Bioresource Technology 101 (2010) 3541–3547

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Concurrent bio-electricity and biomass production in three Plant-Microbial Fuel Cells using *Spartina anglica*, *Arundinella anomala* and *Arundo donax*

M. Helder [a], D.P.B.T.B. Strik [a], H.V.M. Hamelers [a,*], A.J. Kuhn [b], C. Blok [c], C.J.N. Buisman [a]

[a] Sub-department of Environmental Technology, Wageningen University, Bomenweg 2, P.O. Box 8129, Wageningen, The Netherlands
[b] Forschungszentrum Jülich Institute Phytosphere (ICG-3), 52425 Jülich, Germany
[c] Greenhouse Horticulture, Wageningen University and Research Center, Violierenweg 1, 2665 MV Bleiswijk, The Netherlands

ARTICLE INFO

Article history:
Received 1 October 2009
Received in revised form 21 December 2009
Accepted 21 December 2009
Available online 25 January 2010

Keywords:
Plant Microbial Fuel Cell
Bio-electricity
Spartina anglica
Arundinella anomala
Arundo donax

ABSTRACT

In a Plant Microbial Fuel Cell (P-MFC) three plants were tested for concurrent biomass and bio-electricity production and maximization of power output. *Spartina anglica* and *Arundinella anomala* concurrently produced biomass and bio-electricity for six months consecutively. Average power production of the P-MFC with *S. anglica* during 13 weeks was 16% of the theoretical maximum power and 8% during 7 weeks for *A. anomala*. The P-MFC with *Arundo donax*, did not produce electricity with a stable output, due to break down of the system. The highest obtained power density in a P-MFC was 222 mW/m^2 membrane surface area with *S. anglica*, over twice as high as the highest reported power density in a P-MFC. High biomass yields were obtained in all P-MFC's, with a high root:shoot ratio, probably caused nutrient availability and anaerobia in the soil. Power output maximization via adjusting load on the system lead to unstable performance of the P-MFC.

1. Introduction

The Plant-Microbial Fuel Cell (P-MFC) is a system that produces bio-electricity from plant derived organic matter without harvesting the plant. Rhizodeposits are excreted by the plant-roots and subsequently converted into electrons, protons and CO_2 by electrochemically active micro-organisms that are present around the roots. These micro-organisms have been found to be able to deliver these electrons to a solid surface, like a graphite electrode, under anaerobic conditions. This electrode (anode) is coupled to a second electrode (cathode) with a membrane in between. At the cathode, electrons are used to reduce oxygen or another compound along with protons which are transported through the membrane to the cathode compartment. The plant, growing in the anode compartment, is put under root submerged conditions to make an anaerobic environment in the anode possible. The P-MFC was first tested by Strik et al. (2008a) and has been claimed to produce non-destructive, sustainable bio-electricity (Strik et al., 2008a). This claim arises from the fact that for bio-energy production in a P-MFC only rhizodeposits have to be harvested and not the biomass. This avoids transportation of the biomass and depletion of nutrients in the ecosystem.

For our research three different plant species were used: *Spartina anglica, Arundinella anomala* and *Arundo donax*. These plants are all three marsh species, which are able to survive and grow under waterlogged conditions as imposed in the P-MFC (Holmer et al., 2002; Wijte et al., 2005). *S. anglica* is a salt marsh species that has been tested in earlier studies and has shown to be able to survive and produce electricity in the P-MFC (Timmers et al., 2010). It was selected in the research of Timmers et al. for four reasons: (I) no competition with food production, (II) high biomass production, (III) worldwide occurrence on mudflats and (IV) salinity tolerance which offers the opportunity of operating the system at high ionic strength (Timmers et al., 2010). To compare with *S. anglica* another grassy marsh species was chosen: *Arundinella anomala*. *A. anomala* is a fresh marsh species and has therefore not the advantage of the low internal resistance that is ascribed to the high ionic strength of the solutions. It is therefore interesting to see whether a fresh water species is able to produce electricity in a P-MFC. *A. anomala* is a marsh species that grows in the Chinese Yangtze River and the Three Gorges Reservoir. It has been shown to be tolerant to flooding (New and Xie, 2008). *A. donax* grows in marshes like *S. anglica* and *A. anomala*. But it is different from *S. anglica* and *A. anomala*. It has a C_3 photosynthetic pathway in contrast to *S. anglica* and *A. anomala*, which have a C_4 photosynthetic pathway. In general a C_3 photosynthetic pathway is less efficient than a C_4 photosynthetic pathway. *A. donax* however, has, in spite of its C_3 photosynthesis, a higher photosynthesis rate than some C_4 species. In other

