Brine management from desalination plants for salt production utilizing high current density electrodialysis-evaporator hybrid system: A case study in Kuwait

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ABSTRACT

The potential of producing salt and low salinity water by treating synthetic brine was investigated in a pilot-scale electrodialysis-evaporator hybrid system as part of brine management. An electrodialyzer with 25 cell pairs of monovalent selective anion exchange membranes (AEMs) and monovalent selective cation exchange membranes (CEMs) were used. Effect of three different current densities (300 to 500 A/m^2) and two different flowrates (400 L/h and 450 L/h) on brine treatment were evaluated in the current study. The results indicated that the aforementioned membranes were efficient in separating monovalent ions over divalent ions. Moreover, higher current density operation was favoured during the electrodialysis (ED) operation as the operation time for producing salt was shorter. Flowrate is a crucial parameter for the operation of the ED system, where higher flowrate (by 12.5%) reduced the operation time (by 30 min), reduced energy consumption (by 32%) and reduced system resistance (by 32.42%) leading to an increase in current efficiency (by 31.4%). The concentrated brine effluent from ED was fed to an evaporator to produce coarse salt with 84.75% salt recovery and low salinity water of 1526 ppm. Thus, ED-evaporator hybrid system was found to be a good option to treat reject brine from desalination plants.

1. Introduction

Water is an essential source of survival for mankind. With the continuous rise in the world's population and pollution of existing freshwater resources, water scarcity has become a global concern [1]. According to World Health Organization (WHO) 2017, there is no access to a reliable source of safe drinking water for over 1 billion people and about 2.3 billion people live in areas of severe water scarcity. Seawater desalination has become an important solution for water shortages near the coastal regions [2]. Up to 95 million m^3 of desalinated water is produced daily through 15,906 different desalination technologies worldwide [3]. Of the total, 48% of desalination plants are located in the Middle East and North Africa region. One of the leading desalination technologies is reverse osmosis (RO) as it produces 69% of total global desalinated water followed by multi-stage flash (MSF), multi-effect distillation (MED), nanofiltration (NF) and electrodialysis (ED) [3]. Kuwait has a severe arid climate [4], with low annual rainfall,

and an extremely limited freshwater resource. Kuwait mainly depends on costly MSF process for converting seawater to freshwater, since the 1950s [5]. Kuwait has nine desalination plants located along the gulf coast, seven of which operate with MSF technology, and the rest operate using RO technology [6]. Kuwait accounts for 3.7% of the desalination capacities located in the Middle East and North Africa region [3].

Despite the type of desalination plant, disposal of reject brine from desalination plants into the seawater is a crucial environmental issue. Reject brine contains high salinity, high temperature and residual chemicals from pre-treatment processes, which cause potential damage to the marine and underground habitat [7,8]. While large scale desalination has been a mainstay in the world for many decades, management of high concentration brine has posed technological, economic and environmental challenges [9]. Several studies on brine management have been carried out to mitigate the impact on the environment and to recover valuable elements from it [10,11]. Some of the brine

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management systems include recovery of salt and minerals for commercial purposes, metal recovery, the adaptation of brine for industrial usage, and production of reusable solid product (sodium bicarbonate) [12].

ED is a feasible, cost-effective and environmentally friendly process to treat RO effluent, which has been widely used in water treatment [13,14]. Several studies show the ability of ED technology to treat high saline water. Casas et al. [15], and Reig et al. [16] employed ED as a technological solution to recover NaCl from RO brines, which was then used as a raw material in the chlor-alkali industry. In the study done by Zhang et al. [13], a three-stage ED operation was applied to treat real brine solution with 2 membrane sets (CIMS/ACS and CSO/ASV). They found that the separation performance of CIMS/ACS membranes was superior to CSO/ASV membranes, and also lowering the current density was effective to improve the monovalent ion selectivity. Abdel-Aal et al. [17] showed the capability of ED to desalinate both brackish water and high saline water. Their study also highlighted the effectivity of combining RO and ED systems for pre-treatment, water recovery enhancement and brine effluent reduction. Jiang et al. [18] have used a lab-scale ED stack to treat concentrated synthetic brine using a series of FAS-PET-130, FKS-PET-130, Neosepta-CMX, Neosepta-AMX, LabAM-NR and LabCM-NR membranes. Their main focus was to investigate the effect of different membranes on desalination efficiency and water recovery rate. Their findings reported that high total dissolved solids (TDS) brine could be used to produce coarse salt, edible salt and freshwater from the desalinated brine. Chen et al. [19] evaluated a novel electrodialysis metathesis (EDM) technology to efficiently convert and pre-concentrate reverse osmosis brine effluent into high solubility liquid salts. Y. Zhang et al. [20] investigated the separation efficiencies of monovalent to multivalent ions, from organic solutes using two types of AEMs (monovalent selective AEM and a nonselective AEM), by passing through different conditions (changing initial pH or initial current density). They reported that reducing the current density can help to separate the monovalent anions from the multivalent anions with either of the membranes. The same authors also showed that lowering the current is an effective way than increasing pH, to improve the permselectivity of the monovalent AEM membrane. Korngold et al. [21] and Korngold et al. [22] used ED technology to reduce the volume of RO brine effluent and its disposal cost. The scaling of the membranes was reduced by passing the brine through a separate $CaSO_4$ precipitation tank containing gypsum seeds. Nayar et al. [23] have studied the feasibility of fully hybridizing RO with ED along with optimizing ED current densities to produce brine with a salinity of 120 g/kg. According to their study, the optimisation helped to reduce the brine concentration costs by 33–70% when compared to standalone ED systems. Mavukkandy et al. [25] reviewed recent research and technologies on recovering resources from desalination brine. Membrane distillation in combination with other technologies proved to have the highest potential because of its low energy requirement. Tanaka et al. [26] proved that salt production from RO brine effluent using ED is more energy-efficient than seawater treatment using the same technology. Nayar et al. [24] used RO brine instead of seawater in the ED diluate stream of integrated RO-ED-crystallizer system and found that it reduced the water production cost by 87% but increased the salt production costs by 26%. A qualitative and quantitative study on the effects of operational factors was done by Karimi et al. [27], by implementing a full factorial experiment at three different levels of voltage per cell, temperature, superficial velocity and feed water composition using a laboratory-scale ED setup. Karimi's study proved that the effects of the ion-type and feed composition are important at lower applied voltages; and the effect of the increased voltage will increase the ion removal in a non-linear action. ED being a technology that operates using direct current, can also benefit from the use of solar energy. Gonzales et al. [28] have used a pilot-scale solar-powered ED unit to purify brackish water, the total electricity consumption of that system ranged approximately between 5.46 kWh/m³ and 6.98 kWh/m³.

Panagopoulos et al. [1] evaluated the disposal methods of brine and its treatment technology. They pointed out that direct discharge of the brine into the open sea bodies is never an environmentally sustainable solution. They concluded that a combination of membrane and thermal-based technologies in a zero liquid discharge (ZLD) manner was found to be a good alternative to brine disposal since dual aims of obtaining freshwater and other useful resources can be achieved. Semblante et al. [29] discussed the importance of brine pre-treatment in membrane-based ZLD systems. The most commonly practiced technology in pre-treatment is chemical precipitation, however it is generally costly due to its high chemical consumption. Electrocoagulation and nanofiltration were discussed to have promising performance in hardness and organic removal. Y. Zhang et al. [30], investigated the feasibility of decarbonisation, as a pre-treatment process to minimize the scaling potential of feed stream or concentration stream and to operate the ED installation for a long term. Additionally, ion transport mechanisms and membrane separation efficiency were also investigated in their study.

