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Short communication

Effects of furan derivatives and phenolic compounds on electricity generation in microbial fuel cells

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ABSTRACT

Lignocellulosic biomass is an attractive fuel source for MFCs due to its renewable nature and ready availability. Furan derivatives and phenolic compounds could be potentially formed during the pre-treatment process of lignocellulosic biomass. In this study, voltage generation from these compounds and the effects of these compounds on voltage generation from glucose in air-cathode microbial fuel cells (MFCs) were examined. Except for 5-hydroxymethyl furfural (5-HMF), all the other compounds tested were unable to be utilized directly for electricity production in MFCs in the absence of other electron donors. One furan derivate, 5-HMF and two phenolic compounds, *trans*-cinnamic acid and 3,5-dimethoxy-4-hydroxycinnamic acid did not affect electricity generation from glucose at a concentration up to 10 mM. Four phenolic compounds, including syringaldeyhde, vanillin, *trans*-4-hydroxy-3-methoxy, and 4-hydroxy cinnamic acids inhibited electricity generation at concentrations above 5 mM. Other compounds, including 2-furaldehyde, benzyl alcohol and acetophenone, inhibited the electricity generation even at concentrations less than 0.2 mM. This study suggests that effective electricity generation from the hydrolysates of lignocellulosic biomass in MFCs may require the employment of the hydrolysis methods with low furan derivatives and phenolic compounds production, or the removal of some strong inhibitors prior to the MFC operation, or the improvement of bacterial tolerance against these compounds through the enrichment of new bacterial cultures or genetic modification of the bacterial strains.

1. Introduction

Microbial fuel cells (MFCs) are devices that directly covert chemical energy to electricity through catalytic activities of microorganisms. One of the greatest advantages of MFCs over hydrogen- and methanol-fuel cells is that a diverse range of organic materials can be used as fuels [1,2]. Electricity has been generated in MFCs from various organic compounds, including carbohydrates [3–5], proteins [6] and fatty acids [7,8]. Lignocellulosic biomass is an attractive fuel source for MFCs due to its renewable nature and ready availability. Our recent study indeed demonstrated that all monosaccharides that can be directly generated from hydrolysis of lignocellulosic biomass were good sources for electricity generation in MFCs [5]. However, lignocellulosic biomass cannot be directly utilized by microorganisms in MFCs for electricity generation. In other words, lignocellulosic biomass has to be converted to monosaccharides or other low-molecular-weight compounds [9]. The most commonly used method of converting lignocellulosic biomass to monosaccharides is through a dilute-acid pre-treatment and subsequent acid- or enzymatic hydrolysis processes [10]. In addition to monosaccharides, the dilute-acid pre-treatment and the subsequent acid hydrolysis generate a number of byproducts, such as furan derivatives (2-furaldehyde and 5-hydroxymethyl-2-furaldehyde), phenolic compounds and carboxylic acids (acetic, formic, and levulinic acids) [11,12]. These byproducts negatively affect the cell membrane function, the growth, and the glycolysis of ethanol-producing yeast and bacteria [10,13–16]. However, some of these byproducts such as acetic acid are good substrates for electricity-generating microbes [7,17]. A hydrolysate from a dilute-acid pre-treatment of corn stover could even be directly used for electricity generation in MFCs [18]. However, the effects of these individual byproducts on electricity generation in a MFC are still poorly understood.

In this study, ten selected compounds that are either known byproducts in an acid pre-treatment or acid hydrolysis of lignocellulosic biomass or model compounds of those byproducts were thoroughly investigated as substrates in a MFC for electricity generation.

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2. Materials and methods

2.1. Materials

The following chemicals were purchased from Aldrich Chemical Company (Milwaukee, WI, USA) and used as received: 3,5-dimethoxy-4-hydroxycinnamic acid, 4-hydroxycinnamic acid, syringaldeyhde, *trans*-4-hydroxy-3-methoxycinnamic acid, and 3,4-dimethoxybenzyl alcohol. Acetophenone, 2-furaldehyde, and 5-(hydroxymethyl) furfural were purchased from Acros Organics (Morris Plains, NJ, USA). *Trans*-cinnamic acid was obtained from Eastman (Kingsport, TN, USA) and vanillin was from J.T. Baker (Phillipsburg, NJ, USA). All other chemicals such as glucose and sodium phosphate were purchased from commercial sources. Non-wet proofing carbon cloth (type A) and wet-proofed (30%) carbon cloth (type B) were purchased from E-TEK (Somerset, NJ, USA) and used as electrodes in MFCs. A multimeter (model 2700) with a data acquisition system (Keithly Instruments Inc., Cleveland, OH, USA) was used for measuring voltage in a MFC. Electrically active bacteria that had been enriched from wastewater in Corvallis Wastewater Treatment Plant (Corvallis, OR) and used in our previous study were used in this study [5].