* Corresponding author. Tel.: +31 317 483447; fax: +31 317 482108.
E-mail address: bert.hamelers@wur.nl (H.V.M. Hamelers).

0960-8524/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biortech.2009.12.124

words, it is very efficient in using the sun's energy to produce biomass. Therefore it is an interesting plant for this research since a lot of biomass growth can be expected. In addition, *A. donax* is an energy-crop, used for bio-energy production because of its fast growth and high dry matter content (Angelini et al., 2008; DiTomaso, 1996). *A. donax* was used in this research to see if extra energy can be harvested from this energy-crop via de P-MFC apart from burning for bio-electricity production. In earlier studies *Glyceria maxima* (Strik et al., 2008a) and *S. anglica* (Timmers et al., 2010) were tested in a P-MFC.

Strik et al. (2008a) achieved a maximum power output of 67 mW/m^2 membrane surface area. During the research of Strik et al. plant vitality was monitored and found to decrease after 68 days. As a possible explanation for this decrease in plant vitality, natural decline after the growth season of the plant is suggested (Strik et al., 2008a). Based on the results of Strik et al. we hypothesized for this research that plant growth is not limited by the P-MFC. Secondly, since Strik et al. used a fixed resistance while producing electricity with a P-MFC, we tested a maximization strategy for the P-MFC's by adjusting external resistance to internal resistance of the system in order to maximize power output. For the first hypothesis, we tested whether it is possible to produce bio-electricity in the P-MFC while concurrently producing biomass for other applications, without interfering with plant vitality. This would validate the claim that bio-electricity production in a P-MFC is non-destructive. In this research plant growth was monitored for the first time in P-MFC research. In addition we tried to maximize the power output of the system by adjusting external resistance.

2. Methods

2.1. Experimental set-up

We used a cylindrical P-MFC. The anode consisted of a plexiglas cylinder (Ø 9.9 cm) with a cation exchange membrane (Fumatec, Frankfurt, Germany) glued to the bottom. We filled the cylinder with graphite grains (<1 mm, Le Carbone, UK). The plant-roots and graphite grains were cleaned with demiwater (water demineralized with Ministil P-12, Christ AG, Aesch, Switzerland) and afterwards the plant was planted in the graphite grains. The plants that we used were *S. anglica, A. anomala* and *A. donax. S. anglica* consisted of 2 stems of total 54 cm tall and a total fresh weight of above and below ground biomass of 25 g. *A. anomala* had 10 short stems of total 64 cm and total fresh weight of 59 g. *A. donax* had 1 stem of 31 cm and total above and below ground biomass of 85 g. *S. anglica* was offshoot of the one used by Timmers et al. (2010). It was grown in a greenhouse for approximately 2 months. *A. anomala* and *A. donax* were provided by Forschungszentrum Jülich GmbH (Jülich, Germany). We filled the anode compartment with modified Hoagland solution (Taiz and Zeiger, 2006) as described by Timmers et al. (2010) up to the overflow point (at 19 cm from membrane). On top of the graphite grains sand was put to the level of the overflow point to prevent algae growth on the graphite grains. When the sand showed to be insufficient for preventing algae growth, plastic granules were put on top of the sand. The anode cylinder was placed in the cathode compartment (Ø 12 cm), which consisted of a beaker in which a graphite felt (Grade WDF, 2.8 mm, National Specialty Products Carbon and Graphite Felt, Taiwan) was put on the bottom.

