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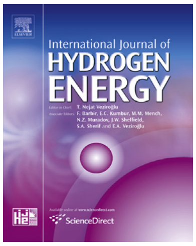

Electricity generation from rice straw using a microbial fuel cell

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ABSTRACT

This study demonstrated electricity generation from rice straw without pretreatment in a two-chambered microbial fuel cell (MFC) inoculated with a mixed culture of cellulose-degrading bacteria (CDB). The power density reached 145 mW/m^2 with an initial rice straw concentration of 1 g/L; while the coulombic efficiencies (CEs) ranged from 54.3 to 45.3%, corresponding to initial rice straw concentrations of 0.5–1 g/L. Stackable MFCs in series and parallel produced an open circuit voltage of 2.17 and 0.723 V, respectively, using hexacyanoferrate as the catholyte. The maximum power for serial connection of three stacked MFCs was 490 mW/m^2 (0.5 mA). In parallelly stacked MFCs, the current levels were approximately 3-fold (1.5 mA) higher than those produced from the serial connection. These results demonstrated that electricity can be produced from rice straw by exploiting CDB as the biocatalyst. Thus, this method provides a promising way to utilize rice straw for bioenergy production.

Introduction

Energy consumption has gradually increased as the world population has grown and due to industrialization of many countries. Fossil fuels, such as petroleum, coal, and natural gas, have been the major resources to cover the increased energy requirement [1,2]. However, they are gradually being depleted because they are not renewable. Therefore, there is

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great interest in exploring alternative energy sources to maintain the sustainable growth of society [2].

Rice (*Oryza sativa* L.) is among the oldest cultivated crops and ranks as the most widely grown food grain crop, serving as the staple food for about half the world's population [3]. Rice straw is one of the most common lignocellulosic biomass residues in the world. The annual production a proximately 731 million tons, which is distributed throughout the world [4]. This amount of rice straw can produce 205 billion liters of bioethanol per year [5]. In Korea, rice straw is one of the most abundant crops; its annual biomass production is approximately 7 million tons. It is usually utilized as a compost or forage in Korea [6]. Nowadays, intensive attention has been paid to rice straw as a potential renewable energy source [6]. Production of ethanol, biofuel, and electricity from rice straw, one of the most abundant agricultural wastes, has been extensively studied [4,7–9]. The composition of rice straw is mainly carbohydrates polymers such as cellulose, hemicelluloses, and lignin.

Microbial fuel cells (MFCs) convert the energy available in biodegradable substrates such as glucose, sucrose, and starch; low molecular weight organic acids such as acetate, oxalate, and fumarate; and amino acids directly into electricity through the catalytic activity of electrochemically active bacteria attached to the electrode [10–15]. These bacteria can oxidize organic compounds to carbon dioxide and transfer electrons to the anode; then, electrons pass through an external circuit to the cathode to produce current [12,14,16]. Protons migrate to the cathode and combine with O_2 and with electrons which released from anode to form water [10,14]. Electron transfer can occur either through membrane-associated components [12,17], soluble electron shuttles generated by specific bacteria [10], or highly conductive nanowires [18]. Microorganisms that have been used in MFCs include pure cultures of obligatory and facultative anaerobic bacteria [10,19,20] and mixed bacterial cultures [12,17,21] and municipal and industrial wastewater [12,22,23].

The maximum current in the MFC depends on (a) the MFC design, which determines the electrochemical losses (such as internal resistance); (b) activation losses, which can be lowered by the microbial production of an electron shuttle or nanowires; (c) the type of substrate and its concentration; and (d) the genus and the activity of the microorganisms; (e) presence and types of membrane, electrode surface area and conductivity; (f) ionic strength and pH [24]. However, electricity production from a single MFC is quite limited due to the low power generation of the unit, which largely depends on the redox potentials between the respiratory enzymes of anodophilic bacteria and the cathodic reactant [25]. Thus far, the highest open circuit voltage (OCV) reported has been 0.80 V [26], which shows this limitation. The use of stacked MFCs in series or parallel is essential to increase the voltages and currents produced by MFCs. Aelterman et al. [27] increased the voltage and current by stacking six individual continuous MFC units. Each MFC unit was composed of two chambers (anode and cathode chamber). In addition, Oh and Logan [28] used stacked MFCs to increase the voltage output; they found that the OCV for serial connection was 1.3 V, but voltage reversal still occurred.

Recent studies have demonstrated that cellulosic biomass can be partially degraded for electricity generation [29–32] using exoelectrogenic bacteria [12,14]. For electricity production from a cellulosic biomass such as rice straw in an MFC, the biocatalyst (bacteria) should be able utilize rice straw under anaerobic conditions and be electrochemically active. Also, the bacteria should not require any electron shuttles for electron transfer to the electrode surface. Mixed bacterial cultures contain both anaerobic and facultative anaerobes, which capable to hydrolyze cellulosic biomasses [32,33]. This study demonstrates that a mixed culture of cellulose-degrading bacteria (CDB) can be used as a biocatalyst to produce electricity from rice straw in MFCs. In order to increase the voltage and current produced by MFCs, a stacked MFC consisting of three identical MFCs was used to investigate the effect of the electrical circuit (in series or parallel) on the power, voltage, and current output of the overall stack and the MFC units in the stack.

Materials and methods

Microorganisms

A mixed culture of CDB was used in this study as inocula in the MFCs. The CDB were isolated by transferring 1 g of soil to modified Dubos' salt medium amended with carboxymethyl cellulose (CMC) as the sole carbon source. The CMC-amended Dubos' salt medium consisted of 10 g/L CMC, 0.5 g/L $NaNO_3$, 1.0 g/L K_2HPO_4, 0.5 g/L $MgSO_4 \cdot 7H_2O$, 0.5 g/L KCl, and 0.001 g/L $FeSO_4 \cdot 7H_2O$. The CDB culture was incubated at 30 °C for one week; then, it was used as the inoculum in the MFC.

Medium

Nutrient mineral buffer (NMB) was used as the medium in the anode and cathode compartments of the MFCs. It consisted of 3.13 g/L $NaHCO_3$, 0.31 g/L NH_4Cl, 0.75 g/L $NaH_2PO_4 \cdot H_2O$, 0.13 g/L KCl, 4.22 g/L NaH_2PO_4, 2.75 g/L Na_2HPO_4, and trace metal and vitamin solutions as previously described by Oh et al. Rice straw (1 g/L) was used as the electron donor and as the carbon source in this study.

Rice straw

Raw rice straw was obtained from a local farm in Chuncheon Si, Kangwon province, Korea, and then cut into lengths of 2–3 cm with scissors. The pieces were powdered in a blender and thoroughly washed with tap water until the washes were clean and colorless, and then the powder was dried in a dry oven at 60 °C for 2 h. The chemical composition of the rice straw was as follows: 12.8 ± 0.2% moisture, 38.6 ± 0.4% cellulose, 13.6 ± 0.6% lignin, and 19.7 ± 0.5% hemicellulose [34].

MFC construction and operation

The H-type MFCs consisted of two chambers, an anaerobic anode chamber and an aerated cathode chamber. The two MFC chambers were constructed by joining two media bottles with glass tubes of diameters suitable to hold the proton exchange membrane (PEM) (Nafion™ 117, Dupont Co., DE, USA) that was clamped between the flattened ends of the tubes