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Pluggable microbial fuel cell stacks for septic wastewater treatment and electricity production

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HIGHLIGHTS

- A pluggable microbial fuel cell stack with easy installation, operation, and low cost.
- The scale-up MFC can be easily implemented in septic systems.
- Detailed electrochemical characterization reveals system improvement potential.

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ABSTRACT

Septic tanks and other decentralized wastewater treatment systems play an important role in protecting public health and water resource for remote or developing communities. Current septic systems do not have energy production capability, yet such feature can be very valuable for areas lack access to electricity. Here we present an easy-to-operate microbial fuel cell (MFC) stack that consists a common base and multiple pluggable units, which can be connected in either series or parallel for electricity generation during waste treatment in septic tanks. Lab studies showed such easy configuration obtained a power density of 142 ± 6.71 mW m^{-2} when 3 units are connected in parallel, and preliminary calculation indicates that a system that costs approximately US $25 can power a 6-watt LED light for 4 h per day with great improvement potential. Detailed electrochemical characterizations provide insights on system internal loss and technology advancement needed.

1. Introduction

Traditional decentralized wastewater treatment systems (DWATS) such as septic tanks and pour flush latrines are cost-effective and low-maintenance ways to protect public health and water resource. In the US, approximately 20% of all homes or 20 million people use septic tanks for the primary wastewater treatment (Zamalloa et al., 2013). In developing countries, billions of people rely on DWATS to provide basic sanitation and protect public health. The wastewater stored in DWATS contain high strength organics, up to 1.47×10^7 J kg^{-1} COD (Shizas and Bagley, 2004), which can be potentially converted to usable energy for onsite use. Such local and renewable energy source can be especially valuable to households that are lack access to electricity.

Microbial fuel cells (MFCs) are an emerging technology that produces direct electricity from wastewater using exoelectrogenic microorganisms. (Wang and Ren, 2013; Logan and Rabaey, 2012; Li et al., 2014). The performance of MFCs has increased dramatically in the past decade, but many MFC studies for wastewater application focused on replacing big aeration tanks to save energy in centralized treatment plants, yet few work has looked at converting DWATS to energy neutral or energy positive systems. Current development of large scale MFC systems for centralized utilities is facing challenges on reactor configurations and cathode systems (Li et al., 2014; Wang and Ren, 2013). While using liquid catholyte is not feasible for such applications, air-cathode using free O_2 as the electron acceptor has been considered more sustainable. However, the structure of air cathode has been complicated, the cost has been high, and the power output remains low compared with other type of cathodes (Zhuang et al., 2012; Forrestal et al., 2014; Zhang et al., 2010). Stacks of MFC units are generally needed to provide applicable voltage or current for direct utilizations, and they can be either connected in parallel or series. However, the power output of the whole system can be significantly affected by one or a few low-performing units, a phenomenon called

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voltage reversal (Wang et al., 2012; Kim et al., 2011). When one unit gone bad, it is hard to take the unit offline due to the interconnection of the many cells, and it becomes a maintenance headache. While the MFC technology holds great potential for converting DWATS to energy generating systems, these challenges make the development and deployment of MFC systems in developing countries extremely difficult, because for such applications the cost has to drop dramatically (to approximately \$20 dollar per unit), the system has to be simple and easy to operate (for non-educated users), and the materials and replacement parts have to be locally available for easy replacement. All these factors are deemed critical during our field studies in Uganda through the Gates Foundation Reinvent the Toilet Grand Challenge program.

In this study, we present an easy pluggable MFC stack for decentralized wastewater treatment and electricity production. Individual column MFC units are connected using a common base and the compact MFC stack float in septic or holding tanks to convert organic waste to electricity. If one unit is broken, it can be easily taken offline for repair, or a new unit can be plugged in as easy replacement, so the whole system won't be compromised. The units can be made available in local hardware stores for easy repair or replacement. We tested performance of a 3-unit prototype system in terms of organic removal and energy production, and we conducted electrochemical characterizations and basic cost analysis to understand the advantages and challenges associated with the design.

