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Microbial mediated desalination for ground water softening with simultaneous power generation

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HIGHLIGHTS

- Desalination of ground and surface water is an emerging green technology.
- Triple chambered MDC for desalination, waste remediation and product recovery.
- Exoelectrogenic activity is the drives desalination under varied circuitries.
- Salts and hardness removal using microbial desalination.

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ABSTRACT

A novel three-chambered microbial desalination cell (MDC) was designed for evaluating desalination of synthetic ground water with simultaneous energy generation and resource recovery. The specific design enabled efficient interelectrode communication by reducing the distance of separation and also maintained an appropriate surface area to volume ratio. MDC were evaluated in different circuitry modes (open and closed) to assess the desalination efficiency, bioelectricity generation, resource recovery, substrate utilization and bioelectrokinetics. The closed circuit operation has showed efficient desalination efficiency (51.5%) and substrate utilization (70%). Owing to the effective electron transfer kinetics, closed circuit mode of operation showed effective desalination of the synthetic ground water with simultaneous power production (0.35 W/m^2). Circuitry specific biocatalyst activity was observed with higher peak currents (10.1 mA; −5.98 mA) in closed circuit mode. MDC can function as sustainable and alternative solution for ground and surface water treatment with power productivity and resource recovery.

1. Introduction

Water is an essential and critical commodity to sustain life on Earth. Ground water reserve is one of the major sources apart from the surface water. Current rate of urbanization and population explosion is causing exceptionally high water demand. Excessive withdrawal of sub-surface water, contamination, urban runoffs, domestic activities, etc. are precariously effecting the ground and surface water quality. This vulnerable water resource increases the salinity when the natural sources like rainfall are limited (Khaska et al., 2013). Sustainable water sources is an essential prerequisite to overcome the dearth of usable water (Brastad and Zhen, 2013; Khaska et al., 2013). The water purification and water desalting technologies are highly sought after in geographical locations where natural fresh water sources are limited. The conventional water desalination or softening technologies employing high pressures, temperature, membranes, etc. incur high costs and maintenance, which incurs cost of approximately 0.5–3.0 $ per liter of water (Mathioulakis et al., 2007; Elimelech and Phillip, 2011; Marzooqi et al., 2014, www.lentech.com). Furthermore, the common limitation observed in most of the water purification or desalination technologies is the generation of saline reject in considerable volumes.

Microbial desalination cell (MDC) is one of the extended application of microbial fuel cell (MFC) (Saeed et al., 2015; Venkata Mohan et al., 2014; Butti et al., 2016). Contrary to MFC, MDC involves the inclusion of a desalination chamber in between the anode and the cathode chamber of MFC, separated by an anion exchange (anode) and a cation exchange membrane (Cathode). The operational requirements of MDC include placing the contaminated water or saline water in the middle chamber, biocatalyst in the anodic chamber and oxygenated water in cathodic chamber (Kim and Logan, 2013). Unlike, the migration of salts across the

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membrane based on concentration gradient through diffusion, in MDC the electrochemical gradient created by substrate oxidation in the anodic chamber drives the desalination process. The generated protons and electrons from substrate oxidation enable the transport of anions and cations towards the oxidative anodic chamber and reductive cathodic chamber respectively. The migration of ions to their respective chambers also enables renewable energy production in the form of bioelectricity and resource recovery in the form of acids and bases (Gude, 2016; Sophia et al., 2016; Nikhil et al., 2016; Saeed et al., 2015; Forrestal et al., 2012). Acidic products (HCl, H_2SO_4, etc) and bases/salt (NaOH, $Ca(OH)_2$, etc) that are formed can also be recovered from MDC.

While MDC is a novice technology in comparison with the existing water purification technologies, it garnered attention due to the inherent advantages viz., low economic burden and reducing reject. However, MDC have still significant scope for improvement in terms of the rate and efficiency of desalination through optimization. In this study, MDC are specifically designed to remove TDS and hardness from design synthetic groundwater. The performance of MDC was evaluated under closed and open circuit mode of operation to enumerate desalination efficiencies and rates, resource recovery potential, power production and bioelectrochemical kinetics. The study also focused to understand the regulatory factors of microbial mediated desalination process in terms of operational feasibility for real field applications.

