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Self-powered wastewater treatment for the enhanced operation of a facultative lagoon

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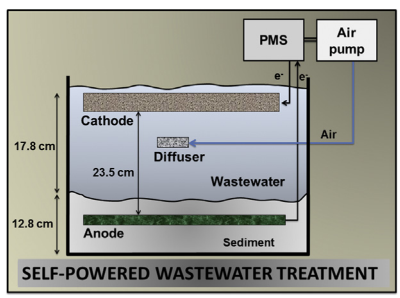
HIGHLIGHTS

- A self-powered lagoon treatment system was developed.
- The designed self-powered system operated autonomously for more than 12 months.
- This is the first demonstration of a microbial fuel cell powering a self-sustainable wastewater treatment system.

GRAPHICAL ABSTRACT



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ABSTRACT

The goal of this study was to harness the redox gradients in facultative lagoons using a lagoon microbial fuel cell (LMFC) to enhance autonomously the delivery of oxygen to the lagoon through aeration and mixing by operating an air pump. To enhance the usability of the low power generated by the LMFC, a power management system (PMS) was used to harvest power continually while only operating the air pump intermittently. Here we demonstrate the LMFC as an alternative energy source for self-powered wastewater treatment systems by treating both artificial wastewater and dairy wastewater in large laboratory-scale simulated lagoons. For comparison, we also used a lagoon treatment system without self-aeration. We show that the integrated LMFC and PMS system was able to improve chemical oxygen demand (COD) removal time by 21% for artificial wastewater and by 54% for dairy wastewater. The LMFC-PMS wastewater treatment system operated for over a year and proved to be robust and provide a measure of sustainability. The LMFC-PMS combination offers an innovative and low-tech approach to increasing the capacity of lagoons for rural communities. We believe that the technology developed in this research is the first step towards providing sustainable self-powered wastewater treatment systems.

1. Introduction

Facultative lagoons are used in rural communities for the treatment and storage of agricultural wastewaters because they are simpler to operate and require less energy than aerated lagoons [1–5]. Commonly deep ponds, facultative lagoons naturally develop three distinct layers with oxygen concentration decreasing

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by depth. Wind-aided air mixing at the surface, possibly in addition to phototrophic oxygen production from resident microorganisms, maintains an aerobic zone above both a middle facultative zone and a bottom anaerobic zone [3,6]. Aerated lagoons require constant energy input, usually in the form of mechanical surface mixing or air infusion agitation, to maintain an oxygen concentration throughout the volume and to keep suspended solids from settling. The added energy input can be advantageous, considering that aerated lagoons have a smaller footprint in the sense that they require less land than facultative lagoons [7]. This footprint is directly related to both the hydraulic retention time and the solids retention time needed to adequately treat the wastewater. Because of the variability of wastewater strength, facultative lagoon hydraulic retention times can reach 120 days or more while those of aerated lagoons can be as short as a few days [2]. Therefore a trade-off exists between the energy input and the treatment time of lagoons that can be manipulated to ensure proper wastewater treatment at the appropriate cost.

At an added cost, renewable energy sources such as solar and wind energy can be utilized to optimize lagoon wastewater treatment. Introducing active aeration utilizing renewable energy into an otherwise passive, facultative lagoon allows more agricultural wastewater to be treated using less land. Although solar and wind are possible sources of this renewable energy, they are often site-specific and seasonal, and they require substantial infrastructure not commonly found in agricultural settings. We suggest that one low-maintenance approach is to harness the redox gradient that already exists in facultative lagoons through the use of microbial fuel cell (MFC) technology; we will refer to our systems as lagoon microbial fuel cells (LMFC) [8]. The redox gradient refers to the variation in redox potential (E_h) from the aerobic zone, through the facultative zone, to both the anaerobic liquid zone and the sediment in the facultative lagoon. Typically, an excess of oxygen drives E_h to positive values in the aerobic zone. In this environment, an LMFC cathode would accept electrons via the oxygen reduction reaction [9–11]:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{1}$$

