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Enhancing desalination and wastewater treatment by coupling microbial desalination cells with forward osmosis

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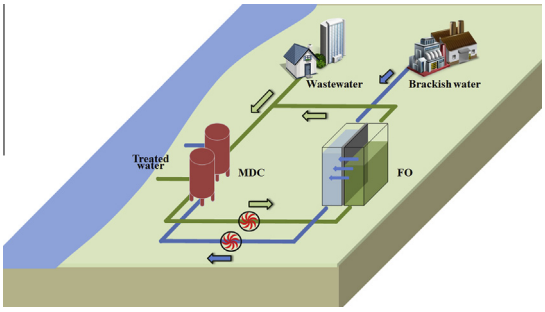
HIGHLIGHTS

- MDCs are coupled with forward osmosis for improved desalination.
- MDCs accomplish organic removal and desalination.
- Forward osmosis realizes water extraction from wastewater and salinity reduction.
- Both HRT and initial salinity have significant effects on desalination performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Both microbial desalination cells (MDCs) and forwards osmosis (FO) are emerging technologies for energy-efficient water/wastewater treatment. However, incomplete treatment/desalination in both technologies creates challenges for further development and also synergy between the two. In this study, an integrated system was developed by coupling MDCs with a FO cell to enhance COD (chemical oxygen demand) removal in synthetic organic solution and desalination of saline water. The organic solution was treated in the MDC anode and its effluent was sent to the FO for water recovery. The diluted draw solution from the FO was desalinated in the MDC. Compared to a standalone MDC, the MDC–FO system reduced the wastewater volume by 64% and improved the conductivity reduction in saline water by two times. The coupled system also achieved higher COD removal than a standalone FO cell. The MDC–FO system was further investigated for the effects of COD, salt concentration and hydraulic retention time (HRT). It was observed that varying COD concentration had little impact on desalination. Lowering the initial NaCl concentration enhanced the COD removal to 93.0% and the conductivity reduction to 99.4%. In addition, the COD removal rate and the conductivity decrease rate were proportionally facilitated with a shortened HRT. These results have collectively demonstrated that the MDC–FO system has improved performance, compared with the standalone process. It holds great promise to either treat brackish water, or serve as pre-desalination of high-salinity water, with simultaneous wastewater treatment.

1. Introduction

Globally there are some 2.4 billion people suffering from water-borne illness due to inadequate sanitation [1]. Effective treatment of saline water and contaminated water can substantially tackle these problems in freshwater supply and wastewater treatment. However, conventional methods for desalination (e.g. reverse osmosis, multi stage flash and electrodialysis) and wastewater treatment (e.g. activated sludge process) are energy-intensive [2,3], posing a major challenge for addressing water issues in the areas that are short of energy supply. In addition, the separate

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treatment of saline water and wastewater results in high capital cost and inefficient utilization of infrastructures. Therefore, novel technologies with integrated desalination and wastewater treatment will be of great interests.

Microbial desalination cells (MDCs) are an emerging technology that can simultaneously treat wastewater and desalinate saline water by taking advantages of microbial respiration with an electrode [4]. In a typical MDC, a salt chamber is separated from an anode chamber with an anion exchange membrane (AEM), and from a cathode chamber with a cation exchange membrane (CEM) [5]. Exoelectrogens growing in the anode oxidize organic compounds in the wastewater and donate electrons to the anode electrode to accomplish extracellular respiration [6]. These electrons flow through an external circuit to reduce electron acceptors in the cathode, creating an electric field between the two electrodes. Driven by the electrostatic force, anions and cations in the saline water migrate to the anode and cathode, respectively [7]. As a result, both saline water and wastewater can be treated with low energy consumption. Both fundamental studies and large-scale tests have advanced MDC technology towards practical applications [8–14]. For example, a tubular MDC with an anode liquid volume of 1.9 L was able to remove 94.3% of the NaCl at a TDS (total dissolved solids) removal rate of 11.61 g L^{-1} d^{-1} [15]. This system was further scaled up to 105 L (total liquid volume) and achieved a salt removal rate of 9.2 g L^{-1} d^{-1} with more than 97% of the COD (chemical oxygen demand) being removed. In addition, the stacked MDCs were also widely studied and recently enlarged to a ten-liter system packed with mixed ion-exchange resins for desalinating the secondary effluent of wastewater treatment [16].

