port flat sheet system with two independent fluid channels separated by Porifera's patented membrane [19]. Table 1 outlines the membrane module specifications. One side of the module is dedicated to input connections, while the other is dedicated to output connections. There are four ports on each side, two for FS and two for DS (Fig. 2).

The input and output pressures of the FS and DS were monitored using pressure gauges linked to two ports on either side of the membrane to make sure they did not

Fig. 5 Cherry tomatoes grown in DWC hydroponic systems

go above the membrane's maximum pressure limit. To provide a constant flow of solutions from the tanks to the membrane and back to the tanks, two 0.55 kW circulation pumps were utilised to provide crossflow. Each pump was connected to feed and draw tanks. It was placed on a platform scale to measure how much the draw solution tank's weight changed. To collect data on weight fluctuations, the scale was connected to data logging software.

Water flux, reverse solute flux, and salt rejection

Water flux J_v (LMH) was calculated using

$$J_v = \frac{\Delta V}{S \times t} \tag{7}$$

Reverse solute flux (g/m^2/h) was calculated using

$$J_s = \frac{(V_i - \Delta V) \times C_s}{S \times t} \tag{8}$$

where V_i is the initial volume of FS, ΔV is the total volume of water displaced from the FS to the DS, C_s is the concentration of the draw solutes in the FS at the end of the experiment, S is the membrane surface area, and t is time.

Furthermore, salt rejection is a key attribute of FO membranes, which was studied by examining the Na^+ and Cl^- ions in the resultant DS from each experiment and calculating using the equation below:

$$Re(\%) = \frac{C_i - \left(\frac{C_{p,D}(V_i + \Delta V)}{\Delta V}\right)}{C_i} \times 100 \tag{9}$$

where C_i is the initial concentration of the ion in FS, $C_{p,D}$ is the final concentration of the ion in DS, V_i is the initial volume of the DS and ΔV is the total volume of water that entered the DS from the FS [16].

Nanofiltration

The unit contains Polyamide ESNA membrane that has 8 inch in diameter and 40 inch in length, it can provide 50–90% of salt rejection with ultra-low pressure operations, high energy saving and low operation costs. Membrane Vessel that can take up to 15 bars of pressure, check valves to control water flow, two product tanks one for the permeate and one for the brine water, pipelines connections that can take up to 10 bars of pressure, pressure gauges on each water inlet and water outlet port to measure water pressure and differences in pressures, and 1.5 kwh centrifugal pump. Figure 3 shows the pump:

F permeability flux was calculated using the following equation:

$$Jv = \frac{Fp}{S} \tag{10}$$

where Jv is the permeate flux; Fp is permeate flow rate; and S is the area of the membrane.

While NF salt reject concentration was calculated using the following equation:

$$R = 1 - \left(\frac{Cp}{Cave}\right) \times 100\% \tag{11}$$

Cave is the average feed concentration, which is calculated as follows:

$$Cave = \left(\frac{Cf + Cc}{2}\right) \tag{12}$$

in which R is the salt rejection (%); Cp is the permeate concentration, Cf is the feed concentration and Cc is the concentrate concentration.

Alternatively, Concentration Flux can be calculated as follows:

$$J_C = \left(\frac{Fc}{S}\right) \tag{13}$$

where Jc is the concentration flux, Fc is the concentration of the feed and S is the area of the membrane

Hydroponic setup and operation

Cherry tomato and spinach seeds were obtained and germinated in a nursery for 30 and 14 days, respectively, prior to being moved to the hydroponic systems. A commercial hydroponic nutrient solution was procured from a local supplier, to be utilized as the draw solution in FDFO. Spinach was cultivated in a nutrient film technique (NFT) hydroponic systems, demonstrated in Fig. 4, with a capacity of 100 seedlings, and a nutrient tank capacity of 60L. While cherry tomato seedlings were grown using deep water culture (DWC) beds under three replications, as demonstrated in Fig. 5. The DWC systems had 12 seedlings and a nutrient tank capacity of 250L per system.

Table 2 Microwave heating program

Step	Ramp Time (min)	Temperature (C)	Hold Time (min)
1	10	170	5
2	15	200	3
3	10	75	1

Table 3 MP-AES operating conditions

Parameter	Setting
Replicates	3
Background correction	Auto
Read time (s)	3
Viewing position	0
Nebulizer flow (L/min)	Adjusted
Pump speed (rpm)	15
Uptake time (s)	15
Stabilization time (s)	25
Calibration fit	Linear
Calibration Correlation Coefficient Limit:	0.99
Nebulizer	OneNeb Series 2, with nitrogen humidifier
Sample introduction	Manual
Minimum Concentration (ppb)	0
Maximum Concentration (ppb)	3300

Experimental plan

Fertilizer drawn forward osmosis

Feed solution was prepared by dissolving industrial-grade NaCl in dechlorinated tap water in 2.5 g/L (2.5% w/w) concentration. Tap water was dechlorinated by storage in an exposed tank for at least 24 h prior to usage, to allow the Chlorine to evaporate. The Part B of a commercial hydroponic nutrient solution was utilized as the draw solution. 200L of FS and 20L of DS were placed in their respective tanks. The pilot-scale FDFO unit was then run until the FS TDS reached 5000 ppm, which was measured using a portable TDS and EC meter (Hach HQ40D multi). Change in the weight of the DS was recorded through the platform scale and data logging software at 1 min intervals. The 5000 ppm FS was then extracted from the tanks and stored, and the feed tank was refilled with 2.5 g/L NaCl water. FDFO was then carried out a second time, utilizing the same draw solution, until the FS TDS reached 3500 ppm. The 3500 ppm FS was then extracted and stored, and the resultant diluted DS was also extracted and stored. Samples were taken from the initial and final FS and DS, and the ions in each of the samples from were analyzed using spectrophotometry (Spectroquant Nova 60 A), to determine their ionic composition, and calculate SRSF and salt rejection. The diluted DS was then utilized in the hydroponic agriculture of spinach, and both the 3.5 and 5000 ppm feed solutions were utilized in the hydroponic agriculture of cherry tomatoes. This process was repeated whenever more water was required for the cherry tomatoes.

