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Research Paper

Direct electricity generation from sweet sorghum stalks and anaerobic sludge

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ABSTRACT

Dried sweet sorghum stalks were valorized as a raw material for electricity generation in a two chamber microbial fuel cell using anaerobic sludge from a biogas plant as inoculum. The maximum voltage obtained on the sorghum stalks at an operating temperature of 35 °C was 546 mV with a maximum power- and current density of 131 mW/m^2 and 543 mA/m^2, respectively. The coulombic efficiency was 2.2%. Polarization data indicated that Ohmic resistances were dominant with an internal resistance of 182 Ω. The total electrical energy per gram of dried sorghum stalks was 165 J/g. Enzymatic treatment of the sorghum stalks did not improve the total electrical energy obtained. A metabolic study demonstrated that the sugars were quickly fermented to formate, acetate, propionate, lactate and butyrate with acetate and butyrate being the dominant acids during electricity generation.

1. Introduction

With origins in African agriculture over 6000 years ago the C4 grass Sorghum (*Sorghum bicolor* {L.} Moench) has received a lot of attention as an efficient bioenergy crop (Rooney et al., 2007). The combination of high biomass and sugar yield with good water use efficiency and tolerance to drought, established production systems and the potential for genetic improvements makes sorghums highly attractive as alternative feedstock for bioenergy production (Rooney et al., 2007). Sweet sorghums accumulate sugars in their stalks, which consequently are of particular interest to the biorefinery industry. On a dry weight basis, sweet sorghum stalks contain about 50% soluble sugars (sucrose, glucose, fructose), 35% insoluble carbohydrates (hemicellulose and cellulose) and 3.2% lignin (Matsakas and Christakopoulos, 2013). Due to the risk of microbial degradation it is advantageous to dry the stalks before storage (Matsakas and Christakopoulos, 2013). Sweet sorghum has mainly been studied as a feedstock for the production of platform chemicals and biofuels including ethanol (Matsakas and Christakopoulos, 2013), biogas (Ostovareh et al., 2015), butyric acid (Sjöblom et al., 2015), lipids (Matsakas et al., 2014), hydrogen (Antonopoulou et al., 2010a) and 1-butanol (Sirisantimethakom et al., 2016). An alternative use of sweet sorghum could be as a raw material for electrical energy production in microbial fuel cells (MFCs). A two chambered MFC is a common set-up and consists of a cathode chamber and an anode chamber separated by a proton exchange membrane (PEM) (Logan et al., 2006). Microorganisms are grown anaerobically in the anode chamber where they oxidize a substrate to release electrons and protons. The electrons pass to the cathode through an external circuit whereas the protons migrate to the cathode through the PEM. On the cathode surface the electrons and protons participate in the reduction of an electron acceptor and a current is established. The electron acceptor, or catholyte, can be a chemical such as oxygen but for many research purposes a strong electron acceptor such as ferrocyanide is used (Logan et al., 2006; Thygesen et al., 2009). Several pure compounds and complex feedstocks have been studied in MFCs including acetate, butyrate (Liu et al., 2005), glucose, xylose (Thygesen et al., 2009), lactate, starch, cellulose (Rismani-Yazdi et al., 2007; Toczyłowska-Mamińska et al., 2015), manure (Lin et al., 2016), cheese whey (Antonopoulou et al., 2010b), brewery waste (Feng et al., 2008), urban waste water (Rodrigo et al., 2007), etc. Sweet sorghum stalks have not been studied in MFCs as far as the authors know. Complex feedstocks contain a wide range of compounds which the microorganisms have to oxidize in order to generate electricity. For this reason it can be advantageous to utilize environmental inoculums such as anaerobic sludge, manure or urban waste water which contain a broad spectrum of microorganisms that could have synergistic effects in the degradation of the organic matter (Ishii et al., 2015). For example, the microbiota of thermophilic anaerobic sewage sludge have been found to consist of bacteria of the genus *Clostridium*, *Coprothermobacter*, *Synthrophomonas*, archea of the genus *Methanosarcina* and

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Methanobacterium and fungi of the genus *Candida*, *Penicillium*, *Mucor*, *Saccharomyces* and *Trichoderma* (Ritari et al., 2012). Members of firmicutes, proteobateria, acidobacteria and yeasts like *Saccharomyces cerevisiae* and *Hansenula anomala* are known to be capable of producing electricity (Franks and Nevin, 2010).

