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Microbial desalination fuel cell using membrane bioreactor as a sludge supplier: comparison between immersed and side-stream configurations

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ABSTRACT

Microbial desalination cell is an emerging desalination technology offering great promise of high salinity removal with zero energy input. Moreover, membrane bioreactors (MBRs) are of great reliability in treating domestic and industrial wastewater. This paper considers MBR as source of microbial sludge for microbial desalination fuel cell (MDFC). Synthetic wastewater of pure culture (yeast) and substrate (glucose) were used as the anode feed. Two system configurations, namely immersed MBR and side-stream MBR, have been proposed and compared. Experimental results revealed that a bench-scale system of 350 mL chamber capacity can achieve higher salinity removal compared with that of pilot scale (from 4.72% to 10.35%) and voltage production (from 0.572 to 0.007 V) than its alternative 4.5 L chamber. In the case of side-stream cell MDFC, better performance is achieved than that of the submerged MDFC, in which 21.12% salinity removal was achieved with a drop in the total dissolved solids from 32.20 to 25.40 g/L, and maximum voltage attaining 0.6160 V in 12 d. However, the results of using only MDFC showed higher salt removal (27.95%) due to the presence of large numbers of microorganisms.

Keywords: Microbial fuel cell (MFC); Membrane bioreactor (MBR); Desalination; Wastewater treatment; Bioelectricity production

1. Introduction

Water available in nature is not suitable for direct consumption. The main water resource in the Gulf region is from the sea where the salinity levels are so high and not suitable for human use. Moreover, high salinity affects crop production and causes corrosion in water distribution system. Therefore, desalination of seawater is essential in order to provide potable water and avoid its environmental impacts. However, desalination plants are very energy intensive consuming significant capital and operation costs. Desalination systems are classified into two main categories: phase change processes (thermal methods) and single phase processes (membrane processes). Multi-effect distillation, multi-stage flash and vapor compression are the most common thermal methods, while reverse osmosis is the most known membrane technology for desalination [1]. In addition, hybrid systems can be used whether concerning the energy input or the desalination method such as membrane distillation [1].

The use of renewable energy is a good alternative to solve water shortage issues due to lower costs (lower energy consumption) and environmental issues (lower gas emissions) [1,2]. Microbial desalination fuel cell (MDFC) is an emerging technology that performs electro-dialysis for desalination of seawater with high salt removal efficiency. It is a promising energy generation process from biomass resulting in a new form of renewable energy, which is significantly needed in our society. For example, a 60 mL MDFC achieved 60% desalination in 20 h with a maximum mean voltage of 105 mV using 3.2 kΩ and cellulose acetate membrane [3]. Another study achieved 62.2% and 57.6% salt removal using dye house effluent as organic substrate for two bacterial strains with maximum voltage of 0.585 V [4]. However, a larger scale MDFC (105 L total liquid volume) exhibited highly non-uniform

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performance and required applying external voltage to improve desalination rate [5]. A conventional microbial fuel cell (MFC) is a bio-fuel reactor that converts substrates to electricity at high rate and efficiency [6]. MFC technology was also applied for wastewater treatment, environmental sensors, bioremediation, renewable energy production and hydrogen production [7]. For instance, a 2.6 L total volume cell made of plastic containers was used for 528 h resulting in removing 75.9% COD from a hostel sewage water using agarose, and producing 0.95 V with a 10 Ω external resistance [8]. Also, a mixed bacterial culture consuming glucose as the carbon source produced power up to 3.6 W/m^2 in a 40 mL liquid phase volume [6]. Wen et al. [9] considered the use of biocathode MDC, in which the biocathode was aerobic, containing carbon felt and bacterial catalysts. An increase in voltage produced by 136 mV was noticed as compared with an air cathode MDC (i.e., the aerobic biocathode produced a total of 609 mV). The saltwater content of seawater was reduced by 92% when 0.441 L of the anode solution was used. The coulombic efficiency was found to be approximately 96.2% and the total desalination rate was 2.83 mg/h. The desalination performance of an MDC can also be increased using multiple pairs of ion-exchange membranes, inserted between the anode and cathode chambers, to improve the charge transfer efficiency and allow the saline water to flow through a series of MDCs prompting more salt removal [10]. This configuration is referred to as the stack structure MDC system. Choi and Ahn [11] tested five different types of stacked connections for treating domestic wastewater, namely series in parallel flow, parallel in parallel flow, series in series flow, parallel in series flow and individual in series flow. The results of their study showed that the parallel electrode connection in series flow mode resulted in 15%–20% higher electricity generation and 80%–85% more coulombic efficiency compared with the case of series connection. Their study demonstrates the impact of effects of different connections and flow modes on the performance of stacked MDCs. A combination of the electrodialysis and microbial electrolysis cell (MEC) can also do the job and results in what is called microbial electrolysis desalination cell [12-14]. A more creative technique is developed in which the catholyte and anolyte solutions are sequentially re-circulated through the cell to neutralize the pH in the cell [15,16]. Detailed description of these MDFC system and other used ones can be found in the review paper of Saeed et al. [17].