Nanofiltration

As for Nanofiltration, two runs were made to supply the system with enough water for the crop. Both runs were made based on desalinating brackish water with TDS of 2000 ppm acting as a feed solution. Moving on, the system operates using control unit to operate the pump and draw the water from the feed tank into the membrane, where the filtration process takes place. Two types of water are produced the permeate fresh water which is used in the system and stored in the fresh water tank and Brine water which is stored in the reject tank for other uses.

Hydroponic agriculture

Cherry tomatoes were grown in deep water culture (DWC) hydroponic systems. Six DWC basins were utilized, with each two representing a different salinity level (freshwater, 3500 ppm and 5000 ppm), and each table

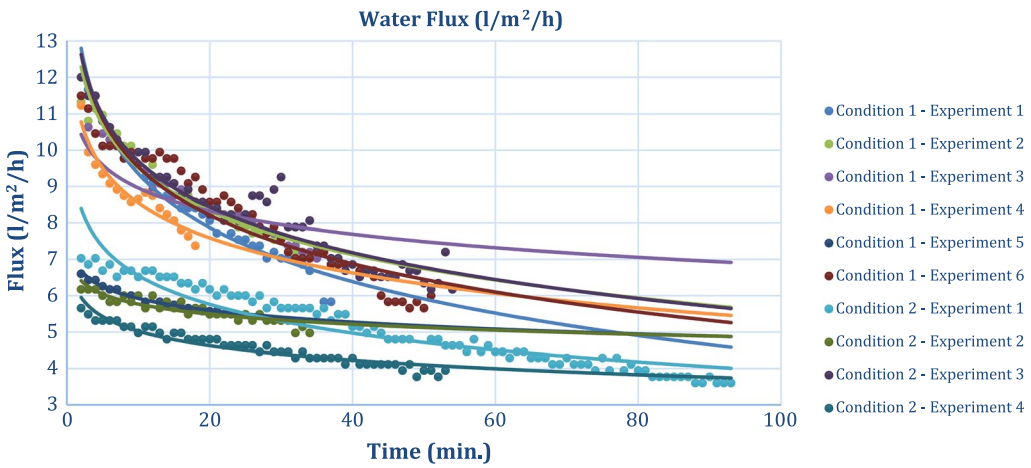

Fig. 6 Water flux

Table 4 Ionic composition of feed and draw solutions

	NH_4 (mg/l)	NO_3 (mg/l)	PO_4 (mg/l)	SO_4 (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	Cl (mg/l)	TDS (ppm)	Osmotic Pressure (bar)
$DS_{initial}$ (Part B of the hydroponic nutrient solution)	225	2940	1815	Below detectable limit	6510	Below detectable limit	Below detectable limit	180	270	10,125	5.1
DS_{final}	255	1395	1395	Below detectable limit	3690	Below detectable limit	Below detectable limit	450	675	6465	3.58
$FS_{initial}$	160	70	90	Below detectable limit	60	Below detectable limit	Below detectable limit	800	1320	2410	1.76
FS_{final}	170	380	400	Below detectable limit	590	Below detectable limit	Below detectable limit	600	970	2710	1.77

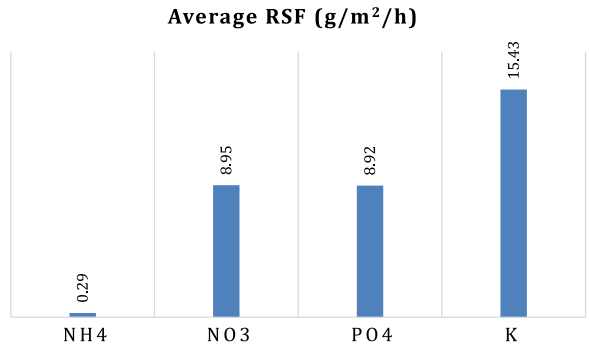

Fig. 7 Average reverse solute flux (RSF)

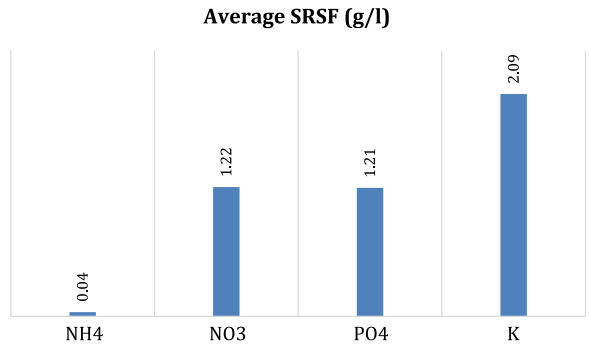

Fig. 8 Average specific reverse solute flux (SRSF)

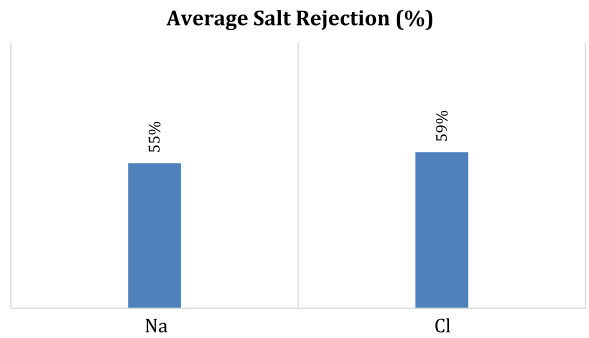

Fig. 9 Average salt rejection

containing 6 plants. The freshwater tables represented the control group and the 3500 ppm and 5000 ppm tables represented the experiment group. Tomatoes were harvested after 3 months, once every week, for 4 weeks. Only ripe tomatoes were harvested, which was identified by color; red and orange tomatoes were harvested, yellow and green tomatoes were left intact until they ripened. The number of tomatoes per plant, weight of the tomatoes per plant, average tomatoes diameter and average brix per plant were recorded. Brix, which is a measurement of dissolved sugar content in a solution, was measured using a handheld refractometer and diameter was measured using a digital vernier caliper.