2. Materials and methods

2.1. MDC configuration

A three chambered specifically designed MDC bioreactor for desalination was fabricated using Teflon based materials. The reactor consists of three identical chambers with dimensions (7.5 cm × 8 cm × 2.5 cm; 60 ml) with considerations of having the smallest possible distance between the electrodes (2.54 cm) to enhance the inter-electrode communication. The dimensions are designed considering the electrode surface area to have an appropriate volume to surface area ratio (0.34) which enables the efficient biocatalyst activity along with desalination. The desalination chamber (mDC) was sandwiched in between the biotic anode (BA) and abiotic cathode (AC) separated by anion exchange membrane (AEM, AMI-Membranes International Inc., USA) and cation exchange membrane (CEM, CMI-7000, Membranes International Inc., USA) on either side. The chambers are clamped air tight together with gaskets (silica sheet) and O-rings using stainless steel bolts. The either ends of the reactors are closed with perspex sheets, each chamber is individually provided with four different ports on the four side, which were used for sampling, recirculating and for draining out the contents. The reactors were designed with the possibility to operate in both batch and continuous mode with efficient recirculation. Non-catalyzed carbon cloth (Ballard AvCarb Co. Ltd.) with geometrical surface area of 28.2cm^2 was used as anode and cathode. Prior to use, the carbon cloth was treated using NH_4Cl solution to increase the conductivity (Kondaveeti and Booki, 2013; Moon et al., 2014). All the components of the bioreactor after being clamped together were sealed using a rubber sealant to prevent leaks and sparged with nitrogen to maintain anaerobic conditions in the BA chamber (Fig. 1).

2.2. Biocatalyst and substrate composition

The biotic anode chamber (BA) was inoculated with pretreated microbial consortia obtained from an already operating microbial fuel cell with 3 g/l glucose as the carbon source. The essential nutrients were provided as designed synthetic wastewater (DSW, g/l: NH_4Cl-0.5, KH_2PO_4-0.25, K_2HPO_4-0.25, $MgCl_2$-0.3, $CoCl_2$-0.025, $FeCl_3$-0.025, $ZnCl_2$-0.0115, $NiSO_4$-0.050, $CuCl_2$-0.0105, $CaCl_2$-0.005 and $MnCl_2$-0.015) (Nikhil et al., 2016). The inoculum was administered into the reactor (with 10%v/v) using a long needle syringe and the contents were adjusted to pH 6. The cathode chamber (AC) was fed with deionized distilled water at pH 7.4 to avoid the development of ionic gradient between mDC and AC. Synthetic ground water (SGW mg/l: $CaCO_3$-200, $CaSO_4$-272, 4 $MgCO_3$.Mg $(OH_2)\cdot 5H_2O$-194, $NaHCO_3$-252, KCl-75) (Stewart et al., 2006) was prepared in distilled water. The SGW after adjusting pH to 7 was filtered prior to feeding the mDC. All the redox adjustments were made using 0.1 N HCl and 0.1 N NaOH.

2.3. Operation

Post the start-up the MDCs were operated in batch mode in two phases viz., initial stabilization phase and desalination phase. During the stabilization phase, the MDC was allowed to acclimatize to enable biocatalyst-electrode interactions (6–8 days). During the stabilization period the anolyte and catholyte were replaced for every 48 h. The mDC was operated at lower salt concentration (1800 mg/l). The end of the stabilization phase was determined by the stable cell voltage and substrate removal recorded. Later, the MDC were operated with SGW (2500 mg/l) and the hydraulic retention time (HRT) of 48 h at ambient room temperature (24 ± 3 °C). The system performance was analyzed based on desalination efficiency and rate of desalination.

2.4. Analysis

The total dissolved solids (TDS, mg/l), pH and conductivity (EC) were monitored using compact multi-parameter analyzer (HANNA-5522-02). The changes in the TDS concentrations in mDC, BA and AC were used to calculate the desalination efficiency (DE) using (Eq. (1)), where C_i and C_f represent the initial and final TDS concentrations of the middle desalination chamber respectively (Nikhil et al., 2016; Zuo et al., 2014). The groundwater hardness was quantified titrimetrically using EDTA and was calculated in terms $CaCO_3$ equivalent (mg/l) (Eq. (2)).

$$DE\ (\%) = \frac{Ci - Cf}{Ci} \tag{1}$$

$$\text{Total Hardness} = \frac{volume\ of\ EDTA \times N \times 50 \times 1000}{Volume\ of\ sample} \tag{2}$$

Where N is normality of EDTA (0.02 N), 50 is equivalent weight of $CaCO_3$, volume of sample taken was 20 ml and volume of EDTA is the burette reading. The chemical oxygen demand (COD) of the anolyte was determined using the closed reflux titrimetric method (APHA, 1998). The metabolic intermediates and total volatile fatty acids (VFA) were analyzed using standard methods (APHA, 1998). The composition of VFA was determined by HPLC (Shimadzu LC20A) using refractive index detector (RID 20A; 0.5 ml/min). The sample (0.020 ml) was injected to Rezex column (300 × 7.80 mm; Phenomenex; 80 °C).

The open circuit voltages were recorded using source measure unit (Keithiley, 2400) with a 5 min interval. Post the stabilization phase polarization analysis was performed using a variable resistance box (external resistance from 30 kΩ to 0.05 kΩ) while recording voltage and current using a multimeter. The bioelectrochemical behavior of the biocatalyst in BA was monitored using a potentiostat (Bio-Logic-VMP$_3$). Cyclic voltammetry (CV) and linear sweep voltammetry (LSV) were carried out with a three-electrode setup using anode as working electrode (E_{we}) and cathode as counter electrode (E_{ce}) against Ag/AgCl (3.5 M KCl) reference electrode (R_e) for both open and closed modes of operation. CV