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Improved recovery of bioenergy and osmotic water in an osmotic microbial fuel cell using micro-diffuser assisted marine aerobic biofilm on cathode

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ABSTRACT

The research work demonstrated the performance of an integrated MFC capable of recovering osmotic water and electricity using forward osmosis in a double-chambered baffled channel reactor. The potential of applying electrochemically active (EA) aerobic marine biofilms on the cathode electrode was explored by eliminating the costly Pt-catalyst, thus making the system more eco-friendly and sustainable. The bio-cathode osmotic microbial fuel cell (OsMFC) used in this study was operated by two different conditions of oxygen supplied into the marine EA biofilms (i.e., the conventional oxygen supply by perforated pipes, and the enhanced oxygen supply by micro-pore air diffuser). The system recovered a maximum electrical power, 28.90 W m^{-3} net cathodic compartments (NCC), while removing 63 ± 8% of COD from raw domestic wastewater. The rate of osmotic water recovery was 1.46 ± 0.04 L m^{-2} h^{-1}. The amount of recovered osmotic water showed a great potential for integrating osmosis into the marine bio-cathode OsMFC. The dominating bacterial communities identified in the cathodic biofilms were mainly gamma-Proteobacteria and alpha-Proteobacteria.

1. Introduction

Reuse of wastewater and desalination of seawater are the best possible alternatives for the global shortage of freshwater supply [1,2]. Currently all the desalination technologies are energy intensive process [3]. A recent study reported that the energy consumption for reverse osmosis (RO) would be 1.8 kWh m^{-3}, if the energy requirement for pump was considered without considering the energy requirement for pretreatment [4]. On an average, the energy consumption of RO including pretreatment and pumping was 3.5 ± 0.5 kWh m^{-3}. This cost was significantly higher than the cost of conventional wastewater treatment [3]. Thus, an energy efficient desalination process for global community is essential.

MFC is a new promising technology for the extraction of clean energy. The device uses bacteria as biocatalysts to generate electricity by digesting biodegradable organics present in wastewater [5–9]. Electrons produced by biofilms through the metabolic process are transferred to the anode electrode by conductive monomeric proteins present on the cell membrane (Cytochrome c) or conductive nano-wires present on the outer wall of the bacteria cell [10–12]. Then, the electrons travel from the anode towards the cathode through an external resistor by the electro-motive force (i.e. the difference in redox potential generated between the anode and the cathode due to bio-chemical reactions). The produced protons at anode electrode were diffused through the membrane and reached to the cathode. In the cathode, these combine with oxygen and electrons (traveling through the outer circuit) to form water [5,8,9,13]. This technology is one of the most inexpensive alternative solutions for the production of clean energy by removal of organic wastes from wastewater [9,14–20]. However, the technology showed high potential to recover clean energy, but low potential to produce good quality water [15,19,21]. That is why, few recent studies have modified the MFC technology to achieve desalination by dialysis process [22–24], or by osmosis process [25,26] to produce good quality water. Therefore, a desalination integrated MFC that is proficient for treating wastewater, extracting freshwa-

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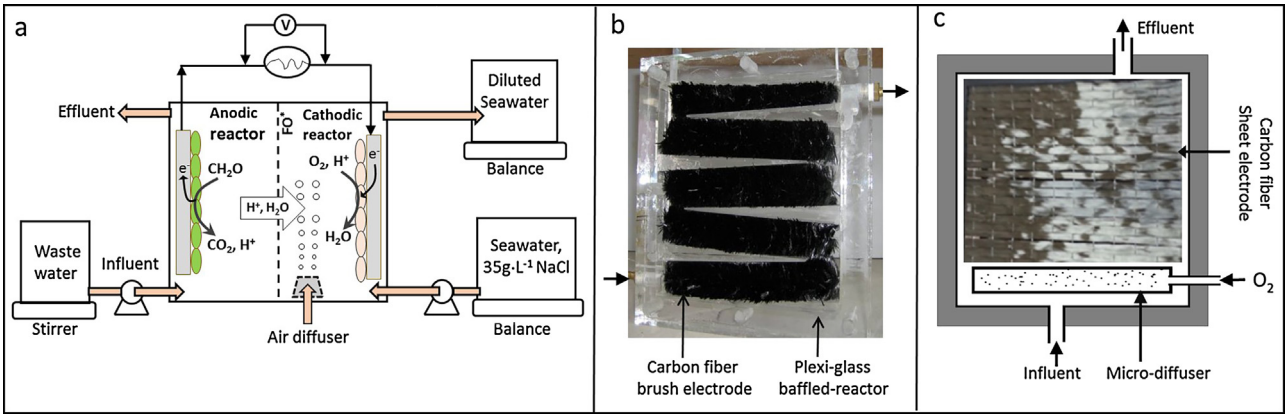

Fig. 1. (a) The bio-cathode based OsMFC system showing all the fluid flows and electrical connections; (b) Internal architecture of anodic reactor with placement of carbon fiber electrode; (c) Internal architecture of cathodic reactor with placement of carbon fiber sheet electrode (**FO: Forward osmotic membrane*).

ter, and recovering clean energy is being competitive in the field of producing bioenergy and freshwater.