The current study investigates the viability of utilizing an ED-evaporator hybrid system in treating synthetic brine water. A systematic approach to optimize the operating conditions for the pilot-scale ED equipment fitted with monovalent selective ion- exchange membranes consisting of three tanks (diluate tank, concentrate tank, electrolyte tank), to treat synthetic brine to produce freshwater and coarse salt, were carried out. In particular, a concentrated brine-concentrated brine (CB-CB) multi-batch series ED method, with internal recirculation of the concentrate effluent was investigated by feeding the effluent from the preceding stage to the next stage, as a solution towards reaching higher salt concentration at a shorter time. This was achieved by preparing synthetic brine with concentrations equal to actual reject brine from MSF plants in Kuwait. The reason for doing such a study is to assess the performance of ED stack in treating synthetic brine before employing it to treat actual reject brine from local desalination plants. Currently, MSF plants in Kuwait discharge the brine effluents after mixing it with a portion of seawater to the Kuwait coast where the bathymetry is extremely shallow [31]. Operational parameters, such as current density and feed flowrate, and their effects on current efficiency, operation time, ion removal rate and water recovery were studied utilizing PCCell P05 ED pilot plant and synthetic brine solution. This study also reports a detailed description of the challenges encountered while carrying out the experiments.

2. Materials and methods

2.1. Materials

Selected salt, mainly sodium chloride was added to tap water to form the brine feed solution used in this study. The concentration of the synthetic brine was chosen to be in between 65,000–68,000 ppm to mimic reject brine from Kuwait desalination plants. The reagents used to prepare the synthetic brine water were of commercial-grade (97–99% purity). Compositions of synthetic feed solutions and tap water are given in Table 1.

Table 1
Properties of synthetic salt solutions (S) and tap water (T) used in the experiments.

Properties	Concentrations (S)	Concentrations (T)
Conductivity (μs/cm)	98,380.00	240.70
TDS (ppm)	67,602.00	107.00
Sodium (ppm)	30,854.60	13.04
Magnesium (ppm)	7.81	2.09
Calcium (ppm)	32.92	19.49
Potassium (ppm)	10.73	0.42
Chloride (ppm)	47,498.00	24.29
Sulphate (ppm)	779.20	14.26

Table 2
Characteristics of PC-MVA and PC-MVK membranes[a,b].

Membrane	Thickness (μm)	pH stability	Transference number	Area resistance (Ωcm^2)	Burst strength (kg.cm^{-2})	Max. temperature (°C)
PC-MVA	110	0–9	> 0.97	20	2	60
PC-MVK	100	0–10	> 0.97	–	3	40

[a] The data were collected from the product brochure provided by the manufacturer.

[b] PC-MVA and PC-MVK membranes have been procured from PC Cell- GMbh along with the PC Cell P05 pilot ED unit.

2.2. Electrodializer cell and membranes

PCCell P05 pilot-scale ED was used to conduct the current study that comprises 25 cell pairs of monovalent selective AEMs and monovalent selective CEMs, which are placed between a pair of titanium electrodes coated with platinum. Each cell pair comprises 1 CEM, 1 AEM and 2 spacers (diluate and concentrate) with a total of 25 parts of AEM (PC-MVA) and 26 parts of CEM (PC-MVK). Characteristics of the AEM and CEM are given in Table 2. The membranes are separated by 24 pairs of spacers, which are made of polypropylene, having a thickness of 0.5 mm each. Each membrane has a dimension of 300*500 mm with an active membrane area of 0.1m^2. The migration of ions across the membranes occurs due to the electrical potential difference created. As a result of this behaviour, ion concentration increases in the concentrate stream but depletes in the diluate stream. A schematic view of the ED stack is shown in Fig. 1.