Membrane bioreactor (MBR) is a process combining activated sludge treatment and membrane filtration. The reactor is similar to a conventional activated sludge process but without the need for secondary clarification and tertiary steps [18]. MBRs represent a great method for treating wastewater as they reduce plant footprint and cost. MBR is used for treating domestic wastewater and different industrial wastewater from textile, dairy, pharmaceutical, etc. [19]. MBR was used for the removal of selected pharmaceuticals, fragrances and endocrine disrupting compounds from wastewater with high removal rate [20,21].

From the appealing features of both techniques (MDFC and MBR) mentioned previously, this work will consider the use of both MBR and MDFC for desalination of seawater where MBR is used as source of sludge supplier. In addition, the electricity generated from MDFC can be theoretically used as an energy input for the MBR; thus, reducing energy costs and achieving sustainability. This work will assess the performance of the MBR–MDFC system using two different sizes (pilot and bench scales) semi-batch hybrid processes as well as the use of two well-known membrane configurations that are normally used for the MBR technology, namely immersed membrane system and side-stream membrane system.

2. Materials and methods

2.1. MBR–MDFC unit setup and materials

Two different units of the MBR and MDFC were prepared from similar materials, but with different scales (named here as pilot scale and bench scale). These units/materials and their dimensions are listed in Table 1.

Acrylic sheet is transparent, thermoplastic, lightweight and shatter resistant; therefore, it was the material of choice for the construction of the cell body. Fuel cells most commonly incorporate fluorocarbon membranes such as perfluorinated Nafion membrane which exhibits excellent chemical durability and high ionic conductivity. Worth mentioning, the cation exchange membranes (CEMs) have cation exchange groups (anionic charged groups), and cations selectively permeate through the membrane. As for the anion exchange membranes (AEMs), they have anion exchange groups (cationic charged groups), and anions selectively permeate through the membrane [22,23]. Carbon fiber and cloth have been extensively used as electrode materials offering high overall internal surface area [24].

Figs. 1 and 2 show the block diagrams of the two proposed MBR–MDFC systems. Chambers 4, 5 and 6 represent the MDFC unit. The AEM and CEM were fixed by setting them on acrylic frame with a cascade. The first diagram (Fig. 1) illustrates a process where the ceramic membrane of MBR (item # 17) is immersed in the anode chamber so as organic degradation and MBR separation occur in the same

Table 1
Unit/materials and dimensions

Unit	Material	Dimensions	
		Pilot scale	Bench scale
MDFC chambers	Acrylic sheet	15 × 22 × 19 cm; 1 cm thickness; 4.5 L effective volume	8 × 11 × 12.5 cm; 2 cm thickness; 350 mL effective volume
MBR membrane	Flat-sheet ceramic membrane	10 × 9.5 × 0.7 cm; 0.2 μm pore size; 22 channels	5 × 5 × 0.7 cm; 0.2 μm pore size
Ion-exchange membranes	Nafion	22 × 19 cm	6 × 9 cm