Spinach was grown in nutrient film technique (NFT) hydroponic systems. Two basins were utilized, control and experiment. Spinach was harvested after a month, and a second time 2 weeks later. The weight of the spinach leaves per plant, height, number of leaves and average spad were recorded. Samples of spinach leaves were weighed and then dried in an oven at 60 °C for 72 h, and weighed after drying to calculate moisture content.

For element composition analysis of tomatoes leaves, fruits and spinach leaves, samples were prepared by digesting them in an acid solution with a Berghof microwave digestion system (speedwave Entry DAP-60K). Then, a sample weight of 300 mg was placed into the digestion vessel, and 8 ml of HNO_3 were added to it at 65% with a power level of 90%. The mixture was shaken carefully and stirred with a clean glass bar and the vessel was closed 10 min after shaking. The sample was then heated in the microwave with the program shown in Table 2.

The resultant sample was then cooled and transferred for element analysis. All measurements were performed using an Agilent 4210 MP-AES fitted with a double-pass cyclonic spray chamber and a OneNeb Series 2 nebulizer. Nitrogen was supplied using an Agilent 4107 Nitrogen Generator. All wavelengths were selected from the MP Expert software library, according to the sensitivity that was required. MP-AES operating conditions are shown in Table 3.

Results and discussion

Fertilizer drawn forward osmosis

Water flux

Equation (7) was utilized to calculate the water flux for all experiments, and the results are demonstrated in Fig. 6. All sets of data points were fit to a logarithmic trendline, to further demonstrate flux behavior. Average flux was taken as the flux at the point, where the flux curve slope decreases, and was taken to be at 40 min from the start of the experiment. It is observed that there are two groups of flux readings, the first with an average flux of 7 to 9 l/m^2/h, and the other with an average flux of 4 to 6 l/m^2/h. This was expected, as the same draw solution was usually used twice; once to concentrate the FS to 5000 ppm (labelled as "Condition 1"), and then once more to concentrate the FS to 3500 ppm (labelled as "Condition 2"). Since the DS was already diluted in the second utilization, flux in the second run was lower than the first run, due to the decrease in concentration, which decreases the osmotic pressure difference, which is the driving force for water flux. The same DS was utilized twice to maximize the dilution and utilization of each DS.

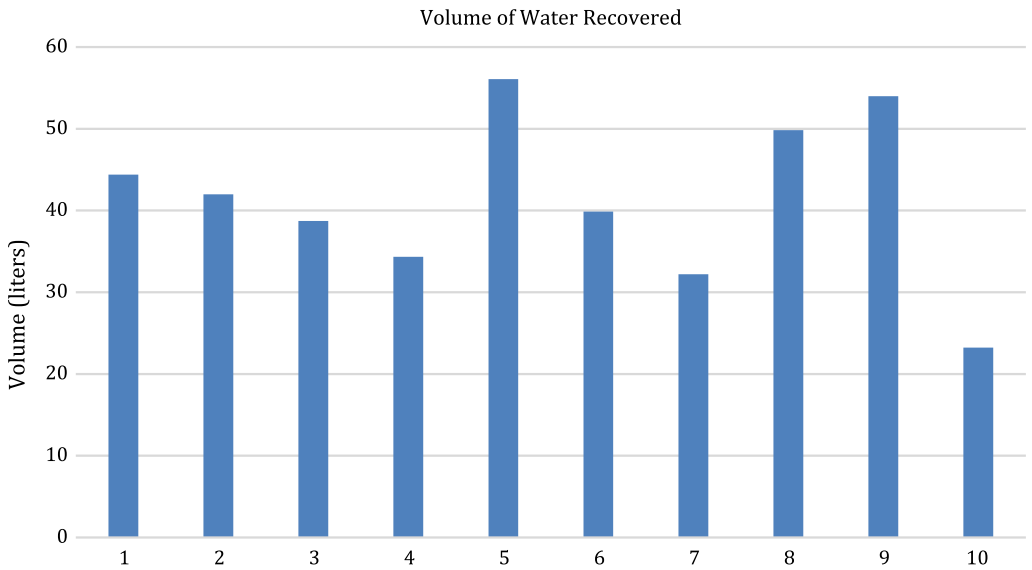

Fig. 10 Water recovery

Table 5 Two runs to produce 360L of permeate fresh RO water

TDS	2000 ppm
NTU	0.6
Flowrate Permeate	360 L/hour
Conc. Flowrate	130 L/hour
Feed TDS	1960 ppm
Permeate TDS	700 ppm
Conc. TDS (Value)	2500 ppm
Feed Flow	2.5 Bar/1500 L/hour

After 2 weeks from Plantation, another run was performed to supply the crops with permeate

Recovery for permeate water = (360/1500)*100 = 24%

Salt Rejection = (700/1960)*100 = 36% hydroponics setup

Ionic composition of solutions

The ionic composition of the feed solution and draw solution before and after FDFO was analyzed utilizing spectrophotometry, and the results are demonstrated (in mg/l) in Table 4. The utilized spectrophotometer is the Nova 60A, and test kits for each of the below ions were used. The test kit for each ion includes specific instructions for adding a specific concentration of the solution, adding specific reagents to the solution, as well as the duration of time that must be waited for the reagent to react with the sample, before the sample is put in the spectrophotometer for measurement of the ion.

Sources of error in the spectrophotometry could be attributed to line voltage fluctuations, vibrations, contamination, or heating of the sample by the photometer. SO_4, Ca & Mg were below the detectable limits for the spectrophotometer test kits. TDS & osmotic pressure were calculated using Lenntech Osmotic Pressure calculator [12].

