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Effects of initial sediment properties on start-up times for sediment microbial fuel cells

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ABSTRACT

Sediment microbial fuel cells (SMFCs) are being developed as a renewable power source to aid environmental remediation and provide remote monitoring. But long start-up times limit their use as a viable industrial approach. In this study, we sampled sediments from seven different levels of eutrophication lakes and investigated the effects of their initial sediment properties (ISP) on the start-up times of SMFCs. After 60 days, ISP showed a clear influence on SMFCs with start-up times ranging from 7 to 21 days at different sampling sites. Organic matter, especially the labile carbon pools and nitrogen (organic and inorganic) contents in sediment, were closely related to start-up times for the SMFCs. In addition, dehydrogenase activity and high-throughput sequencing revealed that microorganisms in the nutrient enrichment sediments increased organic matter degradation and produced special species such as genus *Candidatus Xiphinematobacter* that belong to the *Verrucomicrobia* phyla related to electron transfer. Such active control may improve applicability by accelerating start-up and enhancing SMFC power and bio-catalytic performance.

Introduction

Lakes and other aquatic environments including urban lakes contain sediment caused by rock weathering and soil erosion that carry organic matter, nitrogen and other pollutants that can threaten the integrity of the ecosystem [1]. The removal of contaminants in these sediments is becoming an increasingly important part of mitigating growing risks to the environment.

In the past three decades, the environmental and energy field has witnessed significant developments in the use of microbial fuel cells (MFCs), which can directly degrade organic matter donating “fuels” and simultaneously generate electricity and/or chemical products and electrochemical processes [2–4]. Sediment microbial fuel cells (SMFCs) are a type of MFC that has an anode embedded in the anoxic sediments and a cathode suspended in the aerobic water column [5]. Owing to their unique characteristics, SMFCs could be explored as new technology for removing organic pollutants from sediments [6] and for *in situ* bioremediation of organic rich sediment [7] and wastewater [8]. A number of factors should be addressed, though, before SMFC technologies can be applied at larger scales. Previous research has focused on anode and cathode materials [9], long-term stability [10], the factors affecting the production of maximum voltage [11,12],

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and scale-up of SMFCs [13,14]. However, long start-up times are also one of the main limitations and drawback that delaying their industrialization [4,15].

MFC startup refers to the battery run process culminating in the stability of electricity production. Previous studies of optimal start-up times mainly focused on the cultured MFCs and reported start-up times ranging from 10 or more hours to several days [16,17], depending on the inoculum, electrode materials, reactor design and operating conditions [18]. SMFCs had even longer start-up times (from a few days to several months) due to the complex composition of sediments and mass transfer limitation in sediments [19].

Power generation in SMFCs depends on exoelectrogenic bacteria in sediments to catalyze the oxidation of organic molecules and create extracellular electron transfer towards the anode. Therefore, enhance the activity of exoelectrogens on the anode biofilm may speed up the electron transfer and shorten the start-up times [15]. Previous studies found that different sources of inocula contained different electron acceptors such as O_2, NO_3^-, NO_2^-, metal oxides and SO_4^{2-} [20], and had a strong influence on anode bacterial communities [21] and the performance of MFCs [22]. Therefore, the selection of the sediments containing active exoelectrogenic microorganisms with strong competitive capacity is of crucial importance. In fact, sediments from various water environments reveal differences in hydrodynamic regime, redox potential, sorting process and mineral and chemical components [23] that ultimately result in differences in the activity and composition of the exoelectrogenic microorganisms in those sediments. But the main factors that affect the start-up times were still unknown.

The overall objectives of this study were to investigate the effects of sedimentary inocula taken from different lakes on the start-up times of SMFCs during 60 days of operation, and then identify critical environmental parameters in sediment samples related to the start-up times of SMFCs. Sedimentary samples were taken from a group of seven lakes in China that included eutrophic and mesoeutrophic lakes, large rural lakes and small urban lakes. Reasons for the difference in SMFC performances were explained through in-depth analysis of the physical-chemical and microbial properties of sediment samples.