2. Methods

2.1. MFC stack design and construction

Column air-cathode MFC units without metal catalysts were built by wrapping an assembly of anode, separator, and cathode layers around a perforated PVC plastic tube (L 19 cm × D 3.5 cm), with the anode facing outside exposed to the liquid, and the cathode layer facing inside exposed to air (Lu et al., 2014). Activated carbon cloth (ACC, Zorflex®, Chemviron, UK) was used as the anode, and the air-cathode was constructed according to Zhang et al. (2010) and Lu et al. (2014) by applying 3 layers of polymethylsiloxane (PDMS, Dow Corning®, MI) diffusion layers on activated carbon cloth but without Pt catalysts. Three layers of J-cloth (DuPont™ Sontara®, style 8864) were used as the separator between the two electrodes (Zhang et al., 2009; Haeger et al., 2014). Three column MFC units were then screwed into a common PVC T-connector base, in which passive air circulation can be conducted through the units (Fig. 1). The MFC stack was placed into a 3 L container with synthetic wastewater to simulate DWATS conditions.

2.2. Reactor inoculation and operation

The reactor was inoculated with anaerobic sludge from the Boulder Water Resource Recovery Plant, and the volume ratio between the sludge and the media was 1:9. The medium with 50 mM phosphate buffer solution (PBS) contained (per liter) 1.6 g $NaCH_3COO$, 0.13 g KCL, 0.31 g NH_4CL; 5.84 g $NaH_2PO_4 \cdot H_2O$, 15.5 g $Na_2HPO_4 \cdot 5H_2O$, and trace minerals and vitamins (Luo et al., 2012a; Forrestal et al., 2012). The MFC units were operated separately under 100 Ω resistance in a common container without connecting to each other, and when 3 repeatable voltage generation cycles were obtained, the 3 MFC units (1, 2 and 3) were connected in series or parallel and operated for another 3 months. All operations were conducted in fed-batch mode in room temperature (22 ± 2 °C), and the media solution was replaced when MFC voltage dropped below 0.20 V. (Huggins et al., 2014).

2.3. Analysis

The voltage V (V) crosses the external resistor was measured every 10 min using a data acquisition system (Keithley, OH), and the current (A) was determined according to Ohm's law, $I = V/R$. To measure the internal resistance, the MFC units were connected to a Gamry Potentiostat in a two-electrode mode, with the anode serving as the working electrode and cathode acting as both reference and counter electrode (Luo et al., 2012b). Due to the very tight space between the electrodes, it was not possible to use 3-electrode system. The electrochemical impedance spectra (EIS) measurements were performed by using an interface instrument Gamry (Interface PC4.3000™, NJ, USA), after the reactor was operated under open circuit conditions for 1.5 h. The impedance spectra were recorded in the frequency range from 0.01 to 100,000 Hz by applying a sinusoidal excitation signal of 0.10 V (Luo et al., 2012a). The data were fitted to an equivalent electrical circuit by using the Ec-Lab® (version 10.37) impedance analysis software (Ramasamy et al., 2008). Chemical oxygen demand (COD) was measured using standard method colorimetric (Method 5220, HACH Co., CO). Columbic efficiency was calculated as the ratio of total coulombs transferred to each circuit from the substrate to the maximum possible coulombs if all substrate removal produced current.

3. Results and discussion

3.1. Performance of individual MFC units

The voltage profiles of the 3 individual column MFCs are shown in Fig. 2. While for each MFC, the consecutive batches show stable

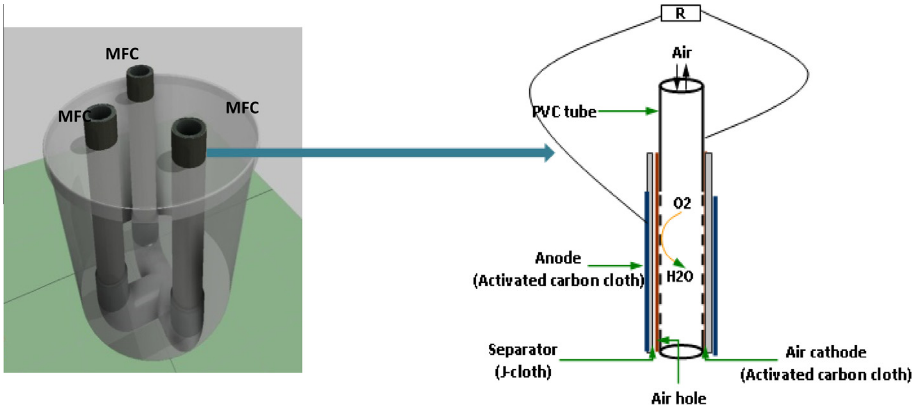

Fig. 1. Schematic design of and detailed structure of the pluggable microbial fuel cell stack.