Forward osmosis (FO) is another promising technology for both desalination and wastewater treatment. An FO process refers to the movement of water molecules from a low-concentration solution (feed) through a semipermeable membrane to a high-concentration solution (draw) under an osmotic pressure gradient [17]. Because of the relatively low osmotic pressure difference, FO is advantageous over conventional membrane technologies such as reverse osmosis, nanofiltration and ultrafiltration, in terms of fouling propensity, water recovery and energy efficiency [18]. When FO is applied to treat wastewater, clean water can be extracted by osmotic pressure, thereby greatly reducing wastewater's volume [19]. For desalination application, fresh water can be recovered from the diluted draw solution by low-grade heat, membrane-based methods, or magnetic separation [20–23].

The facts that FO achieves dilution instead of salt removal and MDCs are low efficient in desalinating high-salinity water provide opportunities for the combination of those two technologies for complementing each other [24]. In a previous study, an osmotic MDC (OsMDC) was developed by replacing the AEM with an FO membrane [25]. In addition to water extraction, the OsMDC could also remove organic matter and salts, which outperformed the FO process and regular MDCs. However, the OsMDC removed less salts than a regular MDC, mainly because ion transportation was blocked by the semi-permeable FO membrane. To overcome this drawback, an OsMFC (osmotic microbial fuel cell) was hydraulically coupled with a regular MDC [26]. Both desalination efficiency and COD removal was distinctly enhanced compared to regular MDCs, but at the expense of a prolonged hydraulic retention time of salt solution (HRT = 3.5 d). Moreover, energy consumption by aeration in the OsMFC was a major hindrance for the development of the OsMFC–MDC system. To achieve better integration of FO and MDCs towards practical applications, one must consider the balance in treatment capacity between the two and reduction in energy consumption.

In this study, we proposed an MDC–FO system that eliminated aeration and significantly enhanced desalination performance at a salt solution's HRT as short as 16 h. The anode effluent from two MDC batches was mixed and used as the FO feed to mimic parallel operation of two identical MDCs (Fig. 1). After clean water was extracted, the concentrated feed of the FO was introduced back into the cathode of the MDC for further COD removal, while the diluted draw of the FO was desalinated in the desalination chamber of the MDC. To demonstrate the feasibility and performance of this coupled system, the effects of initial COD concentration, salt concentration and HRT were examined.

2. Materials and methods

2.1. System setup

The tubular MDC was constructed similarly to that in a previous study [27]. Briefly, an AEM tube (AMI-7001, Membrane International, Inc., NJ, USA) and a CEM tube (cation exchange membrane, CMI-7000, Membrane International, Inc.) were made to form the anode chamber (350 mL) and salt chamber (80 mL) (Fig. 1). A carbon brush (Gordon Brush Mfg. Co., Inc., CA, USA) was used as the anode electrode. The cathode electrode was a piece of 150-cm^2 carbon cloth (Zoltek Companies, Inc., MO, USA) coated with 0.1 mg cm^{-2} Pt/C as previously described [28] and wrapped the CEM tube. The anode and the cathode electrodes were connected to an external circuit across a 0.1-Ω resistor using titanium wire. An FO cell (Sepa CF II Forward Osmosis Cell 316 SS, Sterlitech Corporation, WA, USA) was used for the FO tests, containing an FO

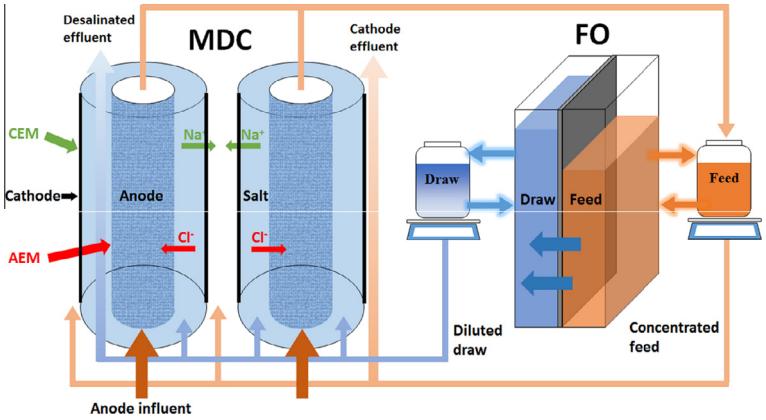

Fig. 1. Schematic of the MDC–FO system. CEM: cation exchange membrane; AEM: anion exchange membrane.