2.3. Electrodializer set up and experimental procedure

The electrodializer used in this study is a pilot-scale ED unit PC Cell ED 1000H (PC Cell GmbH, Heusweiler, Germany). It consists of 3 tanks- a concentrate tank and a diluate tank of 70 L capacity each, and an electrolyte tank of 35 L capacity. A sodium sulphate solution of 60 ppm was used to form the electrolyte solution. Fig. 2 (a) illustrates a schematic setup of the ED used in the present study. The experiments were carried out in a batch mode with 3 different high current densities (I_d) (300, 400 and 500 A/m^2) and 2 flowrates (Q) of 400 and 450 L/h in a concentrated brine-concentrated brine (CB-CB) multi-batch series ED method (Fig. 3). Currents applied were 30A, 40A and 50A which were equal to 300, 400, 500 A/m^2, respectively in current densities as the active membrane area was 0.1m^2. Concentrate and diluate compartments were filled initially with synthetic brine solution. At the end of each run, when the concentration of the solution in diluate stream reached below a certain limit of 2000 ppm, the concentrated solution effluent from the first run was recycled into the ED unit, thus replacing the diluate compartment for the next run of the CB-CB method. This was repeated until the maximum concentration was achieved. The final concentrate effluent was then sent for evaporation to produce coarse salt as the final product using a rotary evaporator (Fig. 2(b) (BUCHI Rotavapor R-200, Switzerland)). Thus, coarse salt and freshwater were produced from the concentrate and the diluate compartments, respectively. After each experiment, samples were taken for analysis. Specific conductance and pH were measured using Accument AB200 (Fisher Scientific, Singapore). The concentration of cations Na$^+$, K$^+$, Mg^{2+}, Ca^{2+} were measured using a microwave plasma-atomic emission spectrometer (MP-AES, Agilent: 4200, Australia) and the contents of the anions were analysed using ion chromatography-mass spectrometry (IC-MS, Metrohm 850, Switzerland). Finally, the fouled up membranes were sent to a local laboratory for carrying out the scanning electron microscope (SEM) (JSM-6010LA, Japan) analysis.
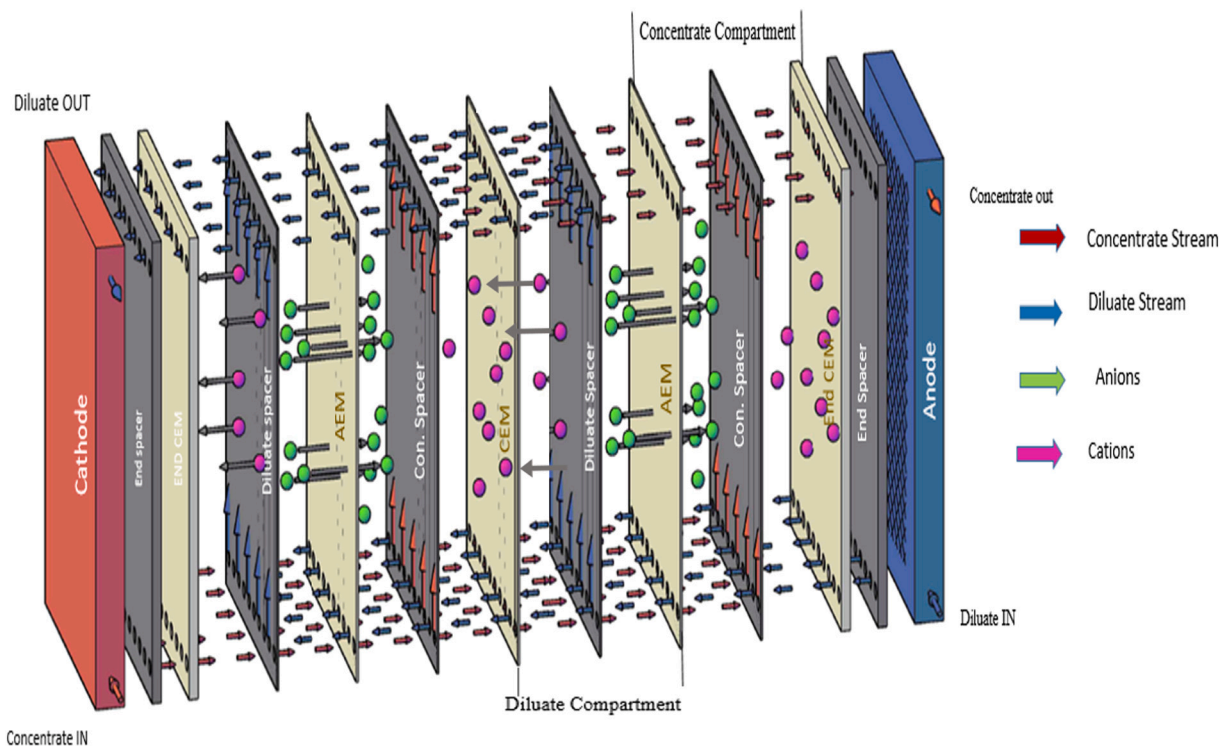
Fig. 1. Exploded schematic of the ED stack, showing the flow pattern of the ions in the presence of the electric field. The diagram also shows the formation of diluate and concentrate compartments.
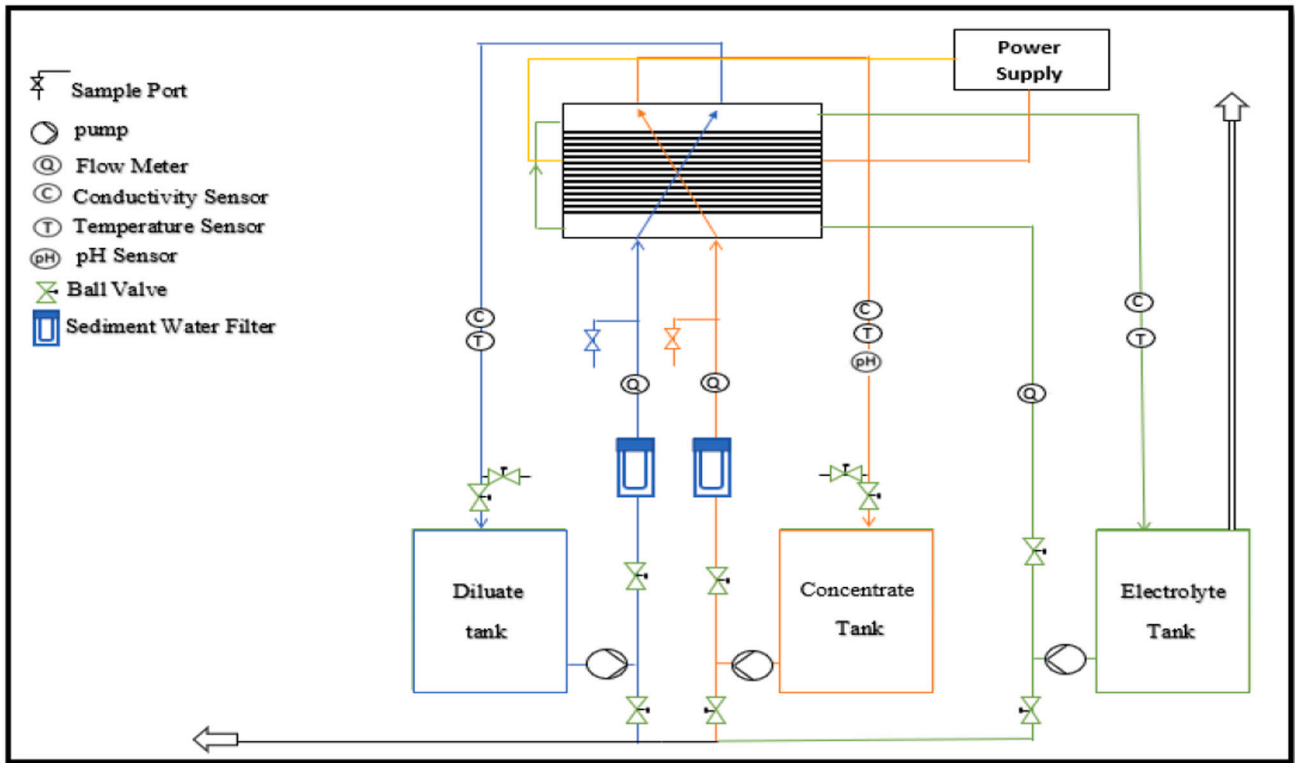
a)
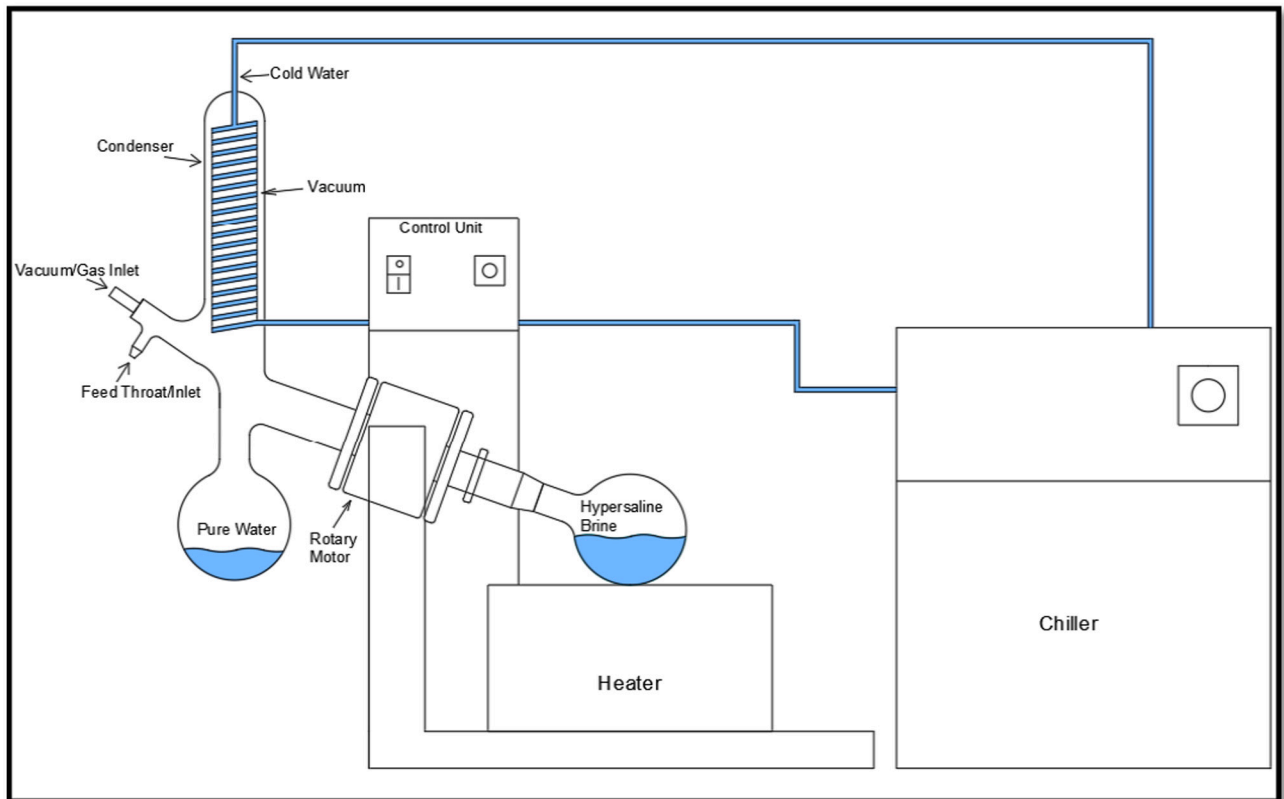
b)