Certain bacterial species are particularly efficient in transferring electrons to the anode in a more direct sense involving specialized sets of cytochromes and other proteins including conductive pili (Lovley, 2012). Other microorganisms can utilize synthetic or self-produced mediators to assist in the electron transfer process without being in direct contact with the electrode surface themselves (Rabaey et al., 2005a). When electron transfer occurs by means of direct contact with the cell (with either pili or the cell's surface) it is imperative that a biofilm forms on the electrode surface and hence there is a lot of work on trying to understand how the electrode should be designed in order to promote good biofilm formation and efficient electron transfer (Sonawane et al., 2017). For fundamental research purposes graphite electrodes have often been used because they are cheap, inert and easy to shape (Gregory et al., 2004). Microbial fuel cells have the potential to contribute to a more sustainable society providing direct electrical energy from a variety of organic matter at ambient to low temperatures at locations lacking electrical infrastructure (Rabaey and Verstraete 2005). For a widespread use of MFCs in our society it is important that a broad range of raw-materials and inoculums for electricity generation can be exploited in these systems. In order to increase the number of potential feed-stocks for MFCs this study intends to investigate dried sweet sorghum stalks as a substrate for electricity generation using anaerobic sludge as a source of microorganisms. Enzymatic treatment of the sorghum stalks with the commercially available Cellic ® CTec 2 was also investigated in order to improve the electrical energy recovery. By enzymatic treatment the amount of extractable sugars could potentially be increased and the cellulosic part could possibly be more susceptible for microbial degradation.

2. Materials and methods

2.1. Microbial fuel cell set up

Two-chamber, H-type, MFCs were used for all experiments (Fig. 1). The chambers consisted of two 250 mL glass bottles connected with a glass tube. A proton exchange membrane (Nafion N117) was used to separate the chambers. The membrane was held in place and sealed by an O-ring and a chain clamp in the middle of the tube. Both the anode and cathode were constructed by embedding a 0.3 cm stainless steel rod, covered using heat-shrink tubing, into cylindrical graphite rods (75 mm long and 20 mm in diameter). The rods were glued in place using a silver conductive epoxy (MG Chemicals, Canada) and the joint was sealed with a standard epoxy (Epotek 730-110, Epoxy technology inc., MA, USA). The electrode rod was fitted tightly in a rubber stopper along with a glass sample tube. The electrodes were connected using copper wires and a 1000 Ω resistor.

2.2. Inoculation and operation

The sludge used for the experiments was collected from an anaerobic digester at a local biogas plant (Biogas Boden, Sweden), which was run at thermophilic conditions (55 °C). The experiments were started up using fresh anaerobic sludge samples. Sludge samples were analyzed using HPLC and no acetate, butyrate or glucose was detected. Prior to operation the sludge was filtered through nylon filter (pore size 200 μm) to remove larger solid particles and supplemented with 10 mL/L of a trace elements solution according to Antonopoulou et al. (2015). The fortified sludge (220 mL) was used as both the inoculum and the medium in the anode chamber and glucose, sucrose, acetate, butyrate or sweet sorghum was added as a carbon source. The dry sorghum stalks were added either as they were, at a concentration of 0.73 g/L, or at a concentration equivalent to 0.73 g/L dry matter (DM) after being hydrolyzed. The hydrolysis was performed at 20% w/v dry matter using the commercially available enzyme preparation Cellic Ctec 2 (Novozymes, Denmark) at an activity of 10 FPU/g DM, pH 5.0, a temperature of 50 °C and an incubation time of 18 h. Since the dry stalks and hydrolysate could not be pumped they were added to the

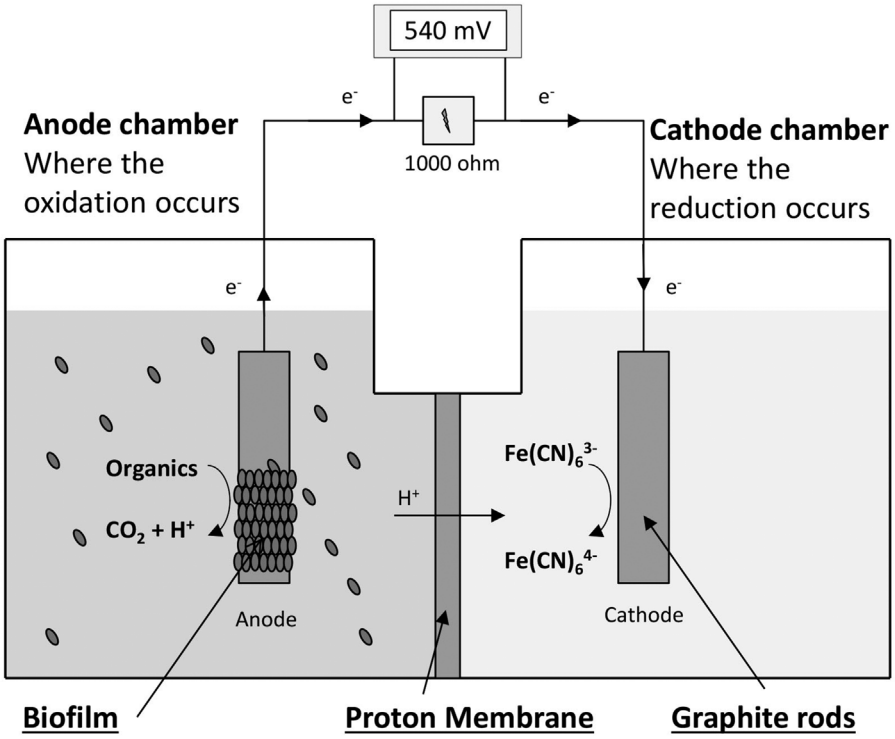

Fig. 1. Schematic figure of the two chamber, H-type MFC used in this study.