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Auto-feeding microbial fuel cell inspired by transpiration of plants

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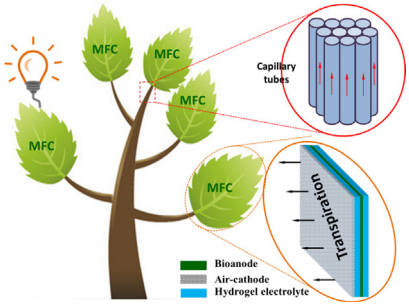
HIGHLIGHTS

- A concept of auto-feeding microbial fuel cell is reported.
- The fuel was auto-fed without assistance of any external equipment and power input.
- The auto-feeding was realized by mimicking the transpiration process of plants.
- The auto-feeding microbial fuel cell generated a power density of 295.5 W m^{-3}.
- This study provides a unique way to fabricate self-sustaining portable MFCs.

GRAPHICAL ABSTRACT



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ABSTRACT

Inspired by the transpiration process in plants, we report an auto-feeding microbial fuel cell (AF-MFC), in which the fuel (substrate solution) is fed automatically through a process similar to transpiration in natural plants without using any external equipment and applying extra power. The AF-MFC consisted of a bioanode, an air–cathode, hydrogel electrolyte, and a glass capillary feeding channel. The auto-feeding process was realized by the fact that evaporative loss of water from the air–cathode of the AF-MFC reduces pressure in the hydrogel electrolyte; which, in turn, pulls substrate solution to the AF-MFC to maintain hydration of the hydrogel electrolyte. The AF-MFC was able to generate a stable voltage of 0.55 V across a 1000 Ω resistor and a maximum power density of 1182 ± 115 mW m^{-2} (normalized to the projected area of air–cathode) and 295.5 ± 28.8 W m^{-3} (normalized to the total volume of the MFC). This study thus provides a new way to fabricate self-sustaining portable MFCs and greatly simplifies the feeding system of the MFCs.

1. Introduction

Some bacteria, referred to as anodophilic bacteria, electroactive bacteria, anode respiring bacteria or electricigens, generate electrons when oxidizing organic matter [1]. Microbial fuel cell (MFC) is one of the most promising energy conversion devices that takes advantage of metabolism of electroactive bacteria to convert chemical energy into electrical energy [2,3]. The chemical energy stored in the organic wastes, such as municipal or domestic wastewaters (WWs), agricultural residues, animal manure, and industrial WWs can serve as the fuel sources [4] for electroactive bacteria in the anode chamber. The pollutants like heavy metal ions [5,6], nitrate and sulfate can act as electron acceptors and be removed in the cathode chamber of MFCs [7]. Thus, the MFC technology holds a great promise for recovering energy from waste organics [8,9] and bioremediation processes [5,6]. However, the realization of practical applications of large-scale MFCs for WW treatment is hampered mainly due to the low efficiency of pollutant removal resulted by the low current or power outputs [10,11].

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Instead, small-size MFCs, e.g., miniaturized and micro-size MFCs are considered or proposed to be promising for portable device applications, such as mobile power sources [12] and biosensors [13].

In comparison to the conventional MFCs, small-size MFCs show better performance because of the larger surface area-to-volume, smaller diffusion resistance, and shorter response times [14–16]. Small-size MFCs have relatively small cell chambers and thus contain a small quantity of electrolyte. Due to the characteristics of good fluidity and ion mobility, aqueous electrolyte is usually used in such MFCs to ensure a stable substrate feeding pattern in the anode chamber. However, substrate supply to the MFCs is usually realized by manually refreshing the aqueous media in batch reactors or by continuous feeding with the assistance of external equipment (e.g., pump) and extra power. A self-sustainable MFC serial-connection stack, in which the power required for the substrate supply is generated by the MFCs, has been demonstrated [17]. However, this approach is cumbersome and might not be suitable for the portable devices. Recently, paper-based self-feeding systems were designed based on the capillary phenomenon of paper and applied to the biofuel cell [18], as well as MFCs [19]. Substrate self-feeding without external equipment and power input would be advantageous to the practical application of the small-size MFCs. Besides substrate feeding, the cathode design is of great importance for the small-size MFCs [20]. The most feasible and convenient cathode configuration for the conventional MFC is air-cathode, in which oxygen is fed by self-diffusion instead of aeration to take part in the oxygen reduction reaction. The non-limiting availability of oxygen to the air-cathode, ultimately makes it possible to achieve higher current densities. However, the use of air-cathode in small, especially miniaturized MFC devices [21,22] is limited by the inevitable water loss due to evaporation through the air-cathode of MFC [23], which leads to unstable power generation.

In nature, water containing nutrients required for normal metabolism of plants is auto-fed by a process called transpiration. In this process, water is absorbed from the soil and transported to and evaporated from the aerial parts like leaves. Studies have shown that the primary impetus for the transport of water is negative pressure generated by the transpiration process [24,25]. Besides the reduced pressure, capillary action in the vascular structure of the plants is also one of the important driving forces for the transpiration process. Under the synergistic actions of both forces, water in the plants is pumped from the soil to more than one hundred meters height, for example, in the case of *Sequoia sempervirens,* a tree with height over 115.72 m [26].