Some recent studies have applied forward osmosis (FO) membrane in bioreactor to recover osmotic water flux from the treatment process of wastewater [27–29]. FO is a phenomenon of spontaneous flow of the water molecules from a solution containing lower concentration of solutes to a solution containing higher concentration of solutes across a semi-permeable membrane [30,31]. The driving potential for FO is the concentration gradient on both sides of the membrane [32,33]. The FO processes have few distinct advantages; firstly, natural osmotic flow does not use any external energy; secondly, it has lower propensity of membrane fouling due to low concentration polarization [34]. That is why; the integration of osmosis in MFC could generate an added benefit by extracting osmotic water flux from the treatment process of wastewater without any extra cost. Recent literature reports have demonstrated the integration of osmosis in MFC for simultaneous recovery of osmotic water, treatment of wastewater and production of bioelectricity using an FO membrane between the anode and the cathode [26,35]. Such integrated OsMFC device showed lower internal resistance for voltage generation due to the concurrent transport of protons with osmotic water flow, and higher anodic columbic efficiency due to the prevention of oxygen leakage by reverse permeate flow [25]. The understanding of those bio-electrochemical phenomenon for optimizing the electricity and osmotic water recovery by OsMFC are currently under investigation [25,35]. However, all the previous OsMFC studies used Pt-coated air-cathode system, in which the metallic catalysts (Pt, Pt-Co, etc.) [26,35] were prone to fouling by the deposition of cations on it [36]. The utilization of Pt catalysts on the OsMFC cathode also made the system costly and unsustainable for long-term application. That's why, the current study focused the replacement of expensive Pt catalysts by an effective marine aerobic biofilms, which is free of cost. This application of marine biofilms on OsMFC could be a sustainable and eco-friendly alternative for low-cost MFC technology.

The objectives of this research were (i) to investigate the possibility of applying aerobic marine biofilms on the cathode in place of costly metallic catalysts of an OsMFC (i.e. assist in simultaneous production of bioelectricity, treatment of wastewater, and recovery of osmotic water flux); (ii) to determine the optimum removal of organics in anode chamber, and to recover osmotic water flux in cathode chamber; (iii) to optimize the stable electricity production based on this marine bio-cathode OsMFC; (iv) to identify the best condition of oxygen supply to cathode biofilms; (v) to identify the bacterial communities involved in formation of cathodic biofilms; and (vi) to understand its shortcomings and their further improvements.

2. Materials and methods

2.1. Design of OsMFC reactor

The marine aerobic bio-cathode OsMFC consisted of two acrylic chambers, anode and cathode, separated by a FO membrane. Domestic wastewater pumped into the anodic chamber, where bacteria promoted the oxidation of organics and produced electrons and protons. The produced electrons during the anaerobic oxidation process were collected at anodic electrode and diverted towards the cathode electrode. In the cathode, electrons were consumed by oxygen. These reduction reactions were catalyzed by EA aerobic marine biofilms. A peristaltic pump (master flex, USA) continuously pumped seawater containing $35 \pm 2\,g\,L^{-1}$ of NaCl into the cathode chamber. Due to osmotic pressure, a continuous flux of osmotic water was created from the anode towards the cathode chamber through the FO membrane. The designs of the integrated OsMFC system as well as the internal architecture of the anode and the cathode electrodes were demonstrated in Fig. 1.The anode chamber had an internal dimension of $15 \times 15 \times 2.5$ cm as length, width and depth, respectively. The chamber was staggered by four trapezoidal bays, which made a long up-flow baffled channel. The trapezoidal bay inclined horizontally at 4.1° to facilitate the collection of possible produced gas (i.e. any possible gas in anode chamber). The baffled channel volume in the anode chamber was 0.5 L or 0.5×10^{-3} m^3 and its total length was 0.62 m (mid line length). The cathode chamber had an internal dimension of $15 \times 15 \times 1$ cm with a total volume of 0.225 L or 0.225×10^{-3} m^3. There were four trapezoidal bays inside the anode chamber with a total area of 45 cm^2. The trapezoidal bays blocked the water flow area through the FO membrane from the anode to the cathode chamber. After reducing the blocked area by the trapezoidal bays, the net membrane area for FO was 180 cm^2.

The anode chamber was filled with a long square cross-sectional fiber brush. The brush was made of carbon fibers (PANEX35 CONTINUOUS TOW, 50 K, ZOLTEK, USA) and possessed properties as: tensile strength of 3.8×10^6 kPa, tensile modulus of 241×10^6 kPa, and density of 1.81 g cm^{-3}. The carbon fiber bunches were cut to a designated length and wound using an industrial brush manufacturing system into a twisted core consisting of two stainless steel wires (0.5 mm diameter). Then the circular cross sectional brush was trimmed to a square cross-sectional brush (3 cm each side, 9 cm^2 sectional area) using a hair dressing electric razor so that the brush could completely fill the square cross-sectional up-flow channel (Fig. 1b). Prior to use, the carbon fibers were treated with ammonia gas as described by Cheng and Logan [21,9]. The mass of the carbon fibers used in anode electrode was 20 ± 1.5 g. In cathode