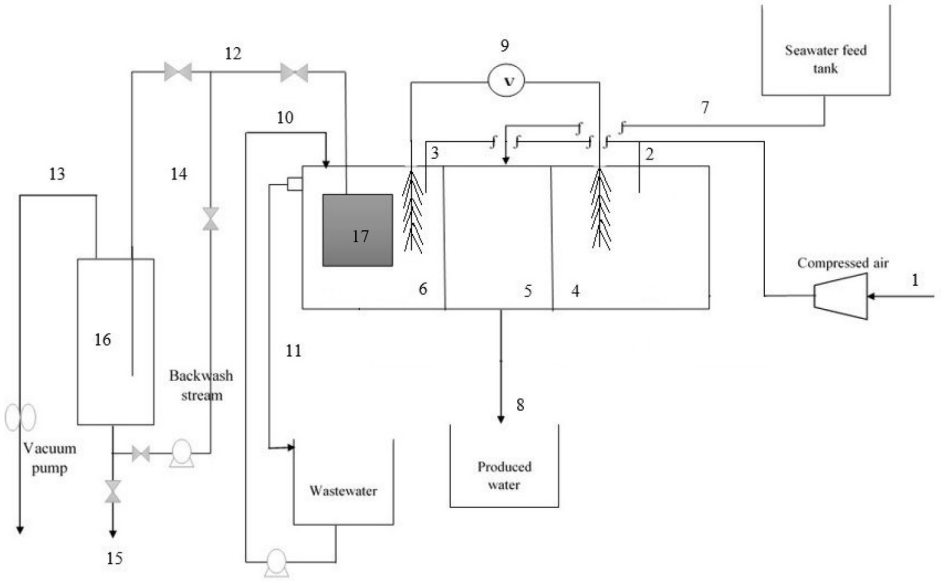

Fig. 1. Block diagram for the first proposed MDFC system (immersed system): (1) air feed stream, (2) compressed air to the cathode diffuser, (3) compressed air to the anode diffuser, (4) cathode chamber, (5) seawater chamber, (6) anode chamber, (7) seawater feed stream, (8) desalinated water product stream, (9) voltmeter, (10) wastewater feed line, (11) overflow stream, (12) membrane permeate, (13) vacuum suction line, (14) backwash stream, (15) drain, (16) permeate and backwash tank and (17) ceramic membrane.

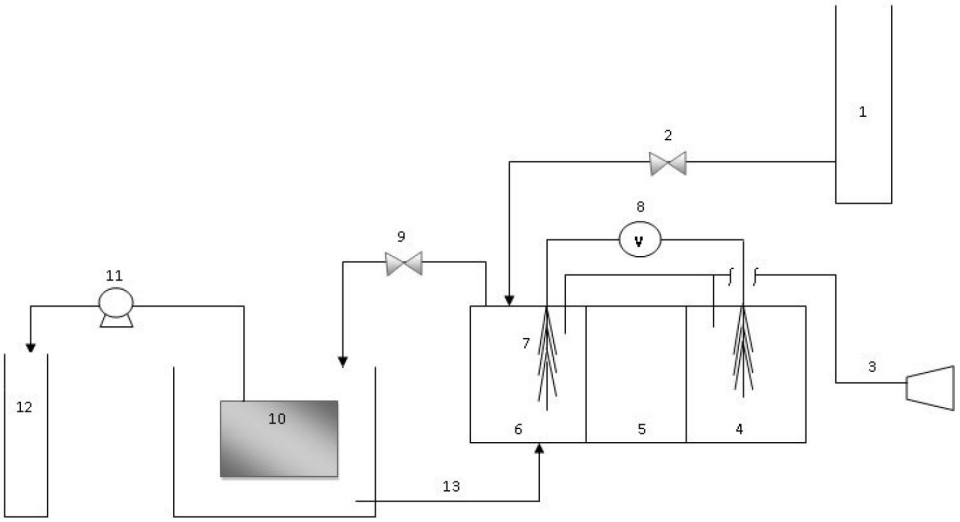

Fig. 2. Block diagram for the second proposed MDFC system (side stream): (1) wastewater feed tank, (2) feed valve, (3) air feed stream, (4) cathode chamber, (5) seawater chamber, (6) anode chamber, (7) carbon fibers as electrodes, (8) voltmeter, (9) MBR feed valve, (10) ceramic membrane, (11) permeate pump, (12) permeate tank and (13) MBR sludge.