Specific reverse solute flux

Equation (8) was used to calculate the reverse solute flux for all the ions in 3 samples of FS, which is demonstrated in Fig. 7. Specific reverse solute flux (SRSF) was calculated from Eqs. (5), (7), and (8) for all the ions in the FS (NO_3^-, K^+, PO_4^{3-}, NH_4^+), which is demonstrated in Fig. 8. It was observed that the highest SRSF was observed in K^+ ion, which is consistent with previous research [1, 2]. It can also be observed that the SRSF for NO_3^- and PO_4^{3-} were very close in values, and that the SRSF for NH_4^+ was almost negligible. The relatively low SRSF values in all ions indicate high membrane selectivity, which is the desired outcome. The flux of nutrients into the feed solution also provides an opportunity to utilize what would otherwise be a waste.

Salt rejection

The selectivity of the membrane towards FS ions (Na^+ and Cl^-) was investigated by calculating salt rejection using Eq. (9). As can be observed in Fig. 9, salt rejection percentage was on average 55% for Na and 59% for Cl, which indicates relatively average membrane selectivity. In general, salt rejection increases as water flux increases, due to the high driving force. However, the ionic composition of the draw solution can sometimes either positively or negatively charge the active layer of the membrane, which attracts oppositely charged ions from the feed solution into the draw solution.

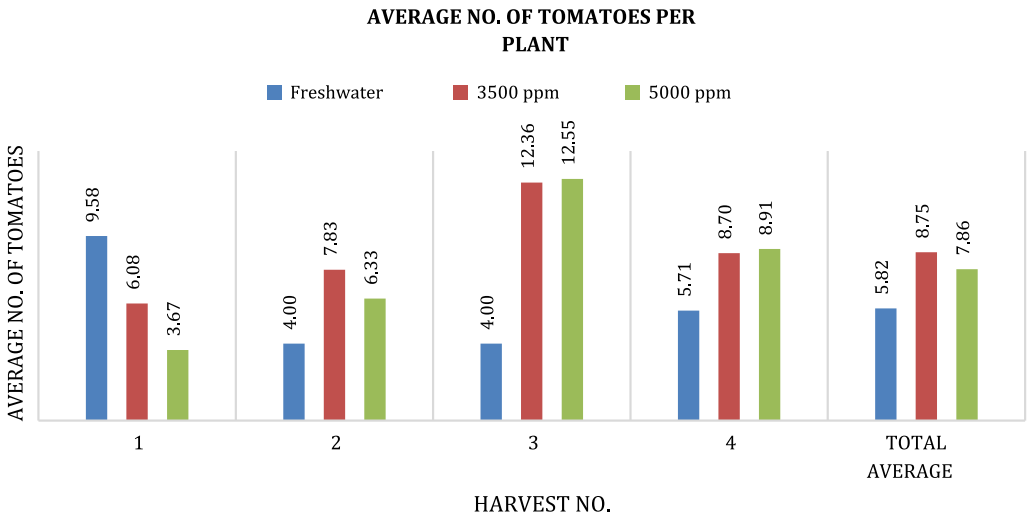

Fig. 11 Average number of tomatoes per plant

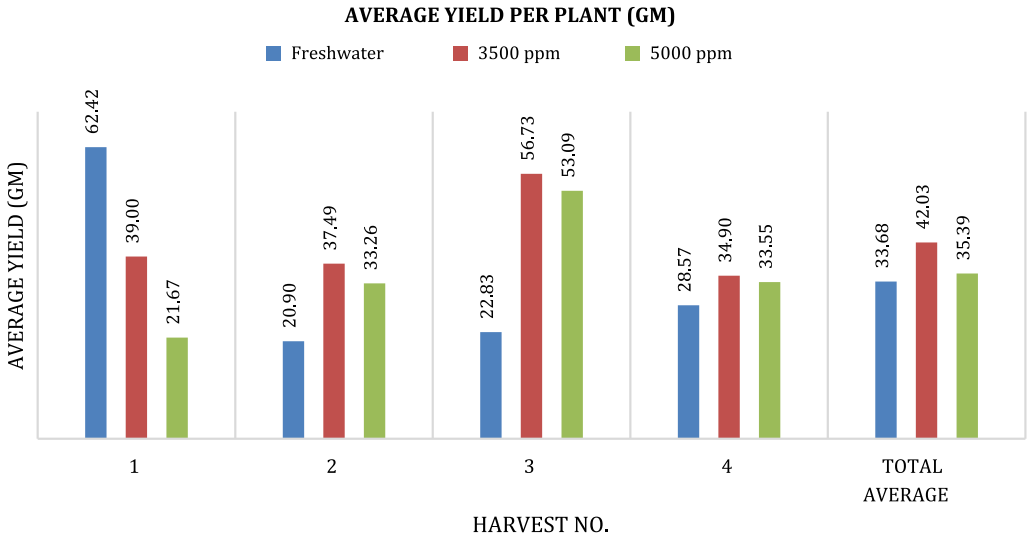

Fig. 12 Average yield per plant

Water recovery

The volume of water recovered during each run of the experiment was recorded, and is demonstrated in Fig. 10.

On average, the volume of water recovered was 41.46 L, which represents an average recovery percentage of 20%. The highest recorded recovery percentage was 28%.

Nanofiltration

Two runs were made to supply the experiment with enough permeate water for the dilution of the draw solution for the spinach control group, in Table 5 that shows the first run results.

