Bioresource Technology 247 (2018) 520–527

Contents lists available at ScienceDirect

Bioresource Technology

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

Microbial fuel cell powered by lipid extracted algae: A promising system for algal lipids and power generation

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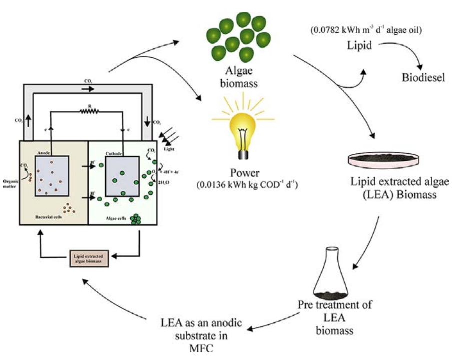
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Lipid extracted algae biomass
Photosynthetic microbial fuel cell
Sustainable process
Energy

ABSTRACT

In this study, a promising microbial fuel cell (MFC) system has been developed, wherein algae is cultivated in the cathode chamber, algae biomass is harvested and lipids are extracted. The lipid extracted algal (LEA) biomass was then used as an electron donor substrate. The performance of MFCs fed with LEA biomass was compared with that of fruit waste fed MFCs (FP-MFCs), wherein LEA-fed MFC was superior in all aspects. Power density of 2.7 W m^{-3} was obtained by LEA-fed MFCs which is 145% and 260% higher than FP MFC and control MFC respectively. The volumetric algae productivity of 0.028 kg m^{-3} day^{-1} in cathode chamber was achieved. The system was able to generate 0.0136 kWh Kg^{-1} COD day^{-1} of electric energy and 0.0782 kWh m^{-3} day^{-1} of algal oil energy. The proposed system is a net energy producer which does not rely heavily on the external supply of electron donor substrates.

1. Introduction

In the last few decades, microbial fuel cell (MFC) has emerged as a potential technology drawing the significant attention of scientific community across the world (Pant et al., 2010). The quest for finding new energy alternatives has encouraged researchers to develop renewable energy resources such as solar energy, wind energy, energy derived from biomass and water. In this context, MFC technology has established itself as a new energy alternative towards sustainable development. Apart from power output, MFC has shown its potential in several other dimensions like waste water treatment, CO_2 sequestration, heavy metals removal, bio-remediation etc. (Zhang et al., 2011). One of the modified versions of the MFC is the microbial carbon capture cell (MCC) or photosynthetic microbial fuel cell (PMFC), which offers high

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http://dx.doi.org/10.1016/j.biortech.2017.09.119
Received 31 July 2017; Received in revised form 15 September 2017; Accepted 16 September 2017
Available online 20 September 2017
0960-8524/

efficiency for waste water treatment, CO_2 sequestration, power generation and algae biomass production (Xiao et al., 2012).

In PMFC, the process relies on the natural process of photosynthesis most commonly by algae. PMFCs involve the use of intact algae biomass as an anodic substrate or the cultivation of algae at cathode for oxygen generation. In some cases, the CO_2 produced at the anode is fed to the cathode for fixation by algae which in turn produce O_2 as an electron acceptor to complete MFC circuit (González del Campo et al., 2013; Lobato et al., 2013; Elmekawy et al., 2014).

The concentration of dissolved oxygen (DO) in algae assisted cathodes was found to be 6.6 mg L^{-1} (Wang et al., 2010). The power generation from MFC depends on oxygen concentration at the cathode and a concentration level of 6.6 mg L^{-1} is considered suitable (Kang et al., 2003). Apart from this, high photosynthetic efficiency, biomass production, and lipid content make microalgae a suitable candidate for oxygen generation in the cathode chamber (Hu et al., 2016). *Chlorella vulgaris* strain of microalgae has been extensively used by MFC researchers for its high photosynthetic efficiency and suitable fatty acid profile for biodiesel production (Wang et al., 2010; Hu et al., 2016).

Despite the potential MFC technology holds, it is far from being called a sustainable system because of several reasons. One of these is the need of the continuous supply of electron donors and the electron acceptor at anode and cathode respectively (Mateo et al., 2014). Electron donor substrates function as a fuel for MFC system. There are various types of substrates used in MFC system in order to achieve high power output, high chemical oxygen demand (COD) removal rate, and high columbic efficiency. These range from simple or defined waste water substrates like monosaccharides, sugar derivatives, polyalcohols, amino acids, organic acids, alcohols, nitrogenous heterocyclic compounds etc. to complex or undefined waste water substrates like beverages industry waste water, confectionary industry waste water, dairy industry waste water and much more (Pandey et al., 2016). However, use of defined or undefined substrates is not economically viable. Hence, there is need to find renewable substrate which can be continuously produced and continuously fed to get consistent power output.