unit; while in the second one (Fig. 2), a stream is withdrawn from the anode chamber and fed to an external MBR acting as a subsequent treatment step. Also, the latter system differs as it requires scrapping off the sludge to return it back to the desalination microbial fuel cell.

2.2. System operation

Before operation, leak tests are performed at least three times by filling the cell for about 1 h until no leak is noticed and ensured. Then, the cell is washed with distilled water; this step acts also as a confirmation for the leak testing part.

A synthetic wastewater feed of known composition [25], namely acetic acid (31.6 g/L), NH_4Cl (8.8 g/L), KH_2PO_4 (1.3 g/L), $FeCl_3.6H_2O$ (0.1 g/L), $CaCl_2$ (0.2 g/L), $MgSO_4$ (0.2 g/L), KCl (0.2 g/L), NaCl (0.2 g/L), $NaHCO_3$ (49.8 g/L), is fed to the anode chamber. A synthetic pure culture of 2 g of yeast (*Saccharomyces cerevisiae*) is prepared in a 50 mL phosphate buffer solution and preheated to 40°C for about 4–6 h; this is the condition to activate yeast before adding to the process unit [26]. Glucose is added as substrate source for the yeast by the same amount as yeast. Air is provided by an air diffuser to improve ion exchange for motion inducing, provision of oxygen necessary for microbial growth, and to

test the behavior of the cell if it will perform. The microbial activity is monitored by the measurement of the dissolved oxygen (DO) occasionally. Measuring of DO value is performed by a Milwaukee DO sensor, in which its probe is immersed in the anode chamber to provide the DO value as mg DO/L.

An oxidizing agent is used at the cathode chamber under aeration. The oxidizing agent is 0.02 M potassium hexacyanoferrate III which is not considered as a hazardous substance according to OSHA 29 CFR 1910.1200. Phosphate buffer solution of pH 7 (4.08 g Na_2HPO_4 and 3.29 NaH_2PO_4 in 500 mL distilled water) is used to maintain the pH at certain level [27]. The cathode chamber is also under aeration to provide more oxygen as an electron acceptor.

Saline water of total dissolved solids analogues to the sea water (33 g/L in average) is fed from the top through cylindrical opening into the middle chamber where desalination occurs. All is fed under room temperature.

Carbon fiber electrodes are inserted in both the anode and cathode compartments and the voltage production is monitored. The carbon fiber was prepared as stick withdrawn from carbon cloth. The carbon fiber brushes were directly submerged in the each MDFC chamber. To measure the cell potential, one can use a crude voltmeter, which works by drawing current through a known resistance. Yet, some energy is wasted due to the frictional heating that occurs when current flows through the wire [28]. Therefore, to determine the cell maximum potential, digital voltmeter was used that draws only a negligible amount of current [28].

The treated water is drawn from the ceramic membrane by a dosing pump set at 100% frequency and 50% stroke. Backwashing is essential to prolong membrane life and avoid clogging; consequently, high-quality effluent. Industrially, it can be done by utilizing a vacuum pump and opening the backwash stream pump and valves and closing the final permeate valve (Fig. 1). In this work, backwashing was accomplished on a weekly and daily basis using distilled water in the first and second proposed systems, respectively. The experimental work performed is done under semi-batch mode in the case of the immersed system.

For the second type of MBR–MDFC unit and according to Fig. 2, the inlet and oulet flowrates are made the same and adjusted to approximately 5 mL/min; this is in order to avoid possible flooding. Low flowrate is preferred for adequate contact time in the anode chamber.