Hydroponic agriculture

Cherry tomatoes

Average number of tomatoes per plant, average yield per plant (mass of tomatoes produced), average weight per tomato per plant, as well as average brix per tomato and average tomato diameter were measured for each of the 4 cherry tomatoes harvests, and results are demonstrated in Figs. 11, 12, 13, 14, and 15. From this data, it can be observed that the number of tomatoes from the freshwater tables decreased dramatically after the 1st harvest, and that the number of tomatoes from both the 3500 ppm and 5000 ppm tables were similar starting from the

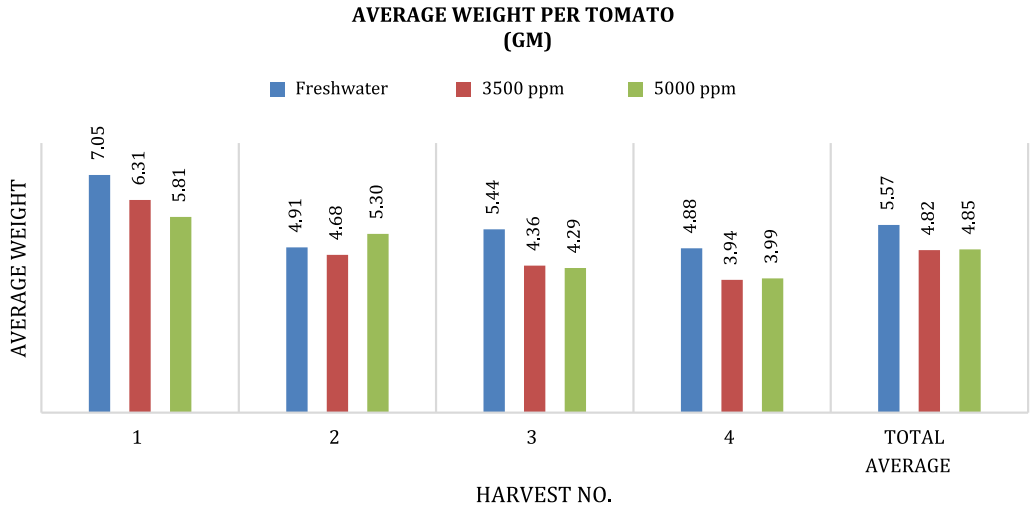

Fig. 13 Average weight per tomato

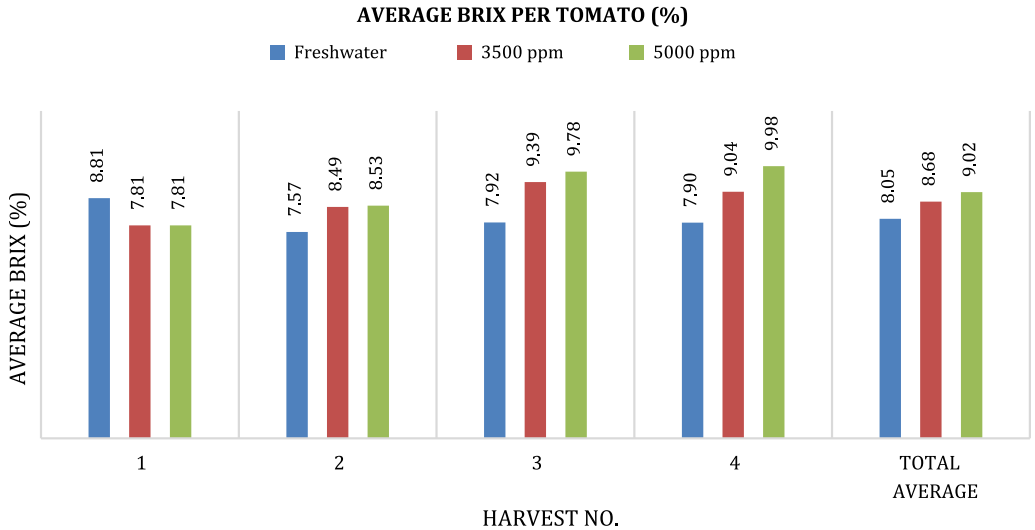

Fig. 14 Average brix per tomato

2nd harvest onwards. This can be an indication of later maturity of the plants grown using brackish water. This is observation is can be also observed in the average yield of tomatoes per plant per table (Fig. 12), where the freshwater plants' yield decreased significantly after the 1st harvest, while the 3500 ppm and 5000 ppm plants harvest peaked during the 3rd harvest. This observation is further cemented by the average diameter per tomato per plant (Fig. 15).

On the other hand, it was observed that freshwater tables had the highest average weight per tomato in all harvests compared to the 3500 ppm and 5000 ppm tables, except in the 2nd harvest, as well as the highest average weight per tomato overall (7.05 gm/tomato). This indicates that while the freshwater plants might have yielded less than the other tables starting from the 2nd harvest, it still yielded bigger tomatoes.

Freshwater brix was higher than the rest of the tables during the 1st harvest, indicating an early ripening. However, starting from the 2nd harvest, both the 3500 ppm and 5000 ppm tables had higher average brix, with the 5000 ppm plants having the higher average than the 3500 ppm plants.

The total number of tomatoes and total weight of tomatoes per water salinity are demonstrated in Figs. 16 and 17, and the total plant lifetime results are demonstrated in Table 6. It can be observed that while the 3500 ppm tables had the highest yield and highest number of

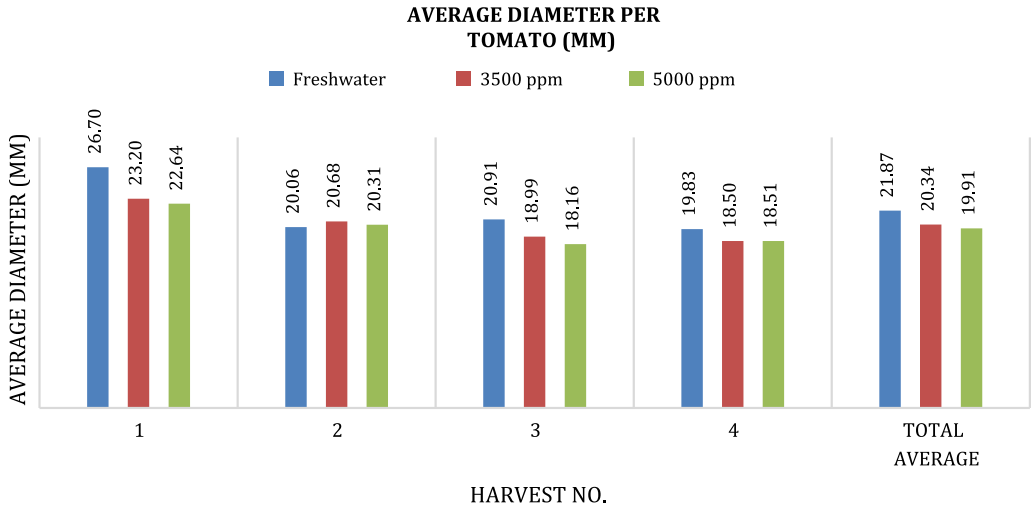

Fig. 15 Average diameter per tomato

Table 6 Overview of tomatoes results

	Freshwater	3500 ppm	5000 ppm
Total no. of tomatoes	199	390	348
Total yield (gm)	1190.5	1890.9	1518.98
Average weight per tomato (gm)	5.98	4.85	4.36

tomatoes throughout the plants lifetime, tomatoes from freshwater tables on average weighed more by about 19%. On average, 5000 ppm tomatoes weighed less than 3500 ppm tomatoes by 10%. This indicates that while cherry tomatoes have a salinity tolerance of up to 5000 ppm or more, the size and yield of tomato plants decreases as salinity increases. 3500 ppm appears to be well within the range of tomato plant salinity tolerance, and yield was not significantly affected.

Element composition analysis of tomato leaves and fruits was performed, and the element composition of the samples (ppb) is demonstrated in Tables 7 and 8. Negative values indicate that the concentration of the element was beneath the detection level for the apparatus. Element composition analysis was performed to investigate if cherry tomatoes grown using saline water absorb more or less salts and nutrient ions than cherry tomatoes grown with freshwater.

From Table 7, it is observed that the 3500 ppm plants had Calcium and Iron deficiencies, which was observed on some of the tomatoes growing on the 3500 ppm

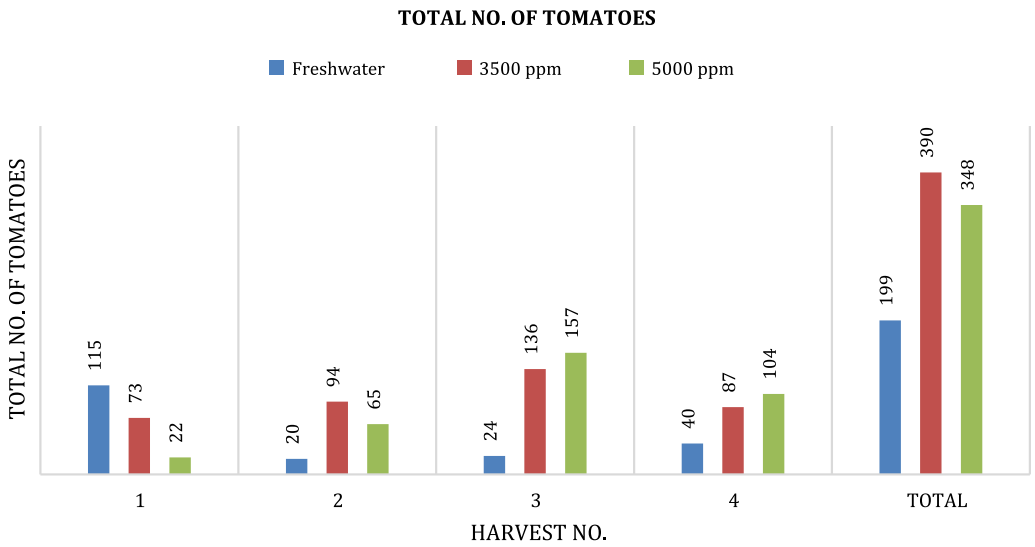

Fig. 16 Total number of tomatoes harvested per harvest and salinity group

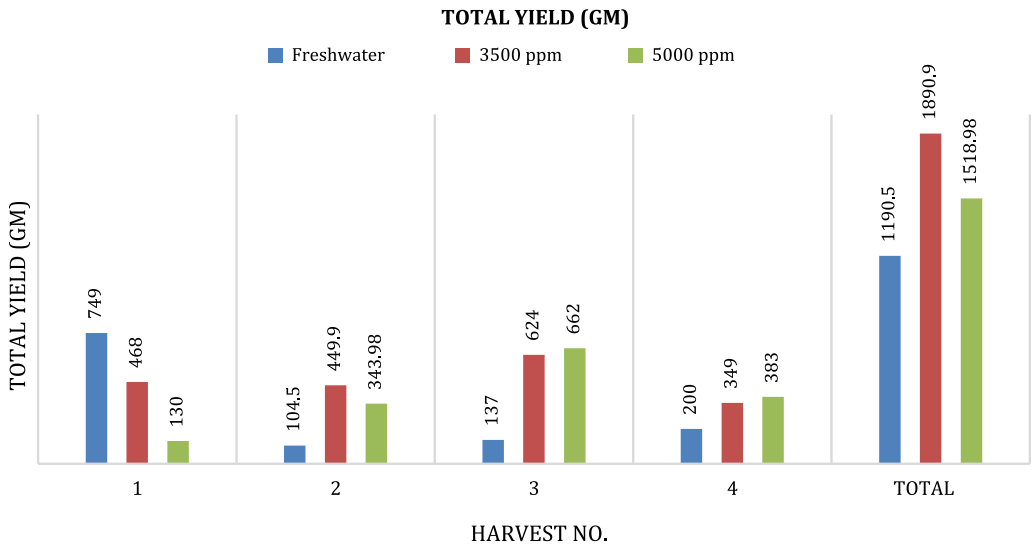

Fig. 17 Total tomatoes yield per harvest and salinity group

Table 7 Element composition of tomato leaves samples (ppb)

Group	P (ppb)	Zn (ppb)	Ca (ppb)	Fe (ppb)	Cu (ppb)	Pb (ppb)	Mg (ppb)	Mn (ppb)	K (ppb)	Na (ppb)
Freshwater	5.04	1.04	92.73	2.79	0.12	0.09	14.46	1.28	252.60	11.13
3500 ppm	2.48	0.46	41.92	0.82	−0.03	0.05	15.57	0.22	226.42	46.08
5000 ppm	4.64	0.99	93.97	2.27	−0.32	0.15	30.51	0.38	349.48	77.79

Table 8 Element composition of tomato fruits samples (ppb)

Group	Sample	P (ppb)	Zn (ppb)	Ca (ppb)	Fe (ppb)	Cu (ppb)	Pb (ppb)	Mg (ppb)	Mn (ppb)	K (ppb)	Na (ppb)
Freshwater	1	1.11	2.00	23.27	2.94	0.69	0.42	103.13	2.09	95.24	3.42
	2	1.31	1.53	15.29	2.18	0.11	0.38	60.98	0.76	61.63	2.38
	Average	1.21	1.76	19.28	2.56	0.40	0.40	82.05	1.43	78.43	2.90
3500 ppm	1	− 0.11	3.68	79.53	6.97	1.09	0.45	192.32	2.87	194.42	23.65
	2	− 0.31	3.66	48.10	6.65	1.34	0.52	149.55	3.29	181.52	14.60
	Average	− 0.21	3.67	63.82	6.81	1.21	0.48	170.94	3.08	187.97	19.12
5000 ppm	1	0.00	2.81	36.10	5.71	0.79	0.41	134.53	3.06	170.30	16.98
	2	0.01	2.74	55.71	6.01	1.26	0.50	144.80	2.64	164.29	20.54
	Average	0.01	2.78	45.91	5.86	1.03	0.46	139.67	2.85	167.29	18.76

plants, in the form of blossom end rot. It is also observed that both the 3500 ppm and 5000 ppm plants had Manganese deficiencies, compared to the freshwater plants. Finally, it is observed that the 5000 ppm plants had higher concentrations of Magnesium and Sodium than the freshwater and 3500 ppm plants. This is expected, as the 5000 ppm plants were the most exposed to higher concentrations of salts than the 3500 ppm and freshwater plants. This was also observed in [3], where it was observed that rise in the nutrient solution salinity, especially when the stress was prolonged, had a deleterious impact on the gas exchange, electrolyte leakage, and photosynthetic pigments of cherry tomato cultivars.

In the element composition analysis of tomato fruits, demonstrated in Table 8, it is observed that both the 3500 ppm and 5000 ppm had deficiencies in Phosphate, compared to the freshwater group. On the other hand, both the 3.5 and 5000 ppm tomatoes had higher

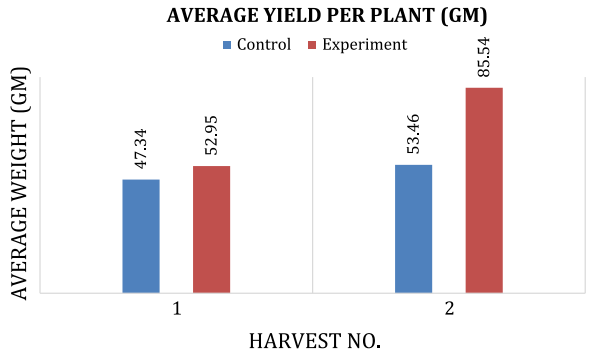

Fig. 18 Average yield per plant

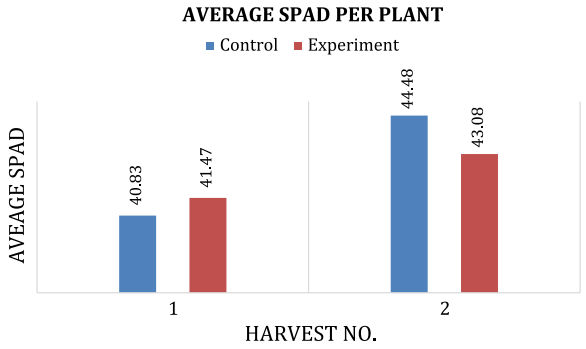

Fig. 21 Average SPAD per plant

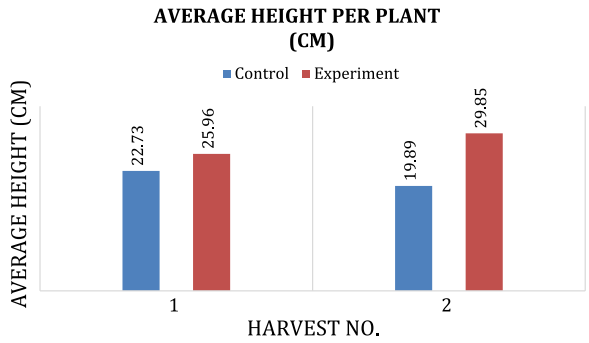

Fig. 19 Average height per plant

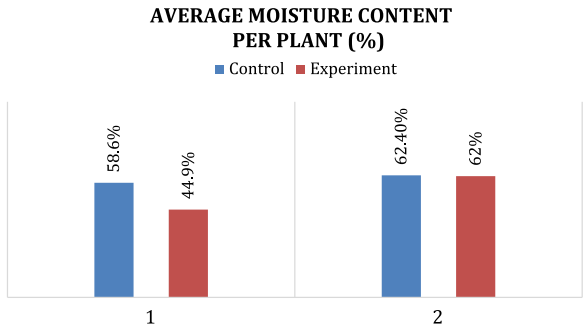

Fig. 22 Average moisture content per plant

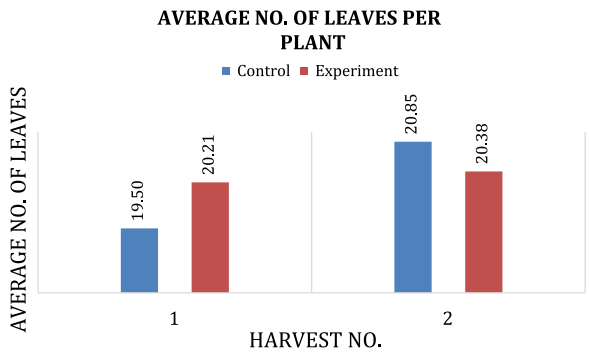

Fig. 20 Average number of leaves per plant

concentrations of all the other elements than the freshwater tomatoes. This is expected, as both the 3.5 and 5000 ppm plants were exposed to a higher concentration of ions present in the concentrated feed solution, due to the flux of some of the draw solutes into the feed (reverse solute flux).

Spinach

It was observed that the average yield per plant, demonstrated in Fig. 18, was slightly higher in the experiment group than in the control group during the 1st harvest, and significantly higher during the 2nd harvest (by 37.5%). Similarly, average leaf height per plant, demonstrated in Fig. 19, was also slightly higher in the experiment group during the 1st harvest and significantly higher during the 2nd harvest (by 33.4%).

However, while average yield and height were higher in experiment table during 2nd harvest, the average number of leaves per plant, demonstrated in Fig. 20, was higher in the control group than experiment group during the 2nd harvest.

Average SPAD is demonstrated in Fig. 21, and it was observed that there was no significant difference in average SPAD between the control group and the experiment group during the 1st and 2nd harvests.

Table 9 Overview of spinach results

	Control	Experiment
Total lifetime yield (gm)	1367.5	1853.3
Total lifetime no. of leaves	543	548
Average weight per leaf	2.52	3.38

Table 10 Element composition of spinach samples (ppb)

Group	Sample	P (ppb)	Zn (ppb)	Ca (ppb)	Fe (ppb)	Cu (ppb)	Pb (ppb)	Mg (ppb)	Mn (ppb)	K (ppb)	Na (ppb)
Control	1	2.80	1.31	42.14	1.29	0.11	0.07	88.26	0.25	311.08	14.36
	2	2.48	0.71	33.23	0.62	− 0.02	0.08	32.94	0.09	350.58	18.07
	3	2.59	0.56	46.23	0.76	0.20	0.06	33.95	0.11	301.86	21.93
	Average	2.62	0.86	40.53	0.89	0.09	0.07	51.72	0.15	321.17	18.12
Experiment	1	1.18	0.34	17.35	− 0.06	− 0.56	− 0.22	19.57	0.36	307.76	36.35
	2	1.47	0.68	47.85	1.20	0.25	0.05	44.64	0.29	288.81	23.56
	3	2.52	0.72	73.62	0.80	− 0.03	0.08	60.06	0.33	319.71	23.35
	Average	1.72	0.58	46.27	0.65	− 0.11	− 0.03	41.42	0.32	305.43	27.75

Moisture content, demonstrated in Fig. 22, was calculated by weighing samples of spinach leaves before and after drying. It was observed that difference in moisture content in first harvest was significant, but negligible in second harvest.

Analyzing the total lifetime yield of both the control and experiment groups provides us with the results outlined in Table 9. It is worth noting that while both groups yielded similar number of leaves, the average weight per leaf for the experiment group was higher than the control group (by 25%).

To better understand why the control group had a much lower yield than the experiment group during the 2nd harvest, an element composition analysis was performed on samples of spinach leaves from the 2nd harvest. The results are demonstrated in Table 10.

It was observed that aside from Calcium, Manganese and Sodium, the control group had higher element concentrations than the experiment group.

Conclusion

This study investigated the feasibility of growing crops utilizing the concentrated feed solution from fertilizer drawn forward osmosis. This would provide a novel opportunity to utilize a byproduct of forward osmosis, which in most cases is unsuitable for use and was considered a waste. This study also investigated the integration of nanofiltration with forward osmosis, which provides a source of further dilution of the draw solution without the need for freshwater resources. Combining the design of this study, a method of growing several crops on non-arable land that has access to low salinity brackish groundwater and no access to freshwater was demonstrated. The combination of the low-energy and low capital requirements of forward osmosis with the potential for growing highly valued crops such as cherry tomatoes presents an opportunity for positive environmental and economic impacts.

It was found that while cherry tomato plants grown using the 3500 ppm feed solution had the highest yield and highest number of tomatoes throughout the plants lifetime, tomatoes grown using freshwater weighed on average more by about 19%. Moreover, tomatoes grown using 5000 ppm feed solution on average weighed less than 3500 ppm tomatoes by 10%. Both the control and the experiment spinach groups yielded similar number of leaves, but the average weight per leaf for the experiment group was higher than the control group by 25%.

To further develop this model, future research efforts should be directed at experimenting with other crops or further investigating the salinity tolerance of cherry tomatoes and crops grown using the concentrated feed solution.

Abbreviations

DS	Draw solution
DWC	Deep water culture
FDFO	Fertilizer drawn forward osmosis
FO	Forward osmosis
FS	Feed solution
NF	Nanofiltration
NFT	Nutrient film technique
RO	Reverse osmosis
RSF	Reverse solute flux
SRSF	Specific reverse solute flux
SWRO	Sea water reverse osmosis
UF	Ultrafiltration

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Not applicable.

Author contributions
MB, FK, YAM, KB and HS contributed to the conceptualization of the study and its design. Material preparation, data collection and analysis were performed by MB, FK, KB and YAM. The manuscript draft was written by MB and KB and reviewed by YAM, FK and HS.

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Availability of data and materials
The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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