2.2. Microbial fuel cell construction

MFCs with an inner volume of 12 mL were constructed as reported previously [7] with a slight modification. A cylindrical MFC chamber with a length of 1.7 cm and a diameter of 3.0 cm was made of plexiglass. Non-wet proofing carbon cloth (type A) was cut into a circular disk with a diameter of 3.0 cm and was used as anode without further treatment. The cathode (a circular disk with a diameter of 3.0 cm) was prepared from the wet-proofed (30%) carbon cloth (type B) according to the procedures described previously [8]. The anode and cathode were fixed to the ends of the cylindrical chamber and connected to the circuit with titanium wire. The anode was parallel to the cathode, and the distance between the two electrodes was 1.7 cm. The anode side of the chamber was covered with a plexiglass plate while the cathode was directly exposed to air.

2.3. MFC operation with selected compounds used as sole carbon sources for electricity generation

A vitamin stock solution and a mineral stock solution were prepared according to literature procedures [17]. A glucose-free culture media solution was prepared by dissolving the following compounds in water at room temperature: $NaH_2PO_4{\cdot}7H_2O$ ($15.47\,g\,L^{-1}$), $Na_2HPO_4{\cdot}H_2O$ ($5.84\,g\,L^{-1}$), NH_4Cl ($0.31\,g\,L^{-1}$), KCl ($0.13\,g\,L^{-1}$), a vitamin stock solution ($12.5\,mL\,L^{-1}$) and a mineral stock solution ($12.5\,mL\,L^{-1}$). A glucose-containing culture media was prepared separately by adding glucose ($1200\,mg\,L^{-1}$) into the glucose-free culture media solution. The stock solutions of the individual furan derivatives and phenolic compounds were prepared by adding each compound in the following amount to the glucose-free culture medium (50 mL) (40 mM): 5-HMF (64 mg), syringaldehyde (45.5 mg), vanillin (38 mg), *trans*-cinnamic acid (37 mg), *trans*-4-hydroxy-3-methoxy-cinnamic acid (48.5 mg), 4-hydroxy-cinnamic acid (41 mg), 3,5-dimethoxy-4-hydroxy-cinnamic acids (56 mg). These stock solutions were diluted with the glucose-free medium solution 1 mL stock solution + 39 mL glucose-free medium to obtain 1 mM concentration of the compound and used to investigate voltage generation from these compounds in the absence of other carbon sources.

The glucose-containing culture medium solution (7.0 mL) was added into each of the MFCs, followed by a suspension of the electrically active bacteria (5 mL) that had been obtained and used for our previous study [5]. Immediately after adding the bacteria suspension, MFCs were hooked up to a data acquisition system to start monitoring the voltage generation. When a stable voltage output was obtained in the MFCs, the glucose-containing culture media solution was replaced by the furan derivatives and phenolic compounds solutions. Ten MFCs were operated in a batch-fed mode simultaneously.

2.4. MFC operation to study the effects of selected compounds on electricity generation from glucose

The stock solutions of furan derivatives and phenolic compounds prepared in Section 2.3 were diluted with the glucose-free medium solution to obtain final concentrations ranged from 0.01 to 40 mM. Glucose was added to each of the diluted solutions to obtain a $1200\,mg\,L^{-1}$ final concentration.

MFCs used in this set of experiments were started up following the same procedures as described in Section 2.3. When a stable voltage output was obtained, the glucose-containing medium solution was replaced by a medium solution containing both glucose and one of the furan derivations or phenolic compounds (0.01 mM). At the end of the batch (voltage output less than 50 mV), the solution was replaced with a new medium solution containing a higher concentration of the selected compound. The concentration of the selected compound was continuously increased until a significantly reduced voltage generation was observed. The medium solution was then replaced with the glucose-containing (without selected compound) medium solution to investigate if voltage generation can be recovered.

All MFCs were operated at a fixed external resistance of $1000\,\Omega$ and kept in an incubator with a constant temperature of $30 \pm 2\,^{\circ}C$ throughout the experiments.

3. Results and discussion

3.1. Voltage generation using selected compounds as the sole carbon sources

All the test compounds were selected based on their potential presence in an acid pre-treatment or acid hydrolysis of lignocellulosic biomass. These compounds were individually tested as the sole carbon source for electricity production in MFCs. A voltage of 0.46 V was produced after the solution was replaced with the 10 mM 5-HMF solution but quickly decreased to less than 0.4 V. In the subsequent batches, i.e, when the MFC solution was replaced with a fresh glucose-free medium containing the same amount of 5-HMF, the voltage decreased to 0.12 V (Fig. 1). None of the other compounds tested were able to produce electricity in the absence of the additional carbon sources (data not shown).

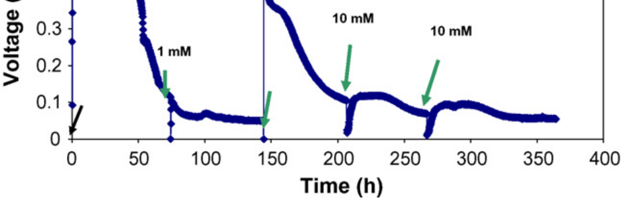

Fig. 1. Electricity generation from 5-HMF in the absence of carbon sources. Black arrow indicates the addition of glucose-containing medium and green arrows indicate the addition of 5-HMF containing medium solution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)