2.3. Water analysis

The turbidity was measured using HANNA instruments (LP 2000, Germany) and is expressed in nephelometric turbidity unit (NTU). The pH and total dissolved solids (TDS) were measured using a 'MARTINI instruments multiparameter bench meter Mi 180'.

3. Results and discussion

3.1. Immersed system: pilot-scale vs. bench-scale systems

For this case study, the first proposed system (Fig. 1) was used, where an immersed ceramic membrane is in the anode chamber performing as an MBR. Table 2 lists the experimental results of the two different scales (pilot scale and bench scale) for the purpose of comparison.

Saline water of 36.00 and 34.80 g/L TDS is fed into a pilot-scale and bench-scale systems, respectively. The large cell achieved 4.722% salinity removal where the TDS dropped from 36.00 to 34.30 g/L for 4 d of operation time producing a voltage of 0.5720 V. As for the smaller cell, 10.35% salinity removal is achieved with a decrease in the TDS from 34.80 to 31.20 g/L in 4 d of operation time producing a voltage of 0.6070 V. The results are shown in Fig. 3.

In addition, the wastewater turbidity and TDS are decreased from 345.0 NTU and 33.60 g/L to 157.0 NTU and 15.00 g/L, respectively, for the case of the bench-scale system; while for the larger scale system they decreased to 73.00 NTU and 21.50 g/L TDS, respectively, as they appear in permeate water from the MBR.

The experimental work revealed the success of the system in voltage generation and seawater desalination, which requires further improvement (side-stream system configuration is suggested and tested). The bench scale exhibited higher salinity removal and voltage production than that of pilot scale for the 4 d operation time. Scaling up the cell leads to many factors causing lower system efficiency. Larger system requires more vigorous mixing for uniform ion distribution and transportation. The bulk volume of salt water adjacent to the ion exchange membranes experience better ion transfer. Therefore, it takes more time for the salt ions to dissociate from the water in a large system, in oppose to a smaller scale system. However, the bench-scale cell potential/voltage is larger than pilot-scale potential throughout the four d of operation as seen in Fig. 3, which shows high electron transferral to the anode due to the high electrode surface area to volume ratio. Nevertheless, the voltage difference between the two systems is not significant after the 4 d of operation.

Fig. 3 demonstrates how in both scale systems the TDS drops most rapidly at the beginning, then decreases in a slower manner throughout the rest of operation time. TDS curve undergoes more fluctuation for the pilot-scale unit due to the ununiform solution. As for voltage generation, it was observed that the pilot-scale system started at a lower value of 0.3430 V, but increased steadily almost reaching the smaller unit voltage value of 0.6070.

Table 2
Experimental results for pilot-scale vs. bench-scale immersed systems

System scale	Pilot scale	Bench scale
Operation time, d	4 d	4 d
Initial TDS, g/L	36.00	34.80
Final TDS, g/L	34.30	31.20
Salt removal, %	4.722%	10.35%
Voltage, V	0.5720	0.6070
Wastewater turbidity, NTU	345.0	345.0
Permeate water turbidity, NTU	73.00	157.0
Wastewater TDS, g/L	33.60	33.60
Permeate water TDS, g/L	21.50	15.00

The turbidity, which gives an indication of the total suspended solids in water, decreased more significantly in the case of pilot-scale system. This can be attributed to the fact that many precipitates settled down and stuck in the bottom of the chamber since the reactor is batch leaving the upper liquid volume clearer and thus indicating better wastewater treatment than the bench scale in regards of turbidity assessment, which is not necessarily the case. For just and fair valuation between the two scales, mixing prior to sampling should be done. However, mixing in large volume unit is of course not as effective as in smaller volume units as it is not possible to reach all corners and may miss few areas. Hence, the bench-scale system presents more uniform solution and more accurate readings. The water TDS in the permeate dropped more in the smaller hybrid system as mentioned indicating higher microbial activity with more dissolved salts consumption (nutrients content) in the wastewater fed to the anode chamber.

