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Evaluation of long-term performance of sediment microbial fuel cells and the role of natural resources

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HIGHLIGHTS

- Doping an electron donor onto the anode allowed quicker power generation and a higher maximum power.
- However, when we compared long-term performances, we found that the improvements were temporary.
- The differences in community structure made no difference in power generation.

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ABSTRACT

Sediment microbial fuel cells (SMFCs) are expected to be used as a renewable power source for remote environmental monitoring; therefore, evaluation of their long-term power performance is critical for their usability. In this paper, we present novel data needed to understand the long-term performance of SMFCs. We used 3-D Microemulsion (3DMe)™ doped anodes, which slowly release lactate and its fermented products. During our tests, anode-limited SMFCs with and without 3DMe-doped anodes were operated for more than 18 months with a load simulating a sensor operation. We found that doping an anode with an electron donor reduced startup time and increased maximum power (55 ± 2 μW compared to 46 ± 2 μW) in the control systems. We found that the long-term steady power performance is approximately 33% of the maximum power (~18 μW). Finally, our small-sized SMFCs generated higher power densities than those in the literature (28 mW/m^2 versus 4 mW/m^2). Using electron donor doped anodes can be practical when a short startup time and initial high power are needed. However, if long-term power is critical, the addition of an electron donor does not provide a practical advantage. In addition, in long-term operation enrichment of the anode surface with electrochemically active bacteria does not provide any advantage.

1. Introduction

Sediment microbial fuel cells (SMFCs) are used as a renewable power source to operate remote sensors for environmental monitoring [1]. They are deployed in lakes, rivers, and oceans [2,3] and generate power where needed without maintenance [3,4]. The main advantages of SMFCs are that they do not generate toxic wastes and that they can be used to power autonomous sensors. The organic compounds in the sediment serve as a source of renewable fuel. Electrons are generated by the oxidation of organics near the anode by native microorganisms present in the sediment [5–7]. These electrons are transferred to the cathode, where they reduce oxygen [8]. In natural systems, natural organic matter (NOM) is renewed by sedimentation processes that provide a continuous flux of organic carbon to the anodes. The oxidation of organic carbon in water produces protons and electrons according to the following reaction:

$$\text{NOM (organic-C)} \xrightarrow{\textit{microorganism}} CO_2 + H^+ + e^- \quad (1)$$

The microorganisms act as a catalyst for this reaction. Therefore, an increase in the reaction rate on the anode (Eq. (1)) can increase the power from an anode-limited SMFC, as the anode reaction (Eq. (1)) is catalyzed by so-called electroactive bacteria. Therefore, the turnover rate is influenced by the types of native microorganisms inhabiting the sediment [3,9–12], and by the availability of NOM [13,14]. Accordingly, the reaction rate is expected to be increased by the addition of organic substrate and by the enrichment of the anode with electroactive bacteria [15]. This is relevant to the practical application of SMFCs as a power source, as an increase in the reac-

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tion rate on the anode directly increases the power output of an anode-limited SMFC.

Initially, a clean anode and a cathode are deployed in the sediment and the water, respectively, to start an SMFC. The cathode generates cathodic current immediately by reducing dissolved oxygen [16]. Depending on the design, electrode material and operating conditions, the cathode of an SMFC can be operated as a non-limiting electrode and can drive the anode potential to values higher than the open circuit potential [17,18]. The anode can then be used as a solid electron acceptor, which promotes the growth and attachment of electroactive bacteria to the electrode surface [19,20]. The electroactive bacteria on the anode surface are typically grow slow because of the low concentration of organic carbon in natural sediment. However, their growth can be speeded up by artificially increasing the concentration of organic substrates near the anode. Previous studies reported that the addition of organic substrates increases the anodic current and power of SMFCs [9,21–28]. Most of the current literature work is focused on short-term performance evaluation. However, to use SMFCs as a remote renewable power source it is necessary to know their power performance over a long term. SMFCs are expected to be used to power autonomous sensors for years, not a few months. In addition, improvements in power performance when anodes are doped with organic substances have only been demonstrated for short periods [20,28,29]. Short-term power data cannot be used to predict the long-term performance of SMFCs. To date, limited knowledge is available on the long-term power performance and the changes in the microbial community of SMFCs after the addition of an electron donor. Our research was designed to address these limitations.