Inspired by the transpiration process of the plants and taking advantage of the respirable characteristic of the air-cathode, herein we report a concept of auto-feeding MFC (AF-MFC) to realize the substrate self-feeding in MFCs without any external equipment and power input. First, the hydrogel performance was studied and optimized for the water evaporation rate and feeding capacity, and then the performance of the AF-MFC was evaluated in terms of voltage and power outputs. Based on this concept, an MFC "tree" can be built for simultaneous soil remediation and power generation processes, as illustrated in Fig. 1.

2. Materials and methods

2.1. Fabrication of AF-MFC

Carbon black modified stainless steel mesh (CB/SSM) was used as the anode material of the AF-MFC. The CB/SSM was prepared by binder-free coating of CB onto the SSM as reported in our previous work [27] and described in SI-1. Before the fabrication of the AF-MFC, electroactive biofilm was pre-grown onto the CB/SSM to form a bioanode according to the protocol published elsewhere [28] and described in SI-2. The air-cathode was fabricated by the rolling method using activated carbon as the oxygen reduction catalyst and stainless steel mesh as a current collector [29], as described in SI-3. The hydrogel electrolyte (HE) was prepared by swelling a superabsorbent polymer, sodium polyacrylate into 50 mM PBS containing 20 mM acetate and 12.5 mL L^{-1} each of vitamin and trace metal solutions as described elsewhere [27].

The AF-MFC consisted of bioanode, air-cathode, HE and HE filled glass capillary (abbreviated as HE-GC) feeding channel. It was constructed using two rubber gaskets and two plexiglass plates (Fig. 2A). The two rubber gaskets and one plexiglass had circular hollow spaces with the same diameter of 3.8 cm. The thickness of the rubber gaskets was 2 mm. The CB/SSM bioanode ($1 \times 3.8\ cm^2$) was sandwiched between the two hollow rubber gaskets, and the air-cathode was placed between one hollow rubber gasket and the hollow plexiglass plate with the diffusion layer facing to the air. The void space left by the two hollow rubber gaskets functioned as the cell chamber to store the HE. The HE was filled in to encapsulate the CB/SSM bioanode with a pre-grown electroactive biofilm. The HE also played the role of separator between the CB/SSM bioanode and the air-cathode (Fig. 2B). Feeding solution was stored in a sealed bottle and put underneath the MFC. In between the HE-GC was connected, which served as a solution feeding channel (Fig. 2Ca). The HE-GC was prepared by filling the sodium polyacrylate hydrogel swelled by 20 mM acetate solution in a glass capillary (GC). Another GC was used to connect the inner and outer atmosphere of the bottle to ensure a constant pressure (Fig. 2Cb). The distance between the bioanode and the air-cathode was approximately 2 mm. The whole AF-MFC consisted the electrodes with a thickness of about 4 mm and volume of about 4.5 mL (Fig. 2Cc).

2.2. Evaluation of the water transport rate in AF-MFC

To evaluate the water evaporation rate (r_e) of the air-cathode, a hydrogel MFC without solution feeding was used. It was determined according to:

$$r_e = \Delta m_{MFC}/t$$

where, the Δm_{MFC} is the weight loss of the hydrogel MFC without solution feeding, and the t is the time.

In order to evaluate the maximum solution feeding rate (defined as a limited feeding rate, r_f) through the GC and HE-GC channels, a blower was used to accelerate the water evaporation rate and maximize the water loss from the air-cathode, as shown in Fig. S3. The blower was used only for measuring the r_f, but not for the following operation of the AF-MFC. The r_f of the capillary was evaluated by water loss rate in the bottle and determined according to:

$$r_f = \Delta m_s/t$$

where the Δm_s is the mass of water loss in the feeding solution, and the t is the time. The r_f of the HE-GC with different inner diameters (Viz., 0.1, 0.3, 0.5, 0.9 mm) and heights (Viz., 2, 4, 6, 8, 12 and 16 cm) were measured. The r_f of the pristine GC was also measured for comparison purpose.

2.3. AF-MFC performance test

The schematic diagram of the AF-MFC is shown in Fig. 2B. The aqueous feeding solution containing acetate was stored in a weighing bottle. Before use, the bottle and the substrate solution were autoclaved and sealed to avoid bacterial contamination in the feeding solution. One HE-GC was used as the channel to feed the substrate solution to the AF-MFC. To ensure pressure equilibrium, another GC without hydrogel was used to connect the feeding bottle with the external atmosphere. The water in the HE was naturally evaporated through the air-cathode of the AF-MFC without using any other equipment and applying extra power. To investigate the relationship between the substrate balance and the performance of AF-MFC, acetate solutions with concentrations of 20, 40 and 60 mM were used. The cell voltages of the AF-MFCs across a 1000 Ω resistor were recorded every 5 min by using a data acquisition system (HIOKI LR8431-30). The polarization curves were recorded by