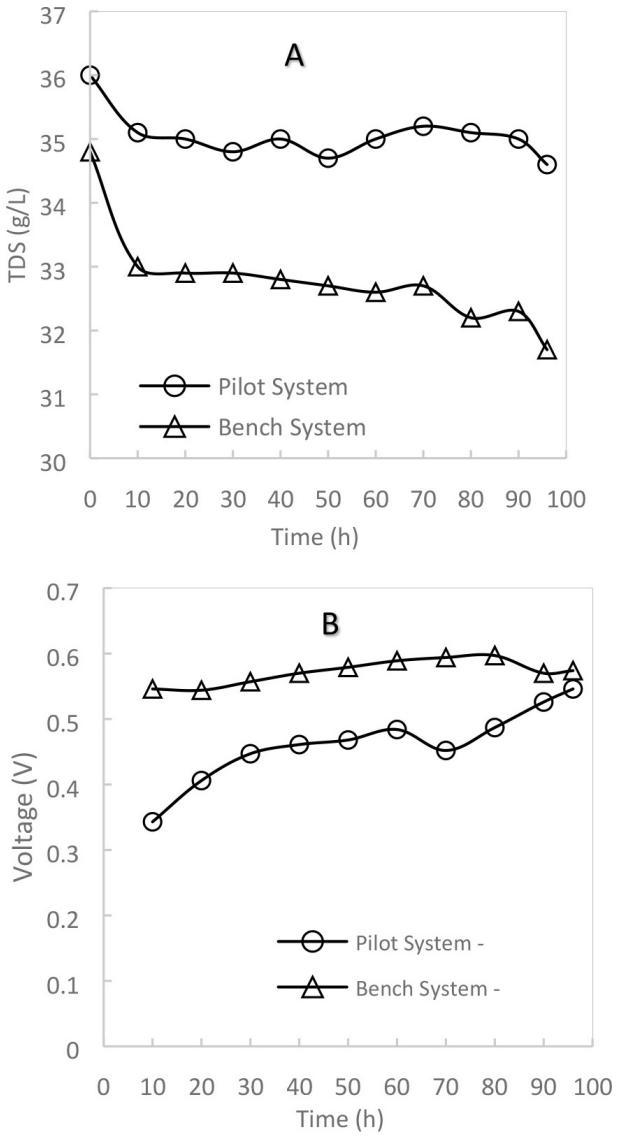

Fig. 3. TDS (A) and voltage (B) experimental results for the immersed MBR–MDFC system.

The set up and handling of the larger unit is much more difficult and is time consuming. Moreover, the membrane cleaning and backwashing require frequent cell disassembling. Hence, backwashing cannot be done more frequently during the process, that is, time, efforts and resources are of concerns. The only advantage of the larger scale, is footprint reduction, nevertheless, a system with side-stream MBR allows easy plant retrofit and unit maintenance. In addition, side-stream MBR would be more practical as suggested in Fig. 1, because otherwise many membranes will be employed for each unit which are considered very costly. Smaller units can be stacked for industrial application where great production is desired. Stacking them up in series would also increase the voltage generation.

3.2. Side-stream MBR–MDFC system vs. MDFC only

The second proposed system (Fig. 2) was used along with a conventional microbial desalination cell (with only yeast in the anode chamber, without use of MBR) for the purpose of comparison. Both are of the same size (350 mL chamber capacity) and fed with saline water of 32.2 g/L TDS. The main experimental results are displayed in Table 3.

In the case of MBR–MDFC system, 21.12% salinity removal was achieved with a drop in the TDS from 32.20 to 25.40 g/L, and maximum voltage attaining 0.6160 V in 12 d of operation time. In the case of MDFC, 27.95% salt removal was achieved with a decrease in the TDS from 32.20 to 23.20 g/L, and maximum voltage production of 0.5880 V in 12 d of operation. The results are shown in Fig. 4.

