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Integrated experimental investigation and mathematical modeling of brackish water desalination and wastewater treatment in microbial desalination cells

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ABSTRACT

Desalination of brackish water can provide freshwater for potable use or non potable applications such as agricultural irrigation. Brackish water desalination is especially attractive to microbial desalination cells (MDCs) because of its low salinity, but this has not been well studied before. Herein, three brackish waters prepared according to the compositions of actual brackish water in three locations in Israel were examined with domestic wastewater as an electron source in a bench-scale MDC. All three brackish waters could be effectively desalinated with simultaneous wastewater treatment. The MDC achieved the highest salt removal rate of 1.2 g L^{-1} d^{-1} with an initial salinity of 5.9 g L^{-1} and a hydraulic retention time (HRT) of 0.8 d. The desalinated brackish water could meet the irrigation standard of both salinity (450 mg L^{-1} TDS) and the concentrations of major ionic species, given a sufficient HRT. The MDC also accomplished nearly 70% removal of organic compounds in wastewater with Coulombic efficiency varied between 5 and 10%. A previously developed MDC model was improved for brackish water desalination, and could well predict salinity variation and the concentrations of individual ions. The model also simulated a staged operation mode with improved desalination performance. This integrated experiment and mathematical modeling approach provides an effective method to understand the key factors in brackish water desalination by MDCs towards further system development.

1. Introduction

Because of the world-wide water shortage and local water scarcity, desalination has been increasingly considered as a viable approach for freshwater supply (National Research Council, 2008). The recently emerged microbial desalination cell (MDC) appears to be a promising alternative or supplement for traditional desalination technologies. An MDC

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converts the energy stored in wastewater directly into electricity by microorganisms and utilizes it *in situ* to drive desalination in a process similar to electrodialysis (ED) (Cao et al., 2009). The difference between MDC and ED is the source of electrons and energy consumption: an MDC uses the electrons released by microbial oxidation of organic compounds, while an ED is driven by electrons from water oxidation; as a result, an MDC does not necessarily require external voltage, but an ED must be applied with a high external voltage or current. The MDC has been advanced with reactor configurations, such as stacked reactor (Kim and Logan, 2011; Chen et al., 2011; Ge et al., 2014), decoupled reactor (Ping and He, 2013), and upflow tubular reactor that has demonstrated a salt removal efficiency >99% (Jacobson et al., 2010, 2011). Optimized operation through recirculation between the anode and the cathode compartments could achieve pH balance without the addition of costly buffer (Chen et al., 2012; Qu et al., 2012). Fundamental studies have also been conducted to reveal the diverse microbial community in the anode of MDC (Luo et al., 2012a). Recently, MDCs have been scaled up to a total liquid volume of 105 L, which encourages further development of this technology (Zhang and He, 2015).

Although MDCs can achieve desalination without external voltage applied, its desalination requires a fairly long time because of slow microbial oxidation, compared with electrochemical oxidation of water in ED. The low desalination rate of MDCs indicates that this technology may be more suitable for application as a pre-desalination process for conventional desalination such as RO (reverse osmosis) or ED (Zhang and He, 2012). Another potential application of MDC technology is to desalinate low-salinity water, such as brackish water that has TDS (total dissolved solids) in the range of 1000 to 10,000 ppm (Levite and Móatsah, 1972), or the treated wastewater. In many arid parts of the world, the local aquifers that contain brackish water are the main source of freshwater. It is of great importance to desalinate brackish water for municipal or agricultural applications. ED and EDR (electrodialysis reversal) are the current technologies for treating brackish water with TDS up to 3500 mg L^{-1}; a higher salinity significantly increases the energy consumption compared with RO (USBR, 2003). The salinity in brackish water comes from two sources: dissolution of minerals, and natural mixing of seawater with groundwater in coastal aquifers (National Research Council, 2008). Most brackish water cannot be directly used for drinking purpose or irrigation due to the high salinity, and specific ion toxicity for plants or the possibility of deteriorating soil conditions (Rhoads et al., 1992). There have been several MDC studies that examined desalination of synthetic salt solution with salinity similar to brackish water (Luo et al., 2012c; Zuo et al., 2013). The study of actual brackish water was reported only in a previous work that focused on the softening of hardness in several groundwater samples (Brastad and He, 2013). The transport behavior of multiple ions across ion-exchange membranes were studied at the same initial molar concentration with only one kind of counter ion (anion/cation) (Luo et al., 2012b); however the results cannot be applied to predict the ion composition in the actual brackish water desalination where the individual ion has different concentration. The transport rate of individual ions is a product of mobility (affected by hydrated radius and ionic charge) and ion concentration (Strathmann, 2004), while the previous study only considered hydrated radius as influencer. Clearly, there is a lack of detailed analysis and understanding of removal of different ionic species during desalinating actual brackish water or saline water with more complicated composition than NaCl solution in MDCs.

To assist the interpretation of the data obtained from the bench studies and to provide guidance for system operation, mathematical models of MDCs treating brackish water will be very valuable. Recently, the first MDC model was reported and it could effectively predict MDC performance under different operating conditions (Ping et al., 2014). However, the model did not well predict the change in salt concentration, likely related to that the low current efficiency, which mostly occurs when maximum current is not reached, was neglected in the model development. Desalinating brackish water in an MDC by using the energy obtained from domestic wastewater comes with two issues: low organic strength in the anode compartment, and low salinity in the desalination compartment, both of which will lead to current deviating from normal values and the low current efficiency due to low current generation. In addition, diffusion element in the previous model might not work for brackish water considering the difference in salt concentration across ion exchange membranes. Therefore, the previously developed MDC model must be improved with new information obtained from brackish water desalination.

In this study, we have adopted an integrated approach of experimental investigation and mathematical modeling to study brackish water desalination in bench scale MDCs. Three synthetic brackish waters were prepared with the recipes to mimic actual brackish water in three locations in Israel. Actual domestic wastewater (primary effluent) was used as an anode substrate to provide driving force for desalination. The objectives of this study were: (1) to demonstrate the MDC performance treating brackish water and actual wastewater; (2) to understand the removal of different ionic species during desalination; and (3) to improve the MDC model for brackish water desalination by incorporating junction potential, current efficiency, restricted diffusion, and osmotic flux. The model was calibrated with steady state values and validated by experimental data of both dynamic and steady state conditions.

2. Materials and methods

2.1. MDC setup and operation

The MDC was constructed as a tubular reactor similarly to the one in the previous study (Ping et al., 2014), consisting of two layers of ion exchange membranes (IEM): anion exchange membrane (AEM, AMI-7001, Membrane International, Inc., Glen Rock, NJ, USA) with a 3.8-cm diameter and 20-cm length formed the anode compartment (300 mL), and cation exchange membrane (CEM, CMI-7000, Membrane International, Inc.) that had a diameter of 5 cm and a length of 20 cm wrapped the AEM tube and created a space between the two membrane tubes forming a desalination compartment (150 mL) (Fig. S1, supplementary information). The distance