The presence of oxygen and possible colonization of the cathode with bacteria enhancing the oxygen reduction reaction create a sustainable biocathode [12–15]. At the other end of the gradient, several centimeters into the sediment at the bottom of the lagoon, anaerobic processes drive E_h to negative values depending on the native anaerobic respiration pathways in the sediment [16,17]. Here we assume that through microbial metabolism organic carbon oxidizes completely to carbon dioxide and releases protons and electrons according to the following reaction:

$$\text{Organic Carbon} + H_2O \rightarrow CO_2 + H^+ + e^- \tag{2}$$

Unlike the cathode, which utilizes an abiotic electrochemical pathway, the oxygen reduction reaction, the anode operates in a bioelectrochemical environment populated by a complex microbial community. This microbial community generates by-products that can be oxidized at the anode [12,18–24]. Based upon Equations (1) and (2), LMFCs are restricted to lagoon systems with both aerobic and anaerobic zones and cannot be utilized in completely anaerobic or completely aerobic lagoons (unless an alternative cathodic/anodic half reaction is used).

There are now almost innumerable demonstrations of MFCs treating various wastewaters and producing electricity in the literature [25–49]. Here the main role of the LMFC is not to treat wastewater and generate electricity but to operate an air pump that enhances wastewater treatment in an otherwise passive, facultative lagoon. To accomplish this enhanced operation, we employed a power management system (PMS). PMSs have been shown in the literature to increase the usability of the energy drawn from MFCs [10,50–61]. Although it has been reported that MFCs can produce high power (on the order of several watts m^{-2} or watts m^{-3}), to the best of our knowledge there is currently no device which can produce watt-level power unless that energy is stored for intermittent use. For example, Donovan et al. used a PMS to operate a 2.5-W wireless sensor system powered solely by an MFC generating only 3.4 mW of continuous power. This was only possible by continuously storing the energy in a capacitor and utilizing it intermittently to generate high power [54]. In this work, we follow the same strategy of harvesting energy continuously but using it intermittently. However, a new PMS needed to be developed to operate from low power generating LMFC compared to higher power generating sediment MFCs operated in rivers.

The goal of this study was to demonstrate the use of an LMFC to generate energy to run an air pump to enhance the operation of a facultative lagoon. Large laboratory-scale (83.3-L) facultative lagoons treating low-strength wastewater were used in this study. An LMFC was deployed in a lagoon with the anode buried in the anaerobic sediment and the cathode suspended in the aerobic liquid. We designed a PMS to harvest energy continuously and use it intermittently to operate an air pump. The addition of subsurface air enhanced the facultative lagoon treatment and increased chemical oxygen demand (COD) removal efficiency. We tested both artificial wastewater (AWW) and dairy wastewater (DWW). Our lagoon systems operated for more than one year in batch cycles. For a control, we used a replicate lagoon system without the aeration components. While running the experimental trials, we sampled at predetermined intervals and determined the COD and dissolved oxygen (DO) concentrations of the wastewater and open circuit potential (OCP) of the electrodes. The operation of the LMFC and the PMS were monitored autonomously using a data acquisition system. Lastly, we measured DO, pH and redox potential changes by depth in the sediment using microelectrodes.

2. Materials and methods

2.1. Lagoon microbial fuel cell and components

Fig. 1 shows a schematic diagram of the LMFC and its components. The LMFC consisted of two electrodes, an anode and a cathode, and a PMS which collected the energy and operated the air pump. For the laboratory-scale facultative lagoon, we used an 83.3-

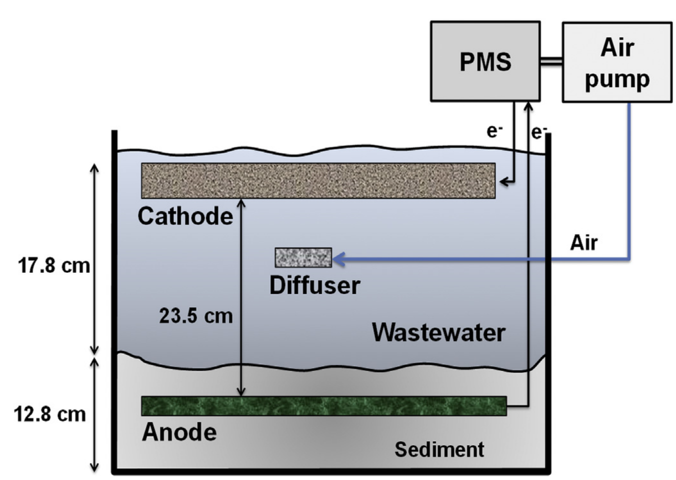

Fig. 1. Schematic diagram of the lagoon microbial fuel cell including a power management system with an integrated air pump that delivers oxygen to the wastewater.