As a current collector for the anode, a graphite rod was placed in the graphite grains of the anode with a wire attached to it. For the cathode, a gold wire was woven through the graphite felt with an electrical wire attached to it. Anode and cathode wires were connected with a resistance (1000 Ω) in between. Ag/AgCl-reference electrodes (3 M KCl, +205 mV versus standard hydrogen electrode, ProSense Qis) were placed in syringes with a capillary attached to it, filled with KCl (3 M). The capillary was placed in anode and cathode to measure anode and cathode potential against the reference electrode.

The anolyte consisted of modified Hoagland solution (Taiz and Zeiger, 2006) with phosphate buffer (K_2HPO_4 and KH_2PO_4, 20 mM, pH 7) (Strik et al., 2008b). The used iron complex in the Modified Hoagland solution was diethylenetraiminepentaacetic acid ferric sodium complex (Dissolvine D-Fe-11, or DTPA-Fe) (AKZO NOBEL Functional Chemicals bv, Herkenbosch, the Netherlands). In case of the *S. anglica* 20 g/l NaCl was added to provide a salt environment. The catholyte consisted of phosphate buffer (K_2HPO_4 and KH_2PO_4, 20 mM, pH 7).

The set-ups were placed in a climate chamber (Microclima 1750 Snijders) that was controlled at 25 °C with 75% humidity, average light intensity of 596 ± 161 μmol m^{-2} s^{-1}, measured at the top of the reactors by a light intensity meter (Photodyne 44XLA), and an illumination period of 14 h per day.

2.2. Analytical techniques

In the first 10 weeks we measured anode and cathode potential manually with a multimeter (True RMS multimeter, fluke 189) against an Ag/AgCl-reference electrode. Starting in week 10, the anode and cathode potential were measured with Fieldpoint (Module S, National Instruments) against an Ag/AgCl-reference electrode. Cell voltage of the P-MFCs was measured with Fieldpoint from the beginning of the experiment. Data were collected with LABVIEW (National Instruments Software).

Maximum power was determined via polarization curves, which were performed either manually or with a potentiostat (Iviumstat, The Netherlands). Manually, external resistance was adapted every 10 min from OCV (open cell voltage) to subsequently 1000 Ω, 500 Ω, 250 Ω, 100 Ω, 1 Ω and then back to 100 Ω, 250 Ω, 500 Ω, 1000 Ω, OCV. With the potentiostat, cell potential was controlled from OCV to 1 mV and back to OCV in nine steps of 10 min.

Plant growth was measured by counting the number of stems and leaves and measuring their length from top of the sand bed to tip (Holmer et al., 2002; Papazoglou, 2007; Spencer et al., 2006). Stem and leaf length were summed up for total length. For *S. anglica* both stems and leaves were measured since relatively much biomass growth is seen as leaf elongation when compared to the other two plants. For *A. anomala* and *A. donax* only stem length was measured. Fresh weight of the plants was determined directly after dismantling of the P-MFC's. Dry weight was determined after air drying until constant weight was reached. Numbers for plant growth are given in kg/m^2 surface area, calculated to a growth season of 6 months. Where numbers from literature are used, these numbers are recalculated to kg/m^2 at a growth season of 6 months as well.

Average weekly power output was calculated via:

$$P = (\overline{E})^2/R/\text{membrane area}$$

Equation 1: Average power output, in which P = average power density in W/m^2 membrane surface area during a week, $\overline{E}$ = mean cell potential calculated per week, R = external resistance which was constant at 1000 Ω. The used period is the moment from the change of cathode solution to ferric cyanide until the maximization strategy was started.

Power output and current densities are all normalized to m^2 membrane surface area, which is equal to the planting surface of the plant.

Calculations for total electricity production were performed with: