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Performance and energy consumption evaluation of a fertiliser drawn forward osmosis (FDFO) system for water recovery from brackish water

R. Lambrechts, M.S. Sheldon*

Cape Peninsula University of Technology, Department of Chemical Engineering, P.O. Box 1906, Bellville 7535, South Africa

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ABSTRACT

Agriculture consumes approximately 70% of total freshwater worldwide. With limited freshwater resources, alternative water resources are required. This study investigated the performance of a fertiliser drawn forward osmosis (FDFO) system for water recovery from synthetic brackish water with repeated use of a cellulose triacetate (CTA) FO membrane under varying fertiliser draw solution (DS) concentrations (0.5, 1 and 2 M KCl); membrane orientations (FO vs PRO) and flow rates (100, 200 and 400 mL/min); with the corresponding effects on the specific energy consumption (SEC). Results demonstrated a robust CTA membrane with no damage. An increased DS concentration from 0.5 to 1 M KCl contributed to a three-fold increase in flux, followed by a 30 to 50% increase for 2 M KCl and a reduced SEC. Membrane orientation and flow rate had insignificant effects on performance, however, flow rate contributed to an SEC increase. FO mode at a lower flow rate combined with a higher DS concentration produced the lowest possible SEC. The study illustrated a potential lower energy process for water recovery from synthetic brackish water whilst at the same time producing a diluted fertiliser that could potentially be used for fertigation.

1. Introduction

With the current world population increasing at an alarming rate, it is estimated that between 2011 and 2050 the population would increase from 7 billion to 9.3 billion [1]. This would account for a 33% increase in population resulting in a 60% increase in food demand for the same period. Agricultural developments constitute for approximately 70% of total freshwater consumption worldwide and will substantially increase in the near future. With limited freshwater resources and the agricultural industry being a major consumer of freshwater, alternative water resources are required.

Forward osmosis (FO) is a membrane technology that has gained interest over the past decades due to the efficient method of water recovery. It is based on the natural osmotic process which is driven by an osmotic pressure gradient (ΔOP) between a feed solution (FS) and DS separated by a semipermeable membrane. FO as a stand-alone process (i.e. where a regeneration step is not required) hold some distinct advantages, one of them being it is considered a lower energy consuming process compared to conventional pressure-driven processes such as Nano-filtration (NF) and reverse osmosis (RO) [2]. It exhibits lower fouling rates and lower irreversible membrane fouling [3,4] which in turn require straightforward membrane cleaning procedures. In addition, FO exhibits high contaminant rejection [5] and can obtain high recovery rates ultimately reducing FS discharge volumes [3,6].

The use of commercial fertilisers accounts for approximately 40 to 60% of global food production [7] and will increase in the near future. The concept of utilising a fertiliser as a DS was first reported by Moody and Kessler [8]. However, more recent studies conducted by Phuntsho et al. [8] investigated several inorganic fertilisers to determine their potential as DSs for direct fertigation. Fertigation is the application of diluted fertilisers to agricultural farmlands via an irrigation system [9]. Thus, making it an ideal concept to recover water from feed water resources to dilute a fertiliser solution which can then be used to fertigate farmland.

FO has been identified as a viable option for a variety of applications such as for seawater desalination, wastewater reclamation, concentrating of landfill lactate or industrial waste streams [10], protein enrichment and for the concentrating of pharmaceutical products [11]. However, one of the factors that have limited the commercialisation of FO is the lack of high-performance membranes [12,13]. Several membrane types have been developed in an attempt to improve FO system performance. This includes synthesising membranes with different materials such as cellulose acetate (CA) or cellulose triacetate (CTA), polyamide including other polymers and polyelectrolytes and biomimetic aquaporin (AqP) based membranes [14]. A recent study by Augustine [15] evaluated the performance of AqP based biomimetic

* Corresponding author.
E-mail address: sheldonm@cput.ac.za (M.S. Sheldon).

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membranes to dilute commonly used fertiliser DSs for the application in the South African wine industry. Augustine reported that AqP biomimetic membranes outperformed a CTA membrane in terms of water flux, however, the reverse solute fluxes (RSF) was greater.

Commercially available FO membranes are typically asymmetric, thus, the membrane can either be orientated in the FO mode where the active layer (AL) is facing the FS (AL-FS) or in the pressure retarded osmosis (PRO) mode where the AL is facing the DS (AL-DS) [16]. It has been reported that the PRO mode produces a greater water flux compared to the FO mode [2]. However, the FO mode has a lower RSF compared to the PRO mode and was recommended for troubled FSs [14] as the PRO mode is more susceptible to membrane clogging [17]. To determine the economic viability of the system, the pump power was theoretically calculated and combined with the volumetric flow rate of water permeation to result in a term SEC.

This study investigated the combined performance and energy consumption of an FDFO system. The system performance was evaluated in terms of water flux (J_w), reverse solute flux (J_s) and the volume of water recovered (R_e) for (i) repeated use of the CTA FO membrane under; (ii) varying fertiliser DS concentrations; membrane orientations and flow rates; (iii) demonstrating the corresponding effects on energy consumption in terms of specific energy consumption (SEC); whilst (iv) simultaneously producing a diluted fertiliser solution that could potentially be used for fertigation.

2. Materials and methods

2.1. Feed and draw solution characteristics and preparations

For the baseline experiments, the FS used was deionised water (DI) with the DS being a 1 M sodium chloride (NaCl) solution. These solutions were chosen as it was commonly used for membrane performance testing [2,18,19]. For the FDFO experiments, the FS utilised was synthetic brackish water (SBW5) with 5000 mg/L NaCl representing the salt content of brackish water (simulating an abundant global water source) [20,21].

For the FDFO experiments the DS comprised of a potassium chloride (KCl) fertiliser with initial concentrations of 0.5, 1 and 2 M. KCl was selected based on its common use as a fertiliser in the South African wine industry and generation of the highest pure water flux in comparison to other inorganic fertilisers evaluated [5,8,9,15]. NaCl and KCl were supplied by Merck, Gauteng, South Africa and was used as is without any further purifications.

2.2. Bench-scale FO system

The bench-scale FO system in Fig. 1 comprised of a (i) FO membrane cell (Sterlitech™ Co., CF042D, Sterlitech, United States of America (USA)) with an effective membrane area of 42 cm^2; (ii) a double head variable speed peristaltic pump (Watson-Marlow, 323E/D, Dune Engineering, South Africa (SA)), for transporting the FS and DS, respectively; (iii) a digital scale (WIS, WA606, Weighing Instrument Services (Pty) Ltd, SA) to determine the DS mass variation over time; (iv) a magnetic stirrer (BANTE, MS400, Labotec, SA), to agitate the FS; (v) two 2 L reservoirs for the FS and DS, respectively; and (vi) a digital multi-parameter meter (Lovibond, SD150, Selectech (Pty) Ltd, SA), to determine the electrical conductivity (EC) of the FS. The system was operated in a batch mode with the FS and DS flowing in a counter-current direction with respect to the membrane. A counter-current flow configuration was selected due to its process efficiency [10] and the provision of a slightly higher water flux [2] in comparison to the co-current flow configuration. As the membrane cell was positioned horizontally, the FS flowed in the top channel of the cell whilst the DS flowed in the bottom channel. This orientation was selected in order for the water flux to flow with gravity and not against it. All experiments were conducted at ambient temperature (± 20 °C). The membrane used was a flat-sheet CTA membrane supplied by Fluid Technology Solutions Inc. (Albany, Oregon, USA) and was selected based on its availability and the utilisation as previously reported in other studies [5,15,22–24].

2.3. Experimental procedures

Baseline experiments were performed in two modes; i.e. forward osmosis mode (FO mode) (AL-FS) and pressure retarded osmosis mode (PRO mode) (AL-DS) modes at a flow rate of 200 mL/min utilising DI water as the FS and 1 M NaCl as the DS, respectively. The volumes of FS and DS used in each experiment were 2 and 0.5 L, respectively. The FS and DS osmotic pressures (OP) were measured at the start and end of each experiment. Experiments were operated for 5 h, whilst the DS mass and FS EC readings were recorded at 1 h intervals. The membrane was then physically cleaned within the membrane cell by circulating DI water in the FS and DS channels at a flow rate of 600 mL/min corresponding to a cross flow velocity of 9.5 cm/s for 30 min.

FDFO experiments followed by utilising SBW5 as the FS, whilst respectively adjusting the DS concentration from 0.5, 1 and 2 M KCl as well as the membrane orientation from FO to PRO mode. Additionally, the system flow rate was respectively changed from 100, 200 and 400 mL/min which corresponded to cross-flow velocities of 1.6, 3.2 and 6.3 cm/s. Each FDFO experiment was operated for 24 h, whilst DS mass and feed solution electrical conductivity (FS EC) readings were recorded at 1 h intervals. Overnight instrument readings were recorded with the aid of a portable camera.

Following the FDFO experiment, the membrane was cleaned following the same procedure after which the membrane integrity was analysed. Membrane integrity was analysed utilising a 0.01% methyl violet dye solution as FS and 2 M NaCl as the DS both circulating at a flow rate of 200 mL/min. The test was performed in the FO mode only as the purpose was to identify any damage on the active layer which will be stained purple. Thus, if the membrane was tested in the PRO mode in previous experiments it was re-orientated to the FO mode before the integrity test commenced. The test continued until a minimum of 10 mL water fluxed from the FS to the DS. If no damage was observed, the membrane was re-used after an additional cleaning procedure. However, if any membrane damage was observed the membrane was discarded. Each experiment was performed in duplicate, however, additional experiments were performed if results deviated significantly.

2.4. Measurement and analysis

2.4.1. Osmotic pressure

The osmotic pressure (OP) of the FS and DS were measured in duplicate using a Genotec osmometer (Osmomat 3000; Scientific Group, Germany). The results reported were the averaged values. Measurements from the osmometer were in mOsmol/kg and were converted to OP (kPa) using Eqs. (1) & (2) [25]:

$$P \cdot V = n \cdot R \cdot T \tag{1}$$

$$P = \left(\frac{n}{V}\right) \cdot R \cdot T \tag{2}$$

where P (Pa) is pressure, (n / V) is the osmolality (mOsmol/kg H_2O), R is the universal gas constant (8.314 m^3·Pa/mol·K), T is absolute temperate (K).

2.4.2. Water flux

The water flux (J_W) was determined based on the mass variation of the DS over time and was calculated from Eq. (3) [26]:

$$J_W = \frac{m_{DSt_2} - m_{DSt_1}}{\rho \cdot A_m \cdot (t_2 - t_1)} \tag{3}$$

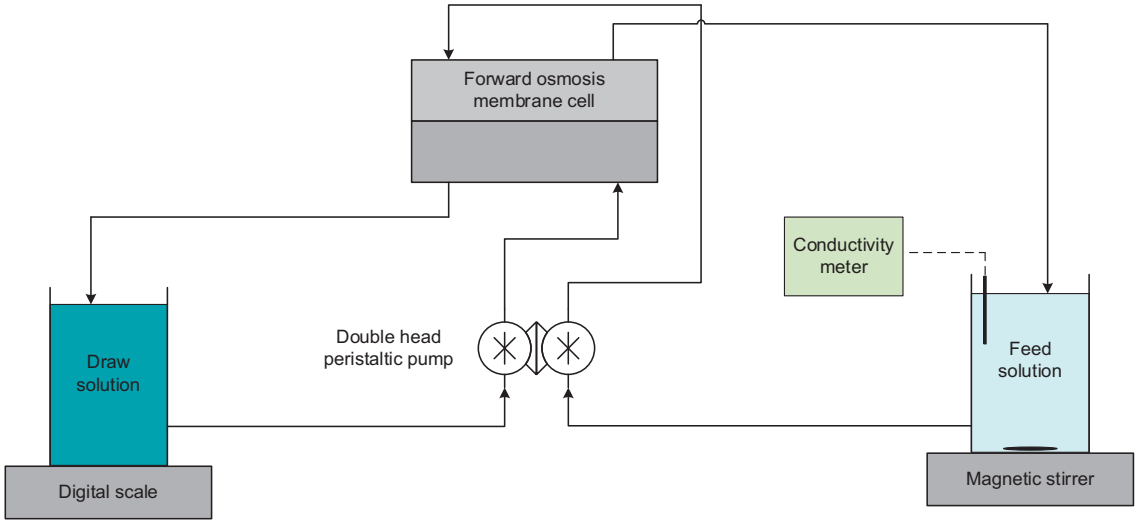

Fig. 1. The bench-scale forward osmosis experimental setup.

where J_W (L/m^2·h) is the water flux, m_{DSt_1} (g) is the mass of the DS at recording time interval t_1 (h), m_{DSt_2} (g) is the mass of the DS at recording time interval t_2 (h), A_m (m^2) is the effective membrane area, and t_1 and t_2 (h) is the recording time intervals, ρ (g/L) is the density of the solution. It is assumed that the change in mass of the DS is mainly attributed to the permeation of pure water.

2.4.3. Reverse solute flux

The RSF (J_s) was determined based on the EC variation of the FS with time and was calculated from Eq. (4) [27]:

$$J_s = \frac{V_{FSt_2}\cdot C_{FSt_2} - V_{FSt_1}\cdot C_{FSt_1}}{A_m\cdot(t_2 - t_1)} \quad (4)$$

where J_s (g/m^2·h) is the RSF, $V_{FS_{t1}}$ (L) is the volume of the FS at recording time interval t_1 (h), $V_{FS_{t2}}$ (L) is the volume of the FS at recording time interval t_2, $C_{FS_{t1}}$ (g solute/L water) is the salt mass concentration of FS at recording time interval t_1 (h), $C_{FS_{t2}}$ (g solute/L water) is the mass concentration of FS at recording time interval t_2. J_s was only calculated for baseline experiments using DI as the FS. For the J_s calculation, the changes in the salt concentration were determined from a standard curve relating EC to the salt mass concentration (C). For the FDFO experiments, the RSF was monitored only by measuring the EC of the FS.

2.4.4. Volume of water recovered

The volume of water recovered (R_e) was determined based on the mass of water that fluxed from the FS to the DS and was calculated using Eqs. (5) & (6) as derived by the author.

$$R_e = V_{FSt_1} - V_{FSt_2} \quad (5)$$

$$R_e = V_{FSt_1} - \left(V_{FSt_1} - \left(\frac{m_{DSt_2} - m_{DSt_1}}{\rho}\right)\right) \quad (6)$$

The variables are as previously defined.

2.4.5. Theoretical specific energy consumption

Energy consumption by the FDFO system is mainly attributed to the circulation pump. Additional factors which affected the system and subsequently pump energy consumption was the volumetric flow rate of the system, feed and draw solutions densities and viscosities. SEC was determined based on the theoretical work done by the circulation pump and was calculated using Eq. (7) [26]:

$$SEC = \frac{P_{System}}{Q_P} = \frac{P_{Pump}}{Q_P} = \frac{3600\cdot(Q_S)\cdot(\rho)\cdot(g)\cdot(H_{Total})}{1000\cdot(Q_P)} \quad (7)$$

where SEC (kWh/m^3) is the specific energy consumption, P_{System} and P_{Power} is the system and pump power, Q_S is the volumetric flow rate of the FS and DS (m^3/h), Q_P is the volumetric flow rate of the permeate through the membrane (m^3/h), g is the gravitational acceleration (m/s^2), H_{Total} is the total head loss produced by the system (m).

3. Results and discussion

3.1. Baseline experiments

Baseline experiments were performed to identify if membrane cleaning was sufficient in restoring membrane performance and to determine how membrane performance was affected by repeated use. Since no membrane damage was observed after the membrane integrity testing, the same membrane was repeatedly used after a thorough cleaning. The initial ΔOP using 1 M NaCl and DI water was ± 4184 kPa which over the 5 h period decreased to a final ΔOP of ± 3655 kPa.

Fig. 2 represents the J_w, J_s and R_e obtained for each baseline experiment. From Fig. 2(a)(i) in the FO mode an average initial J_w of 3.9 ± 0.09 L/m^2·h was obtained which decreased due to osmotic dilution to an average final J_w of 3.3 ± 0.22 L/m^2·h. Whilst Fig. 2(a)(ii) in the PRO mode indicate that an average initial J_w of 3.5 ± 0.13 L/m^2·h was achieved which steadily decreased to an average final water flux of 3.1 ± 0.09 L/m^2·h. It was noted that the PRO mode resulted in slightly lower water fluxes compared to the FO mode. As the same membrane was used for both orientations after a physical membrane cleaning, it was believed solutes from previous experiments remained within the support layer causing concentrative internal concentration polarisation (CICP). As the PRO mode is prone to membrane clogging, this CICP was believed to be the cause of the PRO mode to result in the slightly lower J_w compared to the FO mode. As similar initial water fluxes were obtained, the baseline experiments were stopped after the sixth experiment.

From Fig. 2(b)(i), an average initial J_s of 0.66 ± 0.07 g/m^2·h was obtained and decreased to an average final J_s of 0.46 ± 0.06 g/m^2·h. Whilst from Fig. 2(b)(ii), an average initial J_s of 0.60 ± 0.07 g/m^2·h which declined to an average final J_s of 0.38 ± 0.05 g/m^2·h. J_s deviated slightly greater from one experiment to the next compared to J_w which may be due to solutes from previous experiments trapped within the membrane support layer due to inefficient membrane cleaning. As this layer creates a hydrodynamic static zone, it is particularly difficult to penetrate and clean the layer [3]. As a result, the DI water EC also

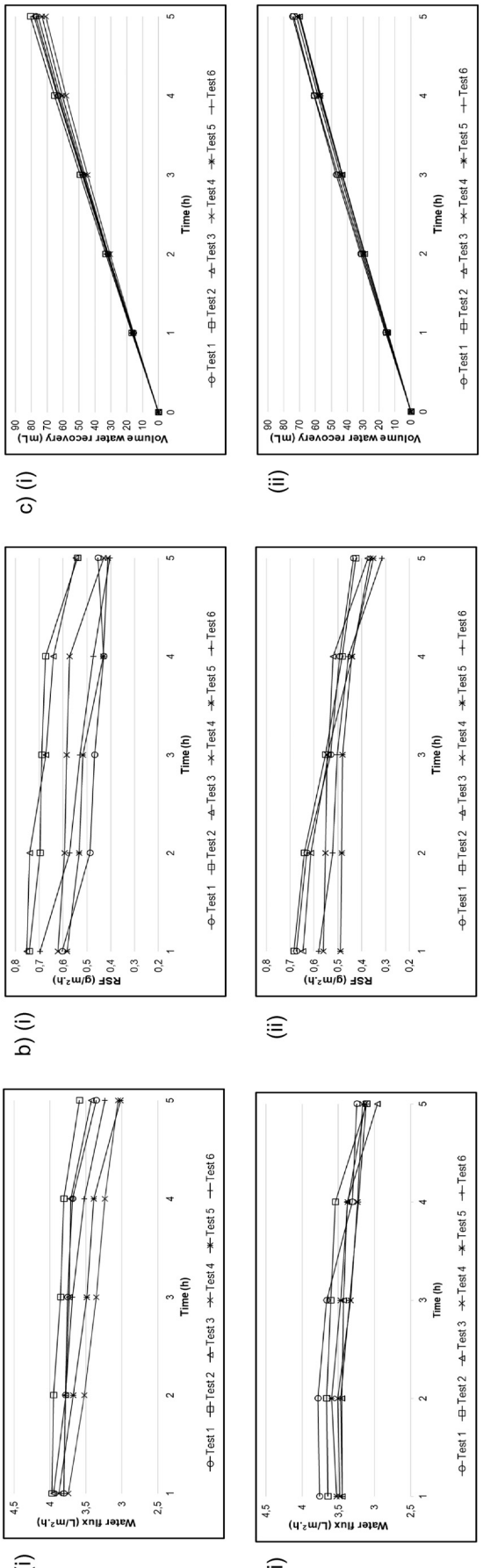

Fig. 2. (a) Water fluxes (J_w), (b) reverse solute fluxes (J_s) and (c) accumulative volume of water recoveries (R_e) obtained during a 5 h operation for 6 baseline experiments using the same membrane whilst operating in i) FO and ii) PRO modes at a DS concentration of 1 M NaCl with DI water as the FS both at a flow rate of 200 mL/min, respectively.

varied from one experiment to the next. However, J_s obtained was still significantly lower compared to Ren and McCutcheon [28] which reported a J_s of up to ± 1 g/m^2·h and ± 7.5 g/m^2·h for FO and PRO modes, respectively, using 1 M NaCl as DS and DI water as FS.

Nonetheless, R_e's between each baseline experiments were nearly identical. From Fig. 2(c)(i) in the FO mode, an average accumulative R_e of 76 ± 3.4 mL was achieved, whilst from Fig. 2(c)(ii) in the PRO mode, an average accumulative R_e of 71 ± 2.1 mL was obtained.

3.2. Water flux trends

Fig. 3 provides the J_w profiles obtained for FO and PRO mode membrane orientations with a DS concentration of 2 M KCl and SBW5 as the FS at a flow rate of 400 mL/min for a new and used membrane. The initial ΔOP achieved at a DS concentration of 2 M KCl and SBW5 as the FS was ± 8613 kPa. Fig. 3(a) shows that in the FO mode the initial J_w decreased by 3.2 L/m^2·h from a J_w of 7.5 to 4.3 L/m^2·h for a new and used membrane, respectively. Whilst on the other hand from Fig. 3(b), operating in the PRO mode, the initial J_w decreased by 5.8 L/m^2·h from a J_w of 9.0 to 3.2 L/m^2·h for a new and a used membrane, respectively. The results in Fig. 3 show that for a new membrane the initial J_w for PRO was higher than for FO which is in line with what was previously reported in the literature. However, after repeated use of the membrane, the FO mode resulted in a higher initial J_w which, shows that the FO mode could be cleaned more effectively. This supports the argument that the repeated use of the same membrane for the baseline experiments in different orientations resulted in the PRO having a slightly lower J_w. Comparing the results to literature, for a new membrane, similar fluxes were obtained compared to studies by Phuntsho et al. [2] who also obtained a J_w of up to ± 9 L/m^2·h at a DS concentration of 1 M KCl whilst operating in the FO mode and up to ± 10 L/m^2·h for the same concentration in the PRO mode both at a flow rate of 400 mL/min.

Fig. 3 also indicates that the physical membrane cleaning used was not effective in restoring long term membrane performance. After repeated use of the membrane for the majority of experiments conducted, an irregular J_w trend was obtained within the first 2 h. The initial J_w's started lower then peaked after 2 h after which it steadily decreased again. This increase followed by a decrease in J_w obtained during the initial stages of the experiment contradicts the FO driving mechanism concept. As previously mentioned the same membrane was re-used throughout the study as no membrane damage was observed.

Nonetheless, the irregular trend observed when re-using the membrane was believed to be as a result of internal concentration polarisation (ICP). The results showed that the physical membrane cleaning procedure used in this study was more effective in cleaning the outer surfaces of the membrane and less effective in cleaning within the membrane support layer. Therefore, it was postulated that when a membrane was re-used, ICP from previous experiments remained as the membrane cleaning was unable to successfully penetrate the support layer. Thus, dilutive internal concentration polarisation (DICP) would remain within the membrane if it was tested in a FO mode orientation whilst CICP would remain if a PRO mode orientation was tested. Consequently, these polarised layers create an additional resistance through which the new bulk solutions must diffuse in order to produce an effective osmotic driving force essential for generating J_w. The lower initial J_w observed during the study may be attributable to a low effective osmotic driving force because of the ICP. However, as the bulk solutions started to diffuse through the ICP layers a greater driving force is generated due to the difference in OP between the bulk FS and DS which in turn produced an increased J_w as was observed. Even though the J_w trend observed was irregular, a study by Zou & He [29] also reported J_w data with a similar trend. However, in their study, the experiment operated in FO mode whilst using wastewater and a multipurpose fertiliser as an FS and DS, respectively. The results from their study indicated that when the same membrane was chemically cleaned

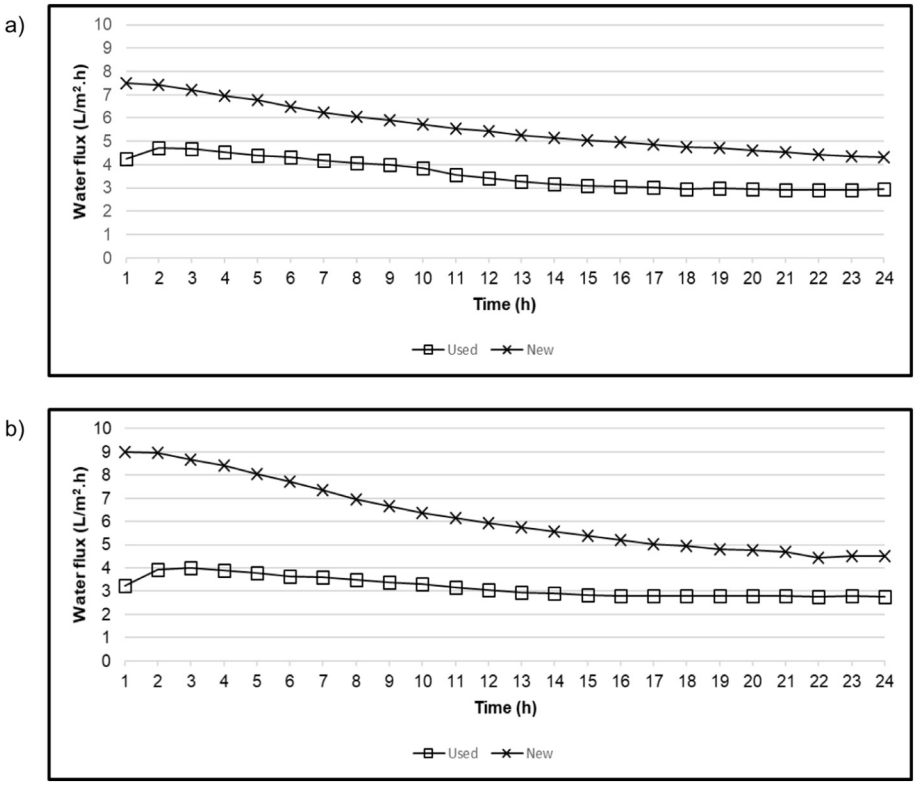

Fig. 3. Water flux (J_w) obtained during 24 h operation between a new and used CTA membrane for (a) FO and (b) PRO modes of operation at a DS concentration of 2 M KCl and SBW5 as FS at 400 mL/min.

and re-used, the results produced a graph trend similar to the results obtained in this study.

3.3. Effects of draw solution concentration on performance and specific energy consumption

Figs. 4, 5 and 6 provide the J_w, FS EC, R_e, and SEC obtained with SBW5 as the FS at different KCl concentrations in FO and PRO mode orientations at different flow rates, respectively. An initial ΔOP of ± 1611, ± 3661 and ± 8639 kPa was obtained which decreased in 24 h to a final ΔOP of ± 1243, ± 2299 and ± 4326 kPa at a DS concentration of 0.5, 1 and 2 M, respectively. Fig. 4 indicates that J_w increased systematically with the escalation of DS concentration, mainly as a result of the upsurge in osmotic driving force. A DS concentration of 2 M resulted in the greatest J_w followed by 1 and 0.5 M. J_w increased approximately threefold from a DS concentration of 0.5 (1.1 ± 0.1 L/m^2·h) to 1 M (3.1 ± 0.2 L/m^2·h) which subsequently increased further by an additional 30 to 50% for a DS concentration change from 1 to 2 M (4.5 ± 0.2 L/m^2·h). Findings from this study are in agreement with literature that an increase in DS concentration leads to an increase in J_w. However, as was previously demonstrated in Fig. 3 the J_w obtained after repeated use of the membrane was significantly lower compared to what was previously reported. It was believed that the difference in J_w was due to the ICP which may have been transferred from one experiment to the next. It was previously reported in the literature that J_w can be impaired by up to 80% due to the effects of ICP [30]. A recent study by Chekli et al. [31] whilst using a new membrane reported J_w's of up to 21.1 L/m^2·h and 26.4 L/m^2·h in the FO mode for a KCl DS concentration 1 and 2 M, respectively, whilst using a synthetic wastewater solution.

As shown in Fig. 5 the FS EC also increased and this was attributed by two factors namely (i) the concentrating effect of the FS due to the water permeation to the DS and (ii) as a result of J_s from the DS. At a DS concentration of 0.5 M the FS EC increased from an initial EC of 9.4 mS/cm to an average final EC of 10.3 ± 0.2 mS/cm followed by 1 M which obtained an average final FS EC of 11.3 ± 0.08 mS/cm and 2 M which resulted in an average final FS EC of 12.1 ± 0.2 mS/cm.

As R_e is related to J_w, an escalation in R_e was observed with an increase in DS concentration (Fig. 5). At a DS concentration of 0.5 M an average R_e of 98.9 ± 3.22 mL was achieved followed by a concentration of 1 M (199.4 ± 9.6 mL) and 2 M (358.7 ± 22.1 mL). Additionally, the increase in DS concentration also dramatically reduced SEC due to greater R_es obtained owing to SEC of a FO system regulated by two factors, viz. (i) pump power and (ii) the rate of permeate through the membrane.

Further observations from Fig. 6 demonstrates that a flow rate of 100 mL/min combined with an increased DS concentration resulted in the lowest SEC. On average for FO and PRO modes at 100 mL/min, the SEC decreased by approximately 42% from at a DS concentration increase from 0.5 to 1 followed by an additional 57% reduction in SEC with a DS increase from 1 to 2 M. J_w is determined by the effective osmotic driving force across the membrane. As OP is a colligative property, an increase in DS concentration will lead to an increase in the OP which in turn produced an increased J_w and R_e which resulted in a reduction in SEC. A study by Xiang et al. [26] also reported a reduction in SEC with an increase in DS concentration whilst utilising a liquid fertiliser as DS and wastewater as an FS using a submerged FO system.

3.4. Effects of membrane orientation on performance and specific energy consumption

Figs. 7 and 8 provide the J_w; FS EC and R_e for FO and PRO mode orientations with SBW5 as the FS at different KCl concentrations and flow rates, respectively. It was noted that for a DS concentration of 0.5 M the PRO mode produced approximately 5.3% greater R_e compared to the FO mode. Conversely, at a DS concentration of 1 and 2 M, the FO mode produced 5.4 and 7.0% greater R_e compared to the PRO mode. A greater difference in J_w and R_e was observed at a DS

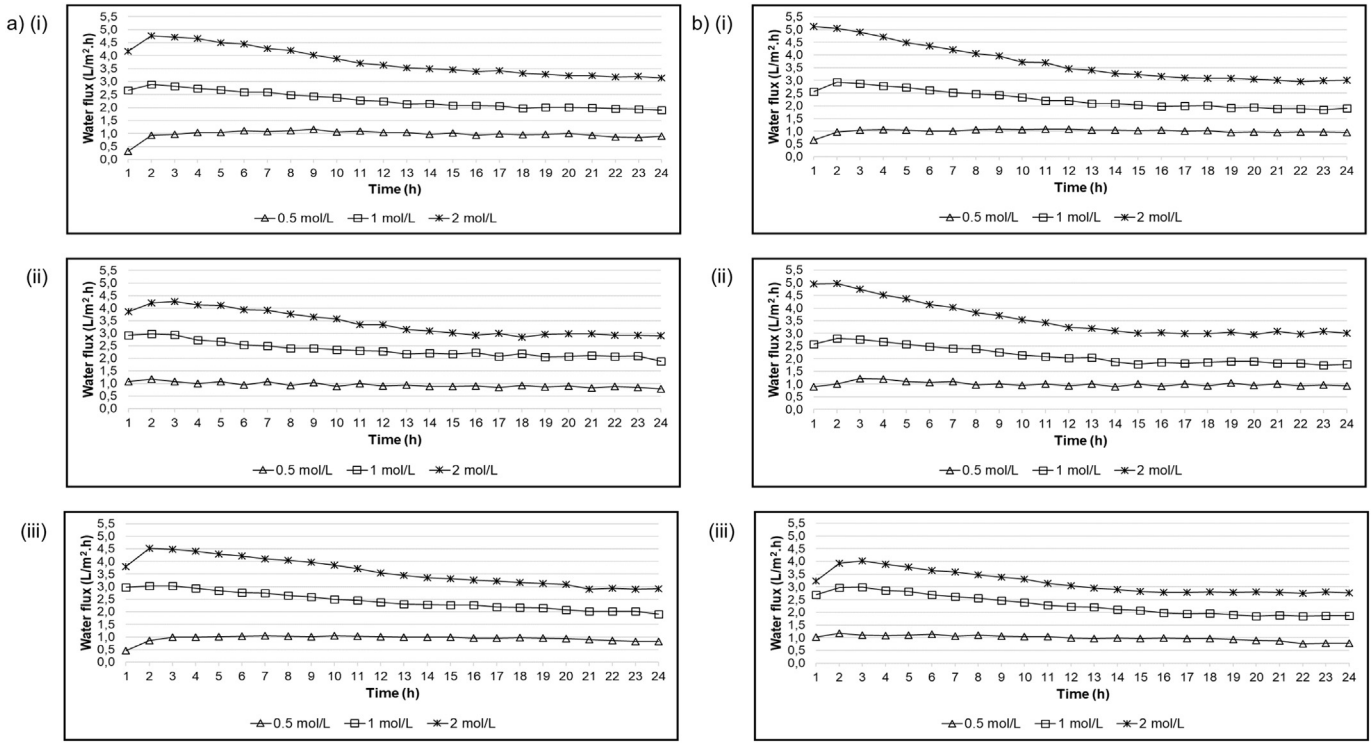

Fig. 4. Water fluxes (J_w) obtained during a 24 h operation for DS concentrations of 0.5, 1 and 2 M KCl with SBW5 as the FS whilst operating in a) FO and b) PRO modes at flow rates of i) 100, ii) 200 and iii) 400 mL/min, respectively.

concentration of 2 M and a flow rate of 400 mL/min. Here, the FO mode produced a J_w of 3.8 L/m^2·h compared to the PRO mode which achieved a J_w of 3.2 L/m^2·h. As can be seen from Fig. 7, for the majority of conditions performed below, the PRO mode produced a slightly improved J_w at the start of the experiment compared to the FO mode which is similar to previous reports that indicated that initial J_w is greater in the PRO mode than the FO mode [2,30].

Fig. 8 shows that the FS EC is dependent on J_s and R_e and with similar R_es obtained between orientations it can be concluded that J_s had to have been similar between FO and PRO modes. However, at a DS

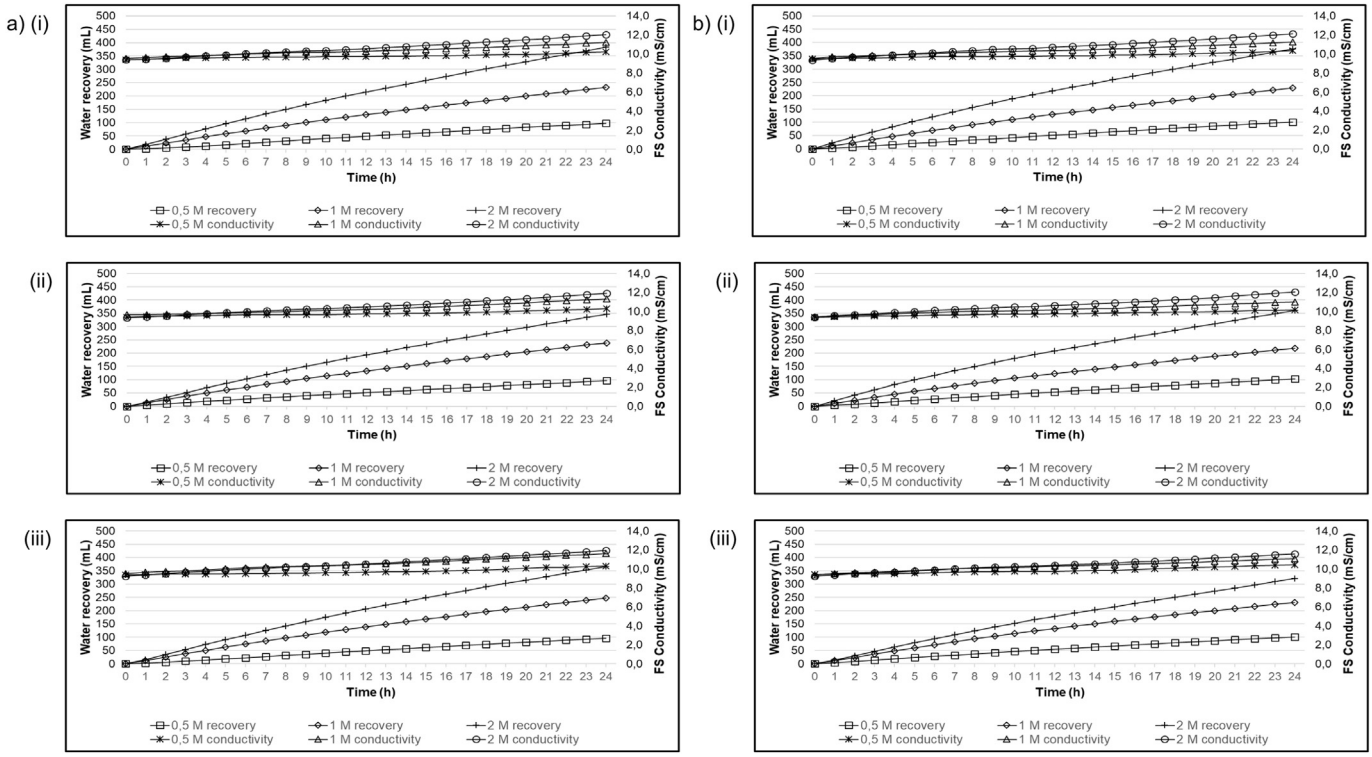

Fig. 5. Feed solution electrical conductivities (FS ECs) and accumulative volume of water recoveries (R_e) obtained during a 24 h operation for DS concentrations of 0.5, 1 and 2 M KCl with SBW5 as the FS whilst operating in a) FO and b) PRO modes at flow rates of i) 100, ii) 200 and iii) 400 mL/min, respectively.

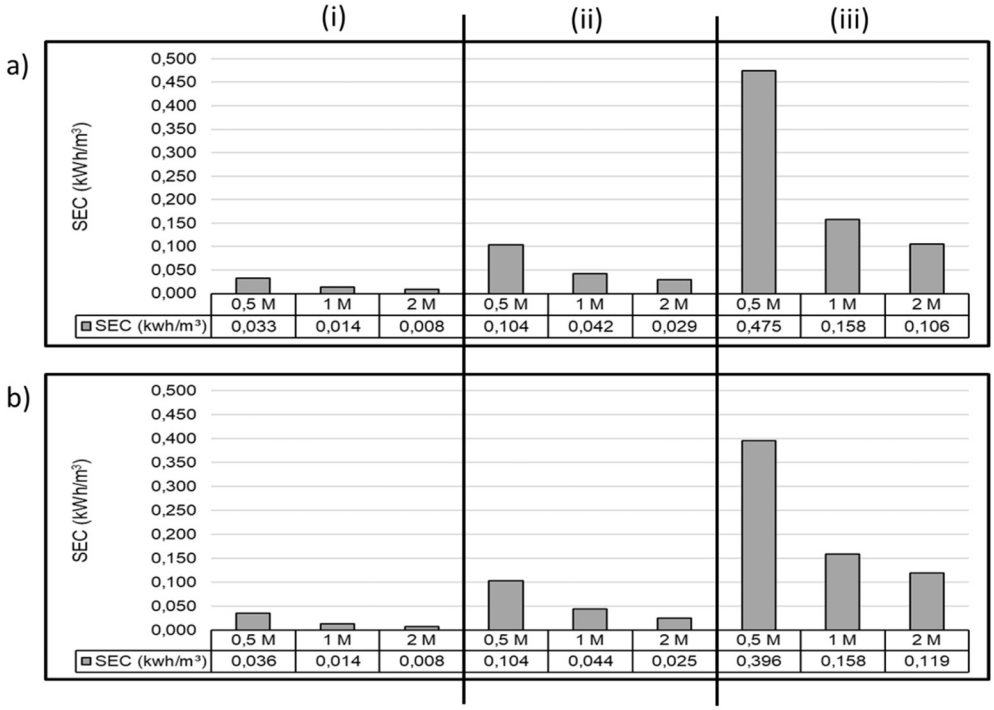

Fig. 6. SEC consumption comparison in a 24 h operation between a) FO and b) PRO mode with SBW5 as an FS at different KCl DS concentrations of 0.5, 1 and 2 M and flow rates of i) 100, ii) 200 and iii) 400 mL/min, respectively.

concentration of 2 M at a flow rate of 400 mL/min the FS EC was nearly identical. However, the PRO mode recovered 11.4% less water compared to the FO mode. This indicates that greater J_ss occurred during the PRO mode compared to the FO mode, which is in agreement with the literature [2].

As previously shown in Fig. 6, the membrane orientation also did not contribute to a significant change in SEC. Considering the only energy consumed by FDFO system was by the circulation pump, the pump energy consumption was unaffected by the membrane orientation. The only significant difference in SEC was at a DS concentration of 0.5 M and flow rate of 400 mL/min. This was attributable to the PRO mode producing a marginally improved initial J_w than the FO mode.

3.5. Effects of flow rate on performance and specific energy consumption

Fig. 9 represents the R_e comparison between FO and PRO mode membrane orientations with SBW5 as an FS at different KCl DS concentrations and flow rates, respectively.

The increase in system flow rate resulted in minimal effects on J_w and R_e. However, a DS concentration of 2 M and flow rate of 400 mL/min resulted in the greatest deviation in J_w and so water R_e. Fig. 9(a) in the FO mode indicates at a flow rate of 100 mL/min achieved the greatest R_e (J_w = 4.8 L/m^2·h) followed by 400 mL/min (J_w = 4.5 L/m^2·h) and 200 mL/min (J_w = 4.3 L/m^2·h), respectively. Whilst from Fig. 9(b) in the PRO mode, the greatest R_e was obtained at a flow rate of 100 mL/min (J_w = 5.1 L/m^2·h) followed by 200 mL/min (J_w = 5.0 L/m^2·h) and 400 mL/min (J_w = 4.0 L/m^2·h), respectively. Preferably an increased system flow rate ought to produce an improved J_w and so R_e owing to the reduction in external concentration polarisation (ECP) layer by reason of the increased shear forces at the membrane surface [26]. However, as can be seen, no significant difference in J_w and so R_e was obtained.

FS EC was also unaffected at flow rates of 100, 200 and 400 mL/min at DS concentration 0.5, 1 and 2 M, respectively. The upsurge in flow rate did, however, contribute to a significant SEC increase (Fig. 6). At a DS concentration of 2 M, SEC tripled from 0.008 kWh/m^3 to ± 0.027 kWh/m^3 for 100 to 200 mL/min, respectively, and quadrupled to ± 0.113 kWh/m^3 for 400 mL/min. It was anticipated that increased flow rate gives rise to SEC by way of the pump consuming more power in order to force greater flow rates. A study by Xiang et al. [26] and Zou and He [29] both concluded that the increase in system flow rate increased J_w marginally, however, significantly contributed to an increased SEC.

4. Conclusions

Results obtained from this study demonstrated the CTA membrane to be robust as no damage to the active layer was observed after repeated use. The repeated use of the CTA membrane resulted in reduced water fluxes due to ineffective cleaning of the membrane support layer. Whilst it is difficult to compare energy consumption due to different scales and operating conditions, this study also illustrated an FDFO as a stand-alone system that do not require a regeneration step as a potentially lower energy consuming process for the recovery of water from brackish water, whilst at the same time producing a diluted fertiliser solution that will require further dilution depending on the fertigation application. The process parameter which largely contributed to an increase in system performance and reduction in SEC was the increase in DS concentration. Membrane orientation and flow rate indicated minimal effects on system performance. However, a flow rate change did affect the SEC significantly. Based on results for this application, a FO mode membrane orientation with a lower system flow rate combined with a relatively high DS concentration should be considered in order to obtain the lowest possible SEC. Although extremely low SEC values were obtained in this study, the relative size of an actual pilot plant should be taken into account to better understand in what manner process factors affect system performance and energy consumption. Additionally, the severity of concentration polarisation on reduced J_w observed in this study is apparent and should be considered a major factor when considering re-using FO membranes.

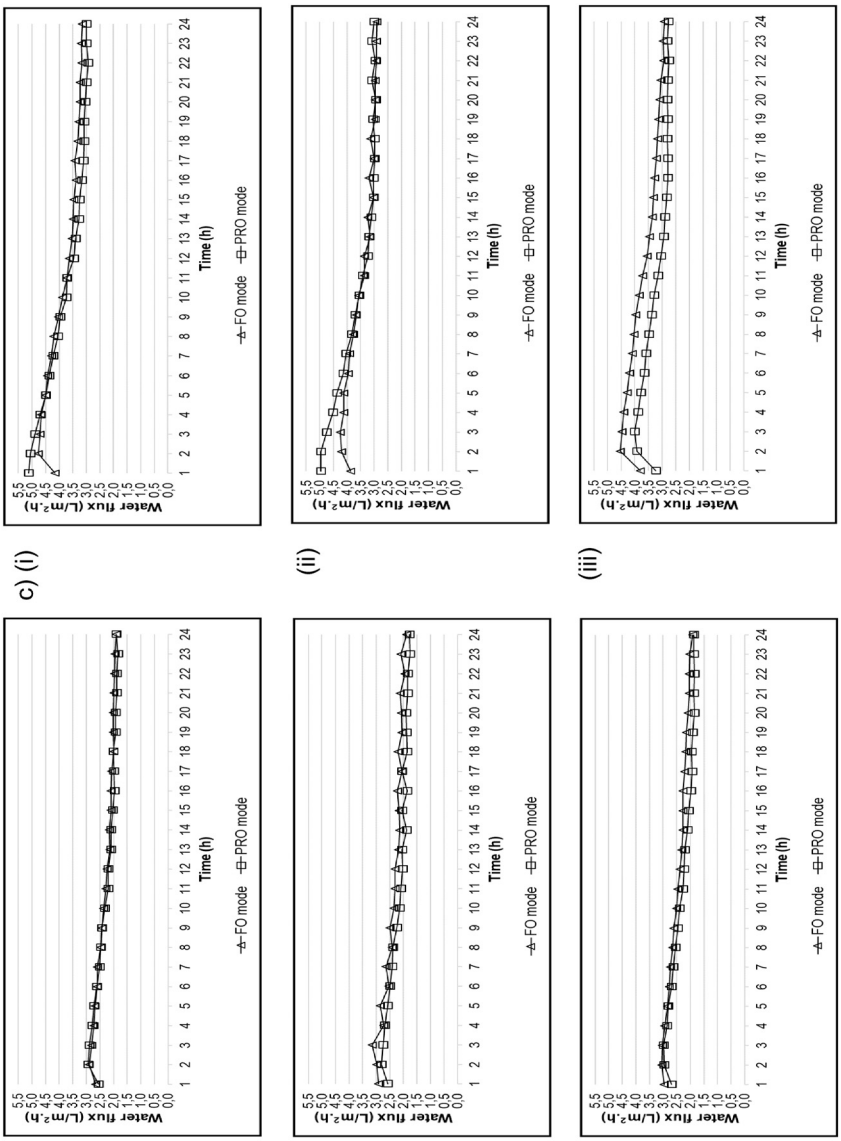

Fig. 7. Water fluxes (J_w) obtained during a 24 h operation for FO and PRO modes at DS concentrations of a) 0.5, b) 1 and c) 2 M KCl with SBW5 as the FS at flow rates of i) 100, ii) 200 and iii) 400 mL/min, respectively.