The goals of this work are (1) to shorten the startup time and increase the power performance of SMFCs by doping the anodes with an electron donor, (2) to test the long-term performance of these SMFCs, and (3) to quantify their microbial community structures and correlate them with the power performance. Since we are interested in the longer-term performance of SMFCs, an organic compound may be more effective if it can be released slowly. The use of slow-release organic compounds is not new. They have been used for many different environmental applications: (1) to accelerate the bioremediation of chlorinated volatile organic compounds [30], (2) to accelerate the biodegradation of volatile organic compounds in groundwater [31,32], (3) to facilitate hexavalent chromium removal in aquifers [33], (4) to accelerate the bioremediation of trinitrotoluene [34], (5) to accelerate the biodegradation of chlorinated solvents at contaminated sites [35] and (6) to facilitate chromium reduction in groundwater [36]. All these examples demonstrate that the slow release of organic compounds can enhance microbial activity in the long term. Therefore, we expected that it would improve microbial activity near the anodes of SMFCs as well as their long-term performance. In this research we used a slow-release organic compound known as 3D Microemulsion (3DMe™, Regenesis, San Clemente, CA 92673, USA). When added to the environment, 3DMe is hydrolyzed and produces a controlled release of lactate [36,37]. The 3DMe is released in three stages. In the first stage, free lactate is released and acts as an immediate substrate. In the second stage, the polylactate ester based portion is metabolized and releases additional lactate. After approximately a year of deployment (third stage), the electron donors in the environment are mainly fermented products, such as acetate and hydrogen. Because of the organic compounds released by the 3DMe, we expected that the experimental SMFCs would start more rapidly and generate higher power than the control SMFCs (without 3DMe). In addition, these organic compounds in the presence of the anode were expected to enhance electrode-respiring activity, resulting in an increase in electroactive microorganisms near the anode [28]. Overall, these combined effects were expected to increase the power performance of the SMFCs.

In this research, we constructed SMFCs to test the feasibility of using 3DMe to shorten the startup time and improve the long-term power performance. We used anodes with and without 3DMe. We called an anode without 3DMe a control anode and an SMFC operating with a control anode a control SMFC. The SMFCs were designed such that the surface area of the cathodes was much larger than that of the anodes so that the cathode would not be the limiting half-cell. In addition, this eliminated other variables affecting cathode performance which could have been reflected in the performance of the SMFCs. To simulate the operation of a sensor, we used a microbial fuel cell tester (MFCT) [18]. The SMFCs were operated more than 18 months to evaluate long-term performance. Finally, we investigated microbial community structure to determine whether the addition of 3DMe caused any change.

2. Material and methods

2.1. Sediment microbial fuel cells

Fig. 1 is a schematic diagram of the SMFCs used in this work. Each SMFC was assembled with an anode and a cathode. We used 10-L plastic buckets with a working volume of 9.5 L. The sediment and water used in this study were taken from the South Fork of the Palouse River in Pullman, WA. The characteristics of the sediment and water chemistry have been previously described [38]. The anode was made of porous graphite (Fuel Cell Store, College Station, TX 77845, USA), and the cathode was made of graphite felt (HP Materials Solutions, Inc., Woodland Hills, CA 91367, USA).

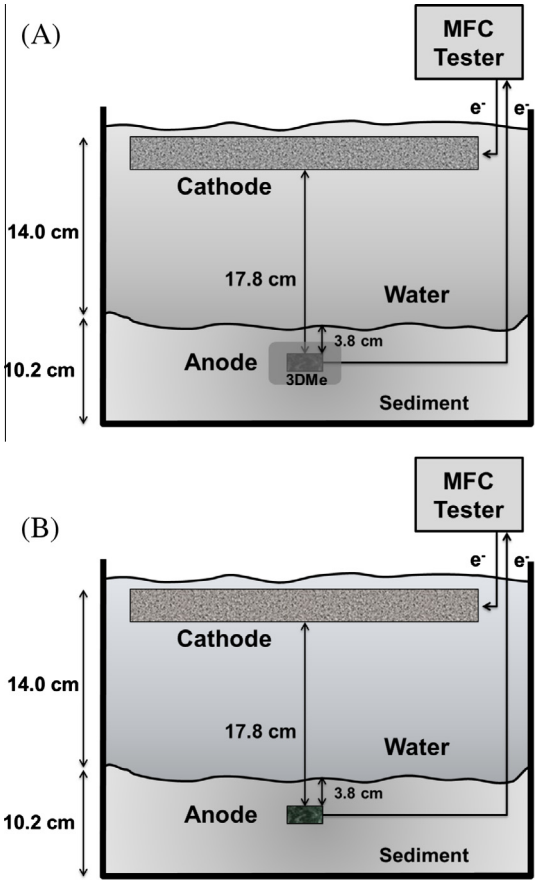

Fig. 1. Schematic diagram of (A) SMFC with 3DMe-doped anode (highlighted) and (B) control SMFC. The figures are drawn without scale for simplicity.

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