This experiment was conducted for a long period (12 d) showing the long durability of the ion exchange membranes. The hybrid system exhibited higher voltage production than the MDFC, but inferior salt deduction percentage. The drop in voltage, in day 4, 7 and 11 as shown in Fig. 4, was mainly due to leaving the unit overnight with no air (due to lab safety regulations). When air and glucose were added to the system, to enhance microbial activity, the microbial cell shortly stimulated voltage production. Overall, the hybrid system voltage generation is less fluctuate than the MDFC as observed in Fig. 4, which may be credited to the microbial nutrients available in the wastewater elements sustaining the microbial growth. The decrease in cell potential when using the MDFC could be due to exhaustion of yeast and thus a decrease in cell potential; however, of using MBR as sludge provider this decrease was not noticed because yeast is provided externally continuously.

Table 3
Experimental results for side-stream MBR–MDFC system vs. MDFC only

System	MBR–MDFC	MDFC
Operation time, d	12	12
Initial TDS, g/L	32.20	32.20
Final TDS, g/L	25.40	23.20
Salt removal, %	21.12%	27.95%
Maximum voltage, V	0.6160	0.5880

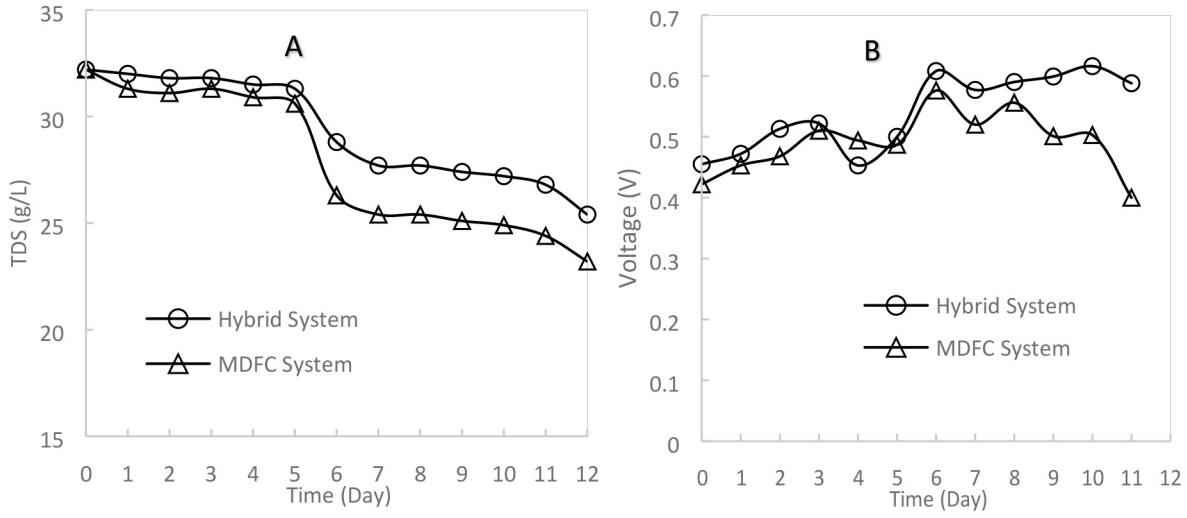

Fig. 4. TDS (A) and voltage (B) experimental results for side-stream MBR–MDFC system.

These results encourage the success and effectiveness of the proposed MBR–MDFC system with further modifications to enhance salt removal percentage such as reducing saline water volume and trying a different ion exchange membrane.

4. Conclusions

It can be concluded that the use of MBR as source of sludge for MDFC is a promising technology as it results in high quality effluent and energy recovery. It serves great benefits of utilizing the sludge from the MBR as the biomass source and generating electricity from it. The proposed continuous MBR–MDFC system was endorsed when compared with a conventional batch MDFC regarding salt deduction and voltage generation. The MBR–MDFC system exhibited slightly lower desalination removal percentage (about 6% difference), but better voltage production (around 35 mV difference) than MDFC only unit. It is worth mentioning that salt removal efficiency can be increased with further attachment of MDFC units.

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