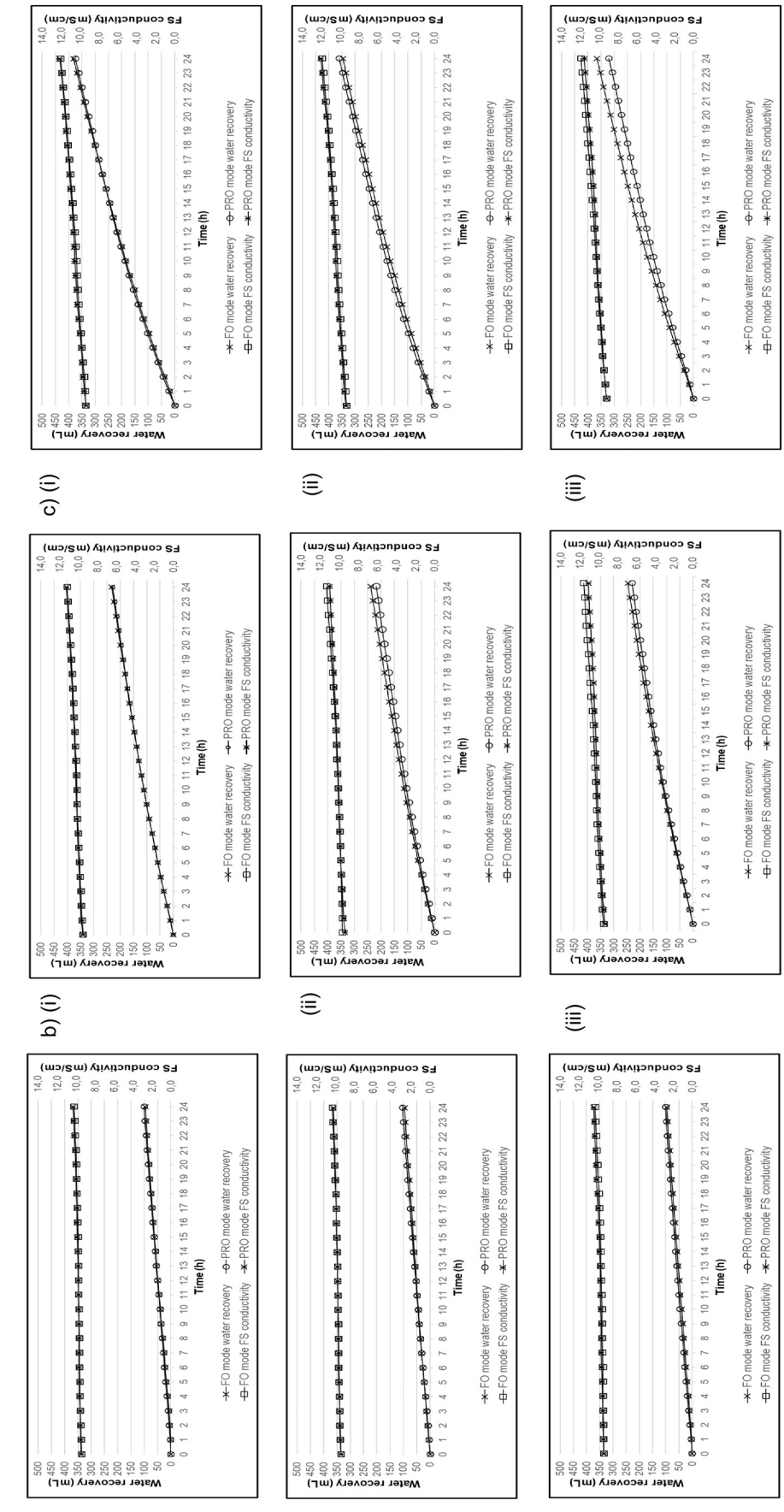

Fig. 8. Feed solution electrical conductivity (FS EC) and accumulative volume of water recovered (R_e) obtained during a 24 h operation for FO and PRO modes at DS concentrations of a) 0.5, b) 1 and c) 2 M KCl with SBW5 as the FS at flow rates of i) 100, ii) 200 and iii) 400 mL/min, respectively.

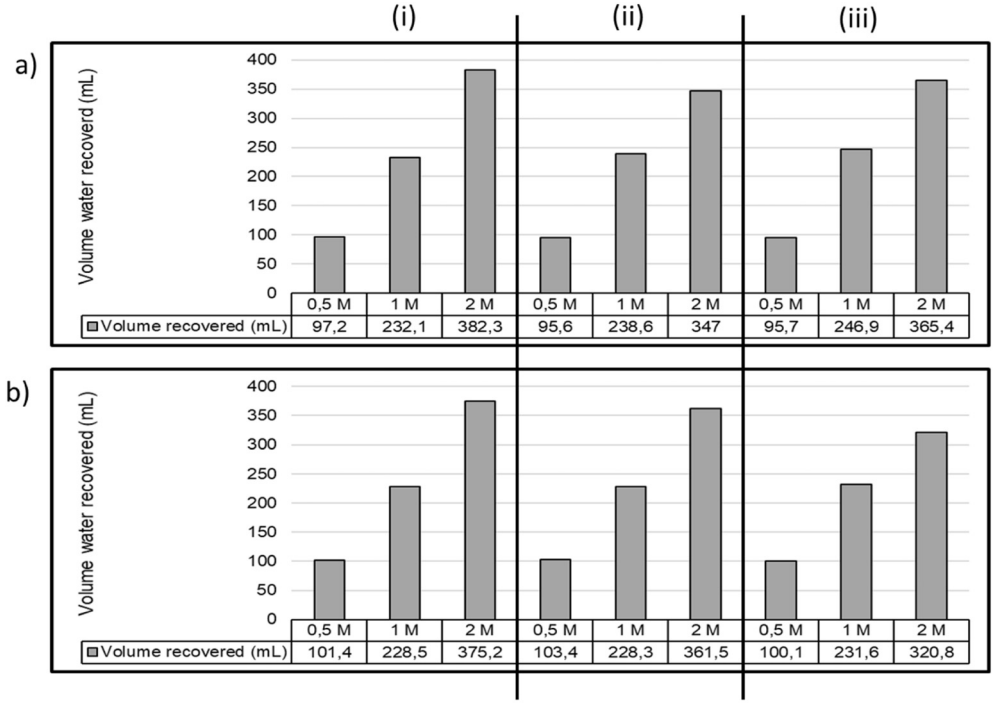

Fig. 9. Accumulative volume of water recovered (R_e) comparison in a 24 h operation between a) FO and b) PRO mode with SBW5 as an FS at different KCl concentrations of 0.5, 1 and 2 M and flow rates of i) 100, ii) 200 and iii) 400 mL/min, respectively.

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