Algal biomass either in the form of dry biomass or living cells can also act as an anodic substrate (Xiao and He, 2014; Salar-garcía et al., 2016; Yuan et al., 2011). Cui et al. (2014) and Velasquez-orta et al. (2009) reported 8.67 W m^{-3} and 277 W m^{-3} of power density respectively, using microalgae biomass as a substrate (Cui et al., 2014;Velasquez-orta et al., 2009). *C. vulgaris* biomass has high nutritional value comprising of proteins (42–55%) and carbohydrates (12–55%) which can be mineralized by electrogenic bacteria to generate electricity (Cui et al., 2014;Safi et al., 2014). In a recent study, *C. vulgaris* biomass has been used as an electron donor fuel in stacking MFCs which revealed that algae biomass supports the growth of anodic bacteria by being a good source of both carbon and other nutrients (Asensio et al., 2017). Apart from this *C. vulgaris* is also a rich source of lipid (5–40%) per dry weight of biomass (Safi et al., 2014;Viegas et al., 2015).

While the need of electron acceptor and electron donor both can be met by algae using PMFC, the process has to be rendered sustainable by enhancing energy recovery from the system. An attempt to increase the energy recovery from the system was made by extracting lipids from algae grown at the cathode and utilizing the lipid extracted algae (LEA) biomass as an anodic substrate. As of now, an unsuccessful attempt to use lipid extracted algae (LEA) as an anodic substrate has been made wherein the authors reported an OCV (Open circuit voltage) of 0.021 V only (Rashid et al., 2013). The reason behind the failure of LEA as an anodic substrate was attributed to the presence of possible inhibitory substances in LEA (Rashid et al., 2013). The present study has demonstrated the use of LEA biomass as an anodic substrate, successfully first time in the literature.

The algae is cultivated in the cathode chamber of MFC. This algae biomass is harvested and lipids are extracted. The extracted lipids can be further processed for biodiesel production. The residual biomass left after lipid extraction process i.e. LEA can be used as an anodic substrate which reduces the dependency on the external supply of electron donor substrate. LEA is also a waste byproduct of the algae based biodiesel industry. Hence, this strategy makes a system self-sustainable and economically viable. Keeping in view the above said points, the present study was conducted with following objectives:-

1. To evaluate the potential of LEA biomass as an anodic substrate.
2. To compare the performance of LEA biomass with another complex yet easily utilizable substrate like fruit waste/pulp.
3. To perform the energy analysis of the system to determine whether the system is a net energy producer.

2. Materials and methods

2.1. Algae cultivation

A pure culture of *C. vulgaris* was obtained from Department of Botany, Jai NarainVyas University, Jodhpur (Rajasthan). *C. vulgaris* was initially grown in a 2 L photobioreactor (Spectrochem instruments Pvt. Ltd. Hyderabad, India). The photo bioreactor was set at 25 °C and filled with BG 11 (Blue green) media at pH 7. The reactor was operated with a 12 h: 12 h light: dark period and constant stirring of 180 rpm. BG-11 media consisted of (g L^{-1}): 1.5 $NaNO_3$, 0.04 K_2HPO_4, 0.075 $MgSO_4{\cdot}7H_2O$, 0.036 $CaCl_2{\cdot}2H_2O$, 0.006 citric acid, 0.006 ferric ammonium citrate, 0.001 EDTA, 0.02 Na_2CO_3, and 1 ml trace elements solution [(mg L^{-1}): 2.86 H_3BO_3, 1.86 $MnCl_2{\cdot}4H_2O$, 0.22 $ZnSO_4{\cdot}7H_2O$, 0.39 $NaMoO_4{\cdot}2H_2O$, 0.08 $CuSO_4{\cdot}5H_2O$, and 0.05 $Co(NO_3)_2{\cdot}6H_2O$] (Zhou et al., 2012). After 15 days of continuously operating photobioreactor, algae biomass was harvested and processed for lipid extraction. Subsequently, algae biomass growing at cathode chamber was harvested and processed for lipid extraction. This lipid extracted algae (LEA) biomass was used as an anodic substrate.

2.2. Lipid extraction

Total lipid extraction from *C. vulgaris* was done using chloroform-methanol 1:2 by modified Bligh and Dyer extraction method, as described previously (Kanaga et al., 2016).

2.3. Preliminary treatment of LEA biomass

LEA biomass obtained from lipid extraction step, was further treated before feeding it at the anode. It was placed at 82 °C in an oven overnight, in order to get rid of residual chloroform and methanol traces. Alternatively, it was also kept in sunlight for a period of 48 h. Both the strategies were equally effective for removing unwanted organic leftovers. This was followed by crushing in a pestle-mortar to convert it into very fine powder. These steps were done to remove any traces of inhibitory organic solvent and to increase the surface area for the microbial attack at the anode. Bypassing these two steps led to complete failure of MFC in terms of power output, COD removal etc.

2.4. Fourier transformation-infrared spectroscopy(FTIR)

FTIR was performed using Bruker FTIR spectrometer vertex 70 V. In order to compare the key functional groups of intact algal biomass, extracted lipids and LEA biomass, FTIR analysis of all these three samples was done. The spectrum was recorded in the range of 4000–400 cm^{-1} (Phukan et al., 2011).

2.5. MFC construction

Dual chamber MFC reactors were fabricated using acrylic material. The working volume of both the chambers was 100 ml. Graphite felt