Materials and methods

Sample collection

Sediments samples were taken from seven lakes in China (Fig. 1): Lake Taihu (Lake S1, 31°10′ N, 120°24′ E), Lake Chaohu (Lake S2, 31°40′ N, 117°36′ E), Lake Luomahu (Lake S3, 34°34′ N, 118°118′ E), Lake Xuanwuhu (Lake S4, 32°4′ N, 118°47′ E), Lake Mochouhu (Lake S5, 32°2′ N, 118°45′ E), Lake Yueyahu (Lake S6, 32°1′ N, 118°49′ E), and Lake Huashenhu (Lake S7, 31°59′ N, 118°47′ E). The sampling sites were divided into two groups: large rural lakes (Lake S1 – Lake S3) and small urban lakes (Lake S4 – Lake S7). Lake S1 is a large, shallow, eutrophic lake with a surface area of 2338 km^2 and a mean depth of 1.9 m with high spatial variability, including regions that are dominated by algae or macrophytes and have multiple sources of organic matter [24]. Lake S2 is the fifth-largest freshwater lake in China and is also eutrophic lakes. Heavy surface blooms of cyanobacteria (mainly *Microcystis* and *Anabaena*) have occurred regularly in the warm seasons of each year in recent decades [25]. Lake S3 is a mesotrophic lake with a surface area of 375 km^2 [26]. The four urban lakes are the main shallow lakes in the urban district of Nanjing, China and differ in trophic status. Lake S4 is mesotrophic and Lake 5 is eutrophic lake, while Lake S6 and S7 are oligotrophic lakes [27].

Surface sediments (at 0–10 cm depth) were taken using a Pedersen grab sampler. Macrophyte *Potamogeton malaianus* (*P. malaianus*), which is one of the dominant submerged plants in Lake Taihu, was also taken. Samples were transported to the laboratory within several hours. Then, the sedimentary samples were sieved through a standard 2-mm mesh screen to obtain a uniform size for sediments. Parts of the sediments from the seven sites were stored in −80 °C refrigerator for chemical and microbial analysis.

Experiment design and SMFC configuration

Twenty-one plexiglass columns with approximately 10 L volume were used for constructing SMFCs to perform the biodegradation experiment in a dark environment at 25 °C. There were three SMFCs of each lake. The schematic diagram of Lake S1 had been put in the supplementary data (see supplementary data Fig. S1) and other lakes showed the same as the Lake S1. Each column contained 5000 g of wet sediment and 4 L of overlying water. The composition of the mineral-salt medium in the overlying water was (g L^{-1}) [6]: $K_2HPO_4 \cdot 3H_2O$, 0.0001; KH_2PO_4, 0.0002; NH_4Cl, 0.0115; $MgCl_2 \cdot 6H_2O$, 0.1; $CaCl_2 \cdot 2H_2O$, 0.1; and $FeCl_2 \cdot 4H_2O$, 0.02. In this experiment, *P. malaianus* biomass was crushed after air-drying and sifted through a 0.45 mm sieve. The overlaying water was aerated with air pumps. In order to obtain the maximum power during the experiments, wet sediment and crushed plant litter were mechanically mixed at a litter/sediment ratio of 3% (dry weight/dry weight). Water loss via evaporation during the operation was routinely replenished with tap water to maintain a constant water level. All treatments were replicated three times.

The lab-scale SMFCs were constructed in detail as described previously [5]. Graphite felt (5 mm in thickness, Sanye Carbon, Beijing, China) was used both as anode (a projection area of 390 cm^2) and cathode (a projection area of 120 cm^2). Prior to the experiments, all electrodes were soaked in 1 M HCl for 24 h, and then washed with deionized water several times until pH levels measured neutral. The anode was affixed to plastic stents and placed approximately 5 cm below the surface of sediments, while the cathode was suspended above the overlying water and its upper surface was exposed to air. A 1000 Ω external resistance was used to connect the anode and cathode via epoxy-encapsulated wires.

Electrochemical measurements and calculations

Voltage signal (V) was measured every 30 min using a precision multimeter (Model 2700, Keithley Instruments, Cleveland, OH, USA) and data acquisition system (Keithley Instruments, USA). Then the current (I) was calculated