Fig. 2. Schematic diagram of the (a) ED unit and (b) rotary evaporator used in our experiment.
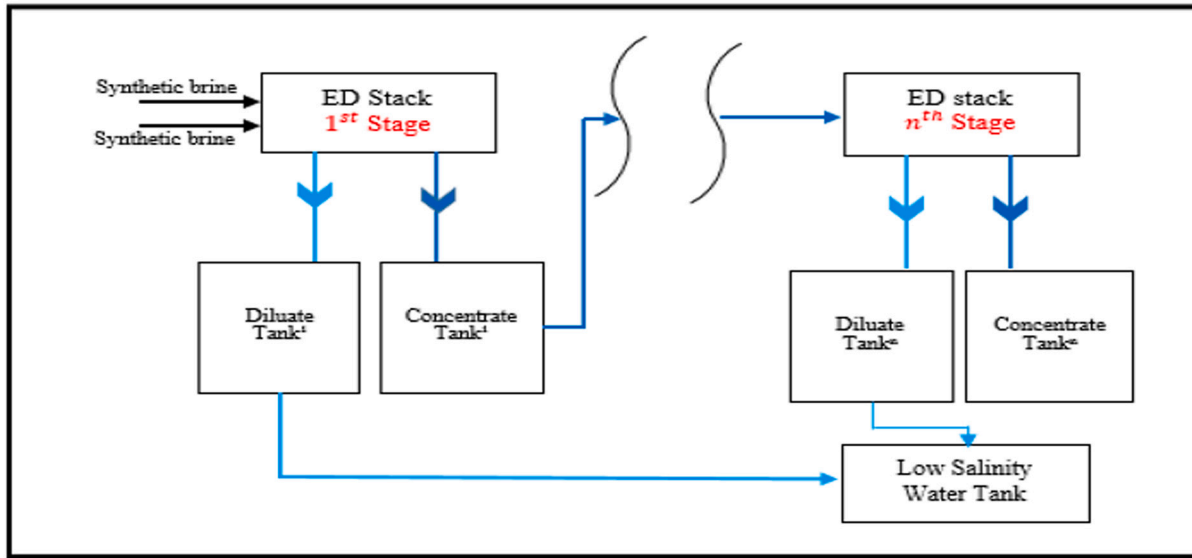
Fig. 3. Flow chart for concentrated brine-concentrated brine (CB-CB) multi-batch ED series method.

2.4. Formulas used for salt production metrics

2.4.1. Ion removal rate

Total ions removed from diluate tank is calculated by the ion removal rate Eq. (1) [13] described below,

$$R = \frac{C_i - C_f}{C_i} \times 100\% \tag{1}$$

where R is the ion removal rate, C_i and C_f are the initial and final concentrations of the diluate tank (ppm) respectively.

2.4.2. Water recovery

Water recovery rate is calculated using Eq. (2) [18],

$$W = \frac{V_f}{V_i} \times 100\% \tag{2}$$

where V_i and V_f are the initial and final volumes of the diluate tank (L).

2.4.3. Current efficiency

Current efficiency (CE) measures the ability of an ED stack in transporting ions through the ion exchange membranes under a given applied current [32]. The current efficiency is calculated using the following Eq. (3) [13],

$$CE = \frac{zFV_t(C_t - C_0)}{NIt} \times 100\% \tag{3}$$

where C_0 and C_t are the initial and final concentrations of the concentrate tank (mol/L), z is ion charge, F is Faraday number (96,485 A s/mol), V_t is the volume of the concentrate tank (L) at time t, N is the number of cells pairs, I is the current (A), t is the operation time (s).

2.4.4. Energy consumption

The energy consumption for the desalination process is calculated using the following Eq. (4),

$$E = \frac{I \times U \times t}{1000} \tag{4}$$

where E is the energy consumption, I is the current (A), U is the voltage (V) and t is the operation time (hr).

3. Results and discussion

3.1. Effect of different current densities and feed flowrates on the operation time and solution concentration

It is a known fact that current densities influence the concentration of the concentrate compartment because of the applied electric field across the ED unit. Generally, varying the current density affected the operation time of the process at different flowrates. The influence of different applied current densities on solution concentration and operation time for two flowrates is depicted in Fig. 4, which shows that solution concentration increased with current density reaching higher concentrations at a shorter operation time. This is due to the enhancement of the mass transfer of ions across the ED with current densities [13]. For example, the maximum solution concentration value of 180,000 ppm (TDS) was achieved at a duration of 480 min faster when the current density was increased by 66.6% (300 A/m² to 500 A/m²) at constant feed flowrate (400 L/h). The operation time reduction was improved by 30 min (from 510 to 480 min) when the feed flowrate increased by 12.5% (400 to 450 L/h) because higher flowrates moderate the effect of concentration polarization [32].

3.2. Effect of feed concentration and flowrate on current efficiency

It is worth noticing that CE is a function of several variables $V_t, \Delta C, I$ and t that are changing simultaneously. Generally, CE increases with the product of volume and concentration difference across the ED stack $(V_t \Delta C)$ and decreases with the product of current and operation time (It). As aforementioned, since all foregoing terms are changing simultaneously, CE values vary according to predominate terms.

Despite this, the study focused on the effect of operational conditions namely C and Q on CE. As shown in Fig. 5, lower current efficiency was achieved at higher inlet feed concentrations at the same flowrate. For example; when the feed concentration increased, through the seven runs, from 65,000 to 175,000 ppm, the current efficiency decreased by 90% (from 50% to 5%). This suggests that few runs should be conducted for optimum results. This is due to the reduction of the electrical resistance of the solution (since CE correlates to the resistance) that enhances the migration of the ions across the ion-exchange membrane along the ED stack. This can be attributed to the electro-osmosis that predominates at such conditions (higher current densities). To illustrate this further, Fig. 6 was generated to show the
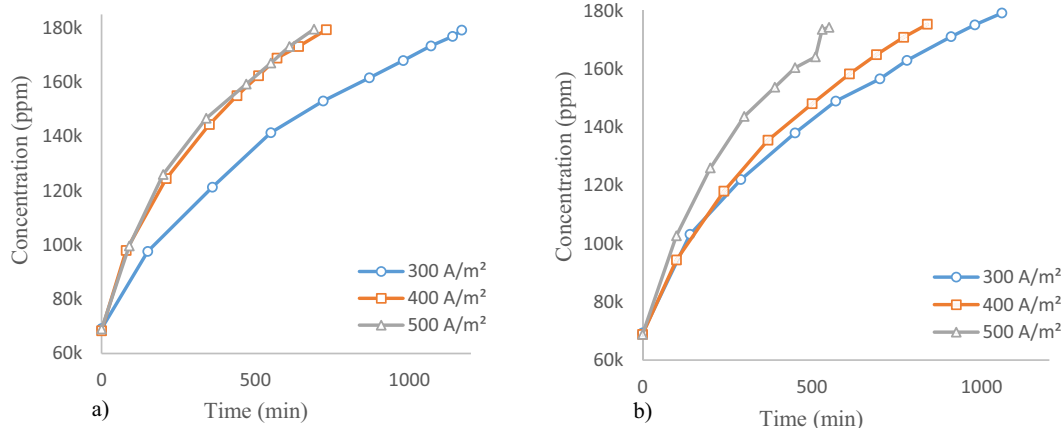
Fig. 4. Process operation time by a) 400 L/h and b) 450 L/h flowrates at different current densities.
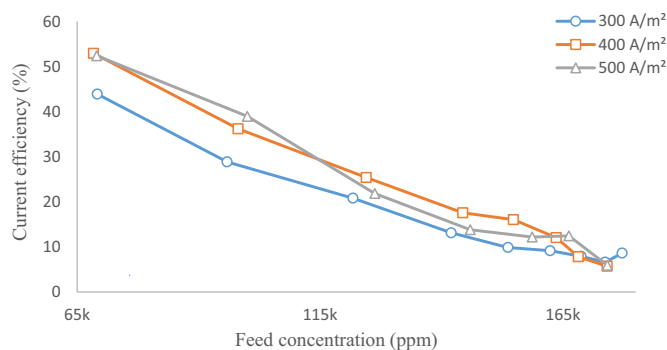

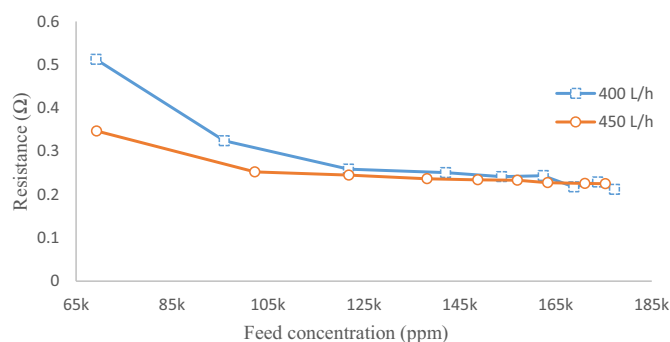Fig. 5. Current efficiencies for the flowrate 400 L/h at different current densities.

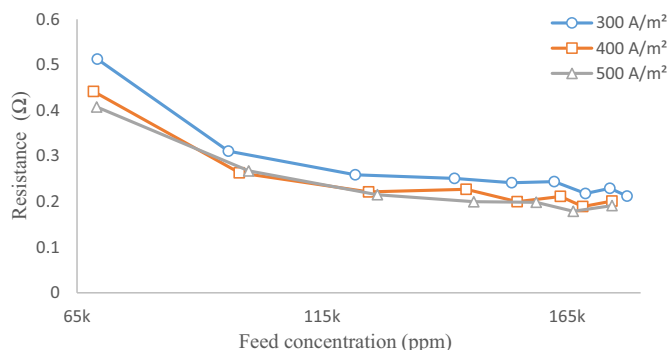Fig. 8. System resistances for the feed flowrates (400 L/h and 450 L/h) at 300A/m².

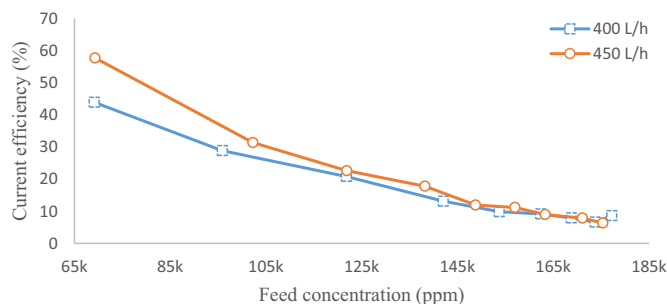Fig. 6. System resistances for the flowrate 400 L/h at different current densities.

Fig. 7. Effect of feed flowrate on current efficiency at current density of 300A/m².

effect of feed concentration on the system resistance. One can see clearly that the system resistance shares a similar trend of CE, decreasing with feed concentration. This means that lower CE values were achieved at lower resistance values for fixed current densities and flowrate and vice versa.

Another graph was generated to show the effect of feed flowrate on CE performance of the ED stack. Fig. 7 shows the effect of the feed flowrate on CE at a fixed current density (300 A/m²). Flowrate effect is more pronounced at lower feed concentration with higher CE values at higher flowrates because higher flowrate reduces the resistance of the system (Fig. 8) through moderating the effect of concentration polarization as mentioned elsewhere [32]. This effect diminished at higher feed concentration where the system resistance is substantially overcoming the slight increase in the feed flowrate (12.5%) coupled with the reduction of ED ion-exchange performance with repeated batch mode operations for the same ED stack.

The back-diffusion effect is a measure of the coulombic efficiency that is equal to the amount of electric charge transported by the ions over that applied to the ED system [35], where coulombic efficiency decreases with back diffusion. Glama et al. [35] found that high coulombic efficiencies (0.85–1.05) were achieved at higher densities (50–300 A/m²) concluding that back diffusion is less pronounced compared to the immigration of ions in the opposite direction at such current densities. This suggests that in the current study, where even higher current densities were used (300–500 A/m²), the back diffusion effect is negligible compared to that of the transported ions.

3.3. Performance of the monovalent selective ion exchange membrane

To understand the performance of the monovalent selective membranes, the total monovalent ions removed from the diluate tank were
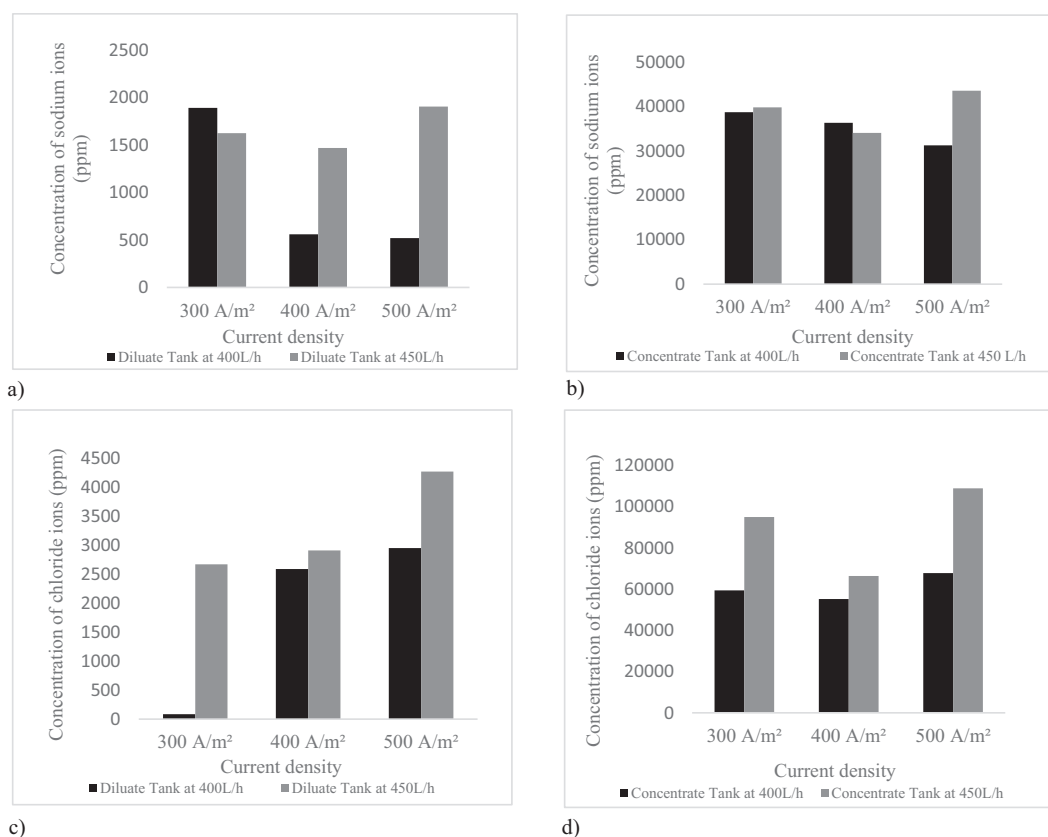
a)

b)

c)

d)

Fig. 9. a, b) Concentration of Na^+ ions in diluate and concentrate tanks and, c, d) concentration of Cl^- ions in diluate and concentrate tanks after the first stage of desalination at various current densities and flowrates.

Table 3

Ion removal rate calculated from the diluate tank for 400 L/h and 450 L/h flowrates.

Ion concentration levels	400 L/h			450 L/h		
	300 A/m^2	400 A/m^2	500 A/m^2	300 A/m^2	400 A/m^2	500 A/m^2
Ca^{2+}	97%	86%	91%	98.48%	80%	75%
K^+	98%	96%	90%	78%	56%	41%
Na^+	94%	98%	98%	95%	96%	94%
Mg^{2+}	89%	79%	89%	96%	73%	50%
Cl^-	99.8%	95%	94%	94%	94%	91%

analysed. Fig. 9 (a, b, c and d) shows the change in concentration of Na^+ and Cl^- ions in the concentrate tank as well as in the diluate tank after the first stage of desalination. We have compared the performance of the membranes through its ion removal capacity also.

3.3.1. Effect of current density on ion removal rate

In this section, the removal efficiency of the monovalent and divalent ions was investigated for different current densities and flowrates. Table 3 shows the effect of the applied current and flowrate on the ion removal rate for the first stage. The applied current density has a considerable influence on the separation of monovalent and divalent ions during the ED process. It can be seen from Table 3 that the ion removal rates of Na^+ ion didn't vary significantly with the current densities. However, the ion removal rate of divalent ions Ca^{2+} and Mg^{2+} is apparent at lower current densities of 300 A/m^2 for both flowrates (400 L/h and 450 L/h) despite its very small concentration. This has also been reported by Zhang et al. [13]. Galama et al. [33] also confirmed that lower current densities could remove more divalent ions, to a larger extent, than monovalent ions. Besides that, the

concentrations of divalent ions (Ca^{2+} and Mg^{2+}) are significantly lower in the initial feed solutions as shown in Table 1, making its calculation very sensitive to even a slight change thus resulting in a higher removal percentage.

3.3.2. Effect of flowrate on ion removal rate

The effect of flowrate on ED performance is noteworthy. On increasing the flowrate from 400 L/h to 450 L/h the ion removal efficiency has decreased, due to the decrease in residence time of the ions inside the ED cell, as previously reported by [34]. However, high flowrate solutions have the ability to reduce the boundary layer thickness, which will reduce the resistance of the solution [27]. Interestingly, it was also noticed that a high flowrate is beneficial in reducing the divalent ion transfer rate from the diluate tank (Table 3). It can be seen from Table 3 that Na^+ and Cl^- were easily transported through the membranes. For 450 L/h flowrate and 500 A/m^2 study, the anions and cations were removed from the diluate tank in the following order: $Na^+ > Cl^- > Ca^{2+} > Mg^{2+} > K^+$. A higher removal rate of 96% and 94% for Na^+ and Cl^- respectively is attributed to the easier migration of monovalent ions through the mono-selective membranes. However, the cationic removal rate can also be affected by the ionic radius in the same condition. For example, although K^+ is a monovalent ion, it showed a lower removal rate at the same feed flowrate (450 L/h). This may be attributed to its large radius of 280 pm coupled with lower residence time that resulted in a lower migration rate through the membranes. Having said that, more studies will be carried out to investigate such phenomena in the future.

3.4. Water recovery rate

The present work isn't about utilizing ED for desalination because that would be inefficient considering the high saline water
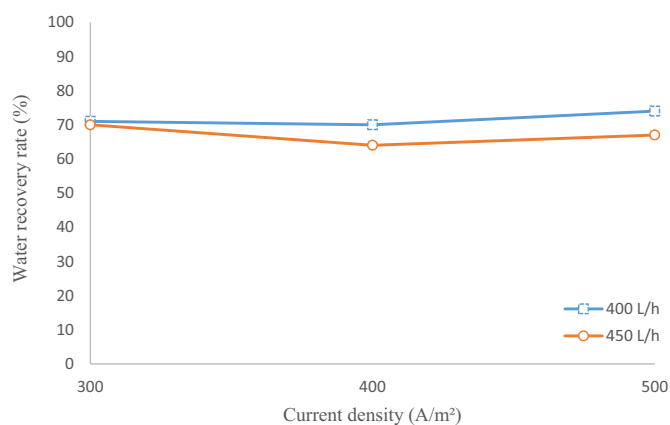
Fig. 10. Water recovery rates for the feed flowrates (400 L/h and 450 L/h) at different current densities.

concentration and high current densities of the current study. The primary goal of this study isn't calculating water recovery resulting from water transport due to free (osmosis) or as bound water (electro-osmosis) [35] but rather the production of hypersaline concentrate for further treatment to produce wet/dry salt and low salinity brackish water as a dilute (1526–2000 ppm). Notwithstanding this fact, water transport phenomena still occur in the present study due to the fact that water molecules co-transport with ions, which increases with ions removal affecting the separation process [35]. It has been shown that for the current conditions, the applied current densities were high and hence water transport due to electro-osmosis predominates that of (free) water osmosis. However, water transport at a high current density is less pronounced than at low current density [35]. This has been confirmed in the current study, where at higher current densities water recovery didn't significantly vary for both flowrates as shown in (Fig. 10). Furthermore, variation in operation time contributed to the slight variations in water recovery values.

3.5. Energy consumption

Energy consumption is directly proportional to the current utilized. For a given flowrate, higher current utilization by the system will result in higher energy consumption [13]. Higher flowrate operation has consumed less energy (E) due to lower residence time of the feed inside the ED unit than that of the lower flowrate. Fig. 11 shows the relationship between energy consumption and feed concentration at various current densities and two flowrates (after 8 stages of operation), where energy consumption increases with feed concentration but not
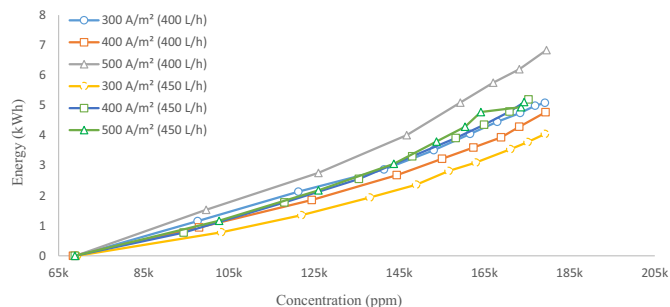

Fig. 11. Energy consumption for flowrates of 400 L/h and 450 L/h at different current densities.

with current densities, suggesting that the relation between energy consumption and current density isn't simple monotonic in nature. At a higher flowrate, however, energy consumption increases with current densities and feed flowrate.

3.6. Membrane characterisation

This section presents some of the challenges encountered during the current study. After finishing the experiment, the membrane stack was dismantled, and few membranes were taken for an insight investigation. Membrane fouling was found to be a serious issue in our experimental work. Fig. 12 (a) and (b) show two fouled up end CEMs and Fig. 12 (c) shows one fouled up inner membrane (CEM). The surface of the CEM showed visible colour change along with a detectable difference in the texture of the membrane. Fig. 12 (c) clearly shows the presence of accumulated salts on the membrane surface (fouling).

Furthermore, SEM images (Fig. 13 (a), (b), (c) and (d)) along with EDX (Energy Dispersive X-Ray) analysis (Fig. 14) were generated to characterize the fouling substance. Despite their low concentration levels in the feed, Fig. 14 clearly suggests that most of the accumulated ions were divalent ions such as Mg^{2+} and Ca^{2+} that suits the monovalent exchange membrane selectivity of the current ED stack. The cations, driven by the cathode attraction, migrated across the last diluate spacer near the cathode side and accumulated on the end CEM. A rise in the electrolyte level was also observed during one of the experimental runs exceeding the permissible level of 2 L inside the electrolyte tank. This is due to a crack formed on the surface of the end CEM near the cathode side due to the continuous accumulation of ions. Consequently, we proposed the following to the manufacturer: to modify the membrane design and include a neutral cell (additional CEM and a concentrate spacer) just prior to the end CEM membrane near the cathode side to prevent the accumulation of divalent cations and protect the end CEM from deterioration. Another way of reducing the fouling phenomena is to introduce a pre-treatment stage to the ED process to remove the divalent ions from the feed and maximize the ion transfer.

3.7. Salt production

Integrating desalination with electrodialyzer has economic and environmental benefits. Economically, this hybrid system reduces overall water production cost through recovering low salinity water for reuse and also producing salts as edible and wet salt for other purposes (human consumption and chemical production in refineries, respectively). Environmentally, it prevents the reject brine from being discharged directly into the coastline. Final concentrate effluent out of the ED stack (102,690 ppm) was introduced to a rotary evaporator to produce wet and edible salts for industrial and human uses, respectively (Fig. 15). The experiments in the present work were carried out under high current densities that hinders the migration of divalent ions across the ion-exchange membrane. Moreover, the monovalent permselectivity of the ion-exchange membranes used in the ED stack that permitted monovalent ions over divalent ions resulted in a high concentration of monovalent ions with respect to divalent ions. SEM images of the reference salt and recovered salt are given in Fig. 16 (a) and (b) respectively. The salt recovery was about 84.75%, whose composition is listed in Table 4.

4. Conclusion

It can be concluded from the current study that the application of ED is an effective method to obtain salt from MSF plant's reject brine. A pilot-scale ED system was used in the CB-CB method with monovalent
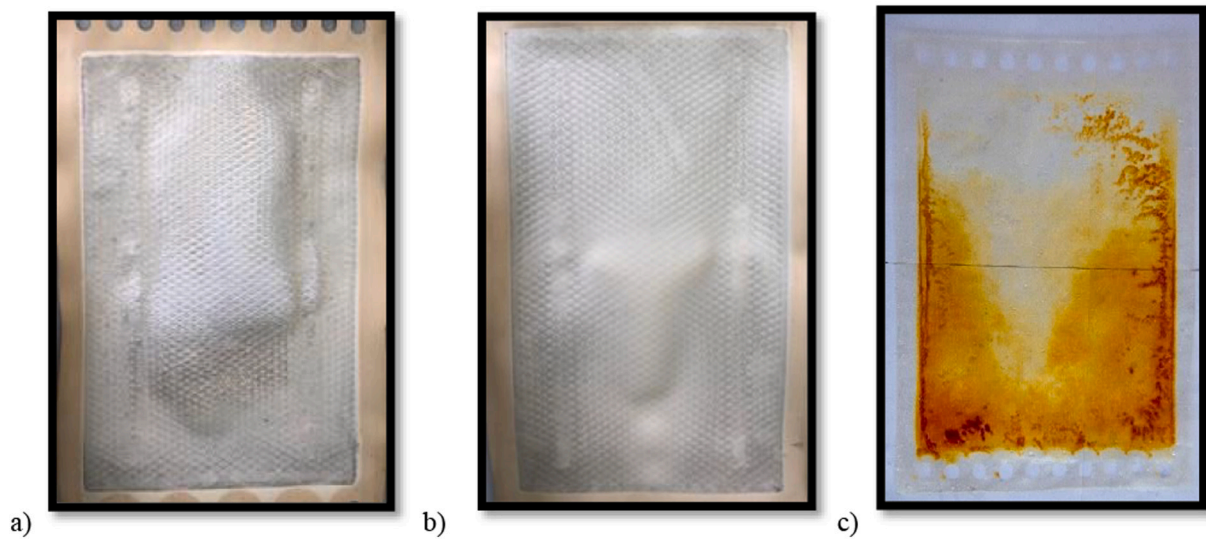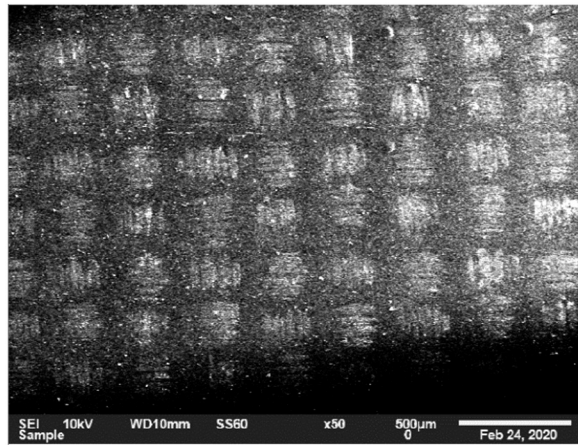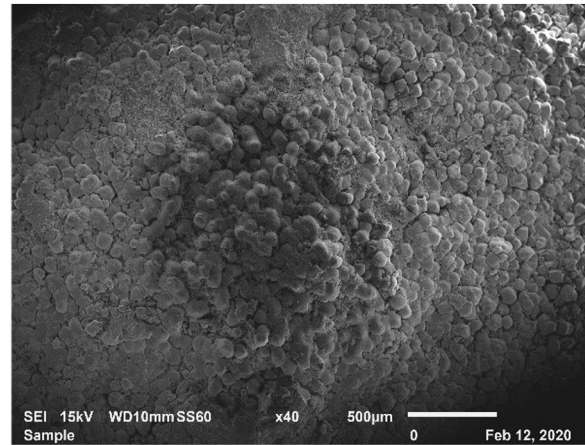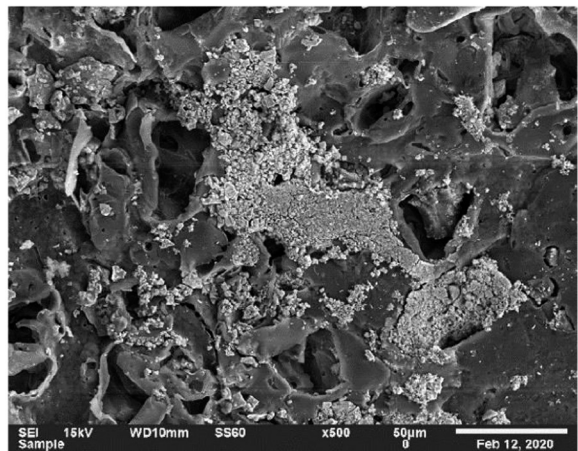
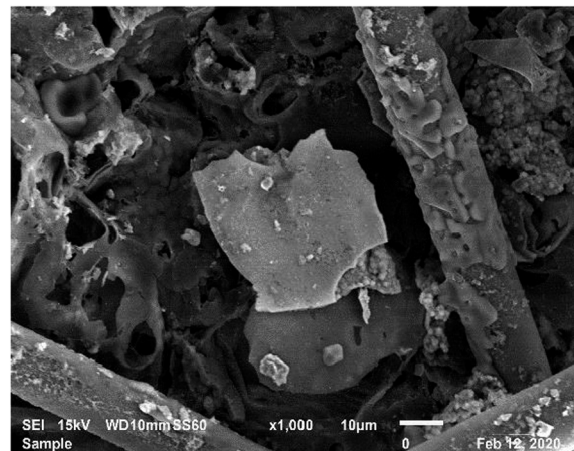**Fig. 12.** a) Fouled up END CEM-near Cathode side b) Fouled up END CEM-near Anode side c) Fouled up CEM.

Fig. 13. (a) Shows the SEM image of the fresh CEM and (b), (c), (d) show the SEM images of the fouled up end CEM near the cathode side taken under different magnifications.
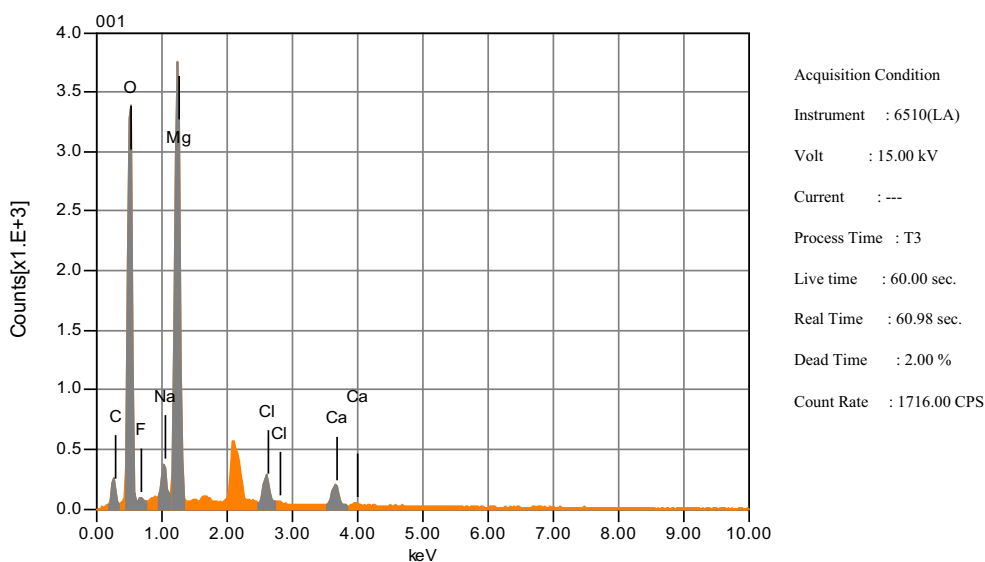
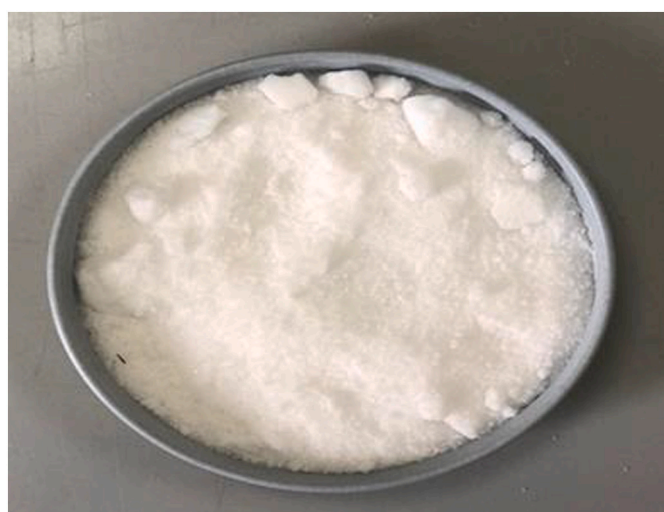Fig. 14. SEM-EDX analysis of the end CEM near the cathode side.

Fig. 15. Salt recovered after the evaporation operation.

selective membranes, PC-MVA and PC-MVK. The ED-evaporator hybrid system was operated in multi-batch series ED method until the effluent concentration reached 180,000 ppm. The membranes were efficient in separating monovalent ions over divalent ions. It was observed that

Table 4
Composition of the recovered salt.

Components	Levels (mg/kg)
Calcium	1333.8
Magnesium	390.94
Sodium	359,776
Chloride	515,369.9

high current density operation was favoured since the time consumed for producing salt was the least along with higher water recovery. Operating at lower current density favoured the removal of divalents than monovalents, which should be avoided. The current efficiency has dropped when the inlet feed concentrations increased indicating the formation of ion concentration polarization layer near the membrane surfaces limiting the number of runs. Flowrate is a crucial parameter for the operation of the ED-evaporator system. Increasing the feed flowrate by 12.5% reduced the operation time (by 30 min), reduced energy consumption (by 32%) and increased the current efficiency (by 31.4%). The optimum parameters for salt production from our study were 450 L/h and 500 A/m^2. Fouling was found to be a serious issue in our experiment. Adoption of a neutral cell compartment along with a good pre-treatment technology will be useful in mitigating the fouling issue, whose studies will be carried out in our future studies.
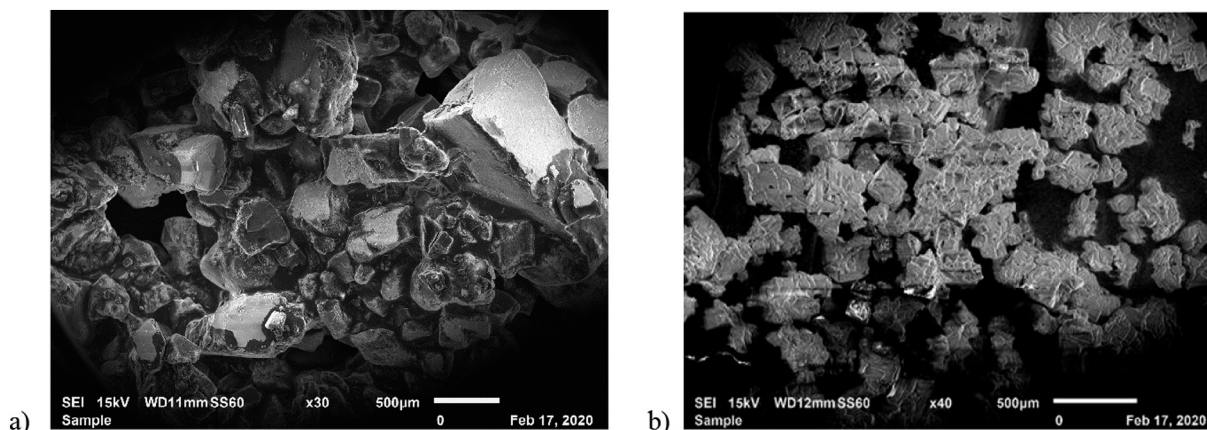

Fig. 16. a) SEM image of the reference salt b) SEM image of the recovered salt.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2020.114760.

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