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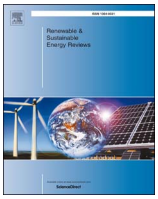

Algal growth in photosynthetic algal microbial fuel cell and its subsequent utilization for biofuels

Madhulika Shukla[a], Sachin Kumar[a,b,*]

[a] Biochemical Conversion Division, Sardar Swaran Singh National Institute of Bio-Energy, Jalandhar-Kapurthala Road, Wadala Kalan, Kapurthala, Punjab 144601, India
[b] Department of Chemical & Biological Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

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ABSTRACT

Electricity generation from biomass has captured a lot of attention these days. Many countries have inclined to start large-scale research projects so that the microbial fuel cells could be installed to fulfill the power requirements of domestic as well as industrial sectors. The chemical energy stored in the algal biomass can be harnessed for sustainable production of fuels and other value-added products. Bioelectricity production using algae seems to be a wise approach to extract energy from sunlight in an economic and sustainable manner. It is achieved through integration of photosynthesis with microbial fuel cell (MFC). Algae have been used commonly in MFCs to reduce oxygen at cathode or as a substrate for bacteria. However, sufficient electric current can also be generated at anode, where cytochromes help indirect shuttling of electrons generated in photosystem II of the algal cells and can be called as photosynthetic algal microbial fuel cell (PAMFC). Despite being environmental friendly, low efficiency makes these neoteric systems unviable. Hence, a good understanding is needed for the bioelectrochemical mechanisms working behind the electron transfer from algae to electrode. Oxygen is also a limiting factor among different variables viz. pH, substrate loading rate etc., affecting the fuel cell performance. The present review addresses the mechanism of electron transfer in algae and algae to electrode and the factors affecting the performance of PAMFC.

1. Introduction

Plenty of energy is stored in the renewable sources like solar, hydro, wind and biomass. However, inefficient utilization of these sources makes them unable to meet the growing energy demand [1–3]. With the exigency of renewable and clean energy alternatives, many feedstocks are now being tested for reducing our dependency on fossil fuels. In recent years, with increasing population and industrialization, the energy demand has also increased. Photosynthetic conversion of solar energy via biomass into renewable energy such as hydrogen, bioelectricity and other biofuels plays a significant role [4]. All photosynthetic organisms exhibit variation in the efficient utilization and conversion of the solar irradiance (photosynthetically active radiation (PAR), which falls between 400 and 700 nm wavelengths). The conversion efficiency ranges from 4.6% in C3 plants to 6% in C4 plants [5], while algae show a maximum output of up to 9%. Owing to the high growth rate, round the year availability, cultivation on non-arable land, non-competitiveness with food and feed, algae stand out amongst the potential biomass feedstocks. Similar to plants, the photosynthesis process is initiated with the photon induction in algal cell resulting in the fixation of carbon into various storage compounds such as carbohydrates, lipids, proteins, etc. A lot of research has been carried out using algal biomass for biodiesel production. However, the research has not been yet commercialized as it involves various energy intensive steps, which increase the cost of whole process. Harvesting of algal biomass alone contributes to 30% of total production cost [6]. Therefore, it would be advisable to utilize the algal biomass in a way, where harvesting and drying can be skipped. To look for the wet biomass utilization, the possible alternatives would be anaerobic digestion, fermentation, hydrothermal cracking, etc. Still the issues are higher cost for single

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Abbreviations: AEM, anion exchange membrane; ATP, adenosine triphosphate; BEMR, bioelectrochemical membrane reactor; BPM, bipolar membrane; CEM, cation exchange membrane; EMBR, electrochemical membrane bioreactor; ETC, electron transport chain; FAD, flavin adenine dinucleotide; Fd, ferredoxin; FMN, flavin mononucleotide; IEM, ion exchange membrane; LHC, light harvesting complex; MBR, membrane bioreactor; MFC, microbial fuel cell; MFM, microfiltration membrane; NADH, nicotinamide adenosine dihydrogen; NADPH, nicotinamide adenine dinucleotide phosphate dehydrogenase; NADP, nicotinamide adenine dinucleotide phosphate; OLR, organic loading rate; PAMFC, photosynthetic algal microbial fuel cell; PAR, photosynthetically active radiation; PCE, power conversion efficiency; PEMFC, proton exchange membrane fuel cells; PS, photosystem; RC, reaction centre; UFM, ultrafiltration membrane; UF-MFC, ultrafiltration microbial fuel cell

[*] Corresponding author at: Biochemical Conversion Division, Sardar Swaran Singh National Institute of Bio-Energy, Jalandhar-Kapurthala Road, Wadala Kalan, Kapurthala, Punjab 144601, India.

E-mail address: sachin.biotech@gmail.com (S. Kumar).

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product. Therefore, utilizing the biomass for variety of products in a biorefinery manner can be a promising approach. Traditional methods including electricity generation using the chemical fuel cell are unable to meet the targets alone. However, recent advances in the microbial fuel cell have added a great scope for bioelectricity generation. MFCs represent a promising, novel, cost effective, environment-benign technology for sustainable energy production.

A microbial fuel cell (MFC) works on the biocatalytic reactions of microbes (such as bacteria) which catalyze the organic substrates to generate electrons at anode [7]. These electrons pass through an external circuit to generate electricity. At cathode, these electrons get reduced, thus, completing the redox reaction. The anode and cathode chambers are separated by proton exchange membrane [8]. The regular MFCs utilize a variety of substrates like glucose [9], acetate [10], alcohols [11] and organic compounds [12,13]. MFCs are an uprising technology that is acquiring notable interest especially due to its potential as a renewable energy source in conjunction with wastewater treatment [14,15]. The power generation using MFC has been summarized in Table 1.

MFC is based on the microbiological process, where specific bacteria oxidize the organic matters under anaerobic conditions and an electrical current is generated for the electron transport through an electrical circuit. Additionally, microbes can metabolize the substrate and produce a secondary product such as hydrogen that can act as fuel and be oxidized and provide electrons for the electrical circuit [34]. Although, bacteria are the most commonly used microorganisms in MFCs, all of them are not electrochemically active [35].

MFCs work in conjunction with waste water, which gets lower down the system performance, thereby, reducing the power output [36]. Although, more power can be produced by increasing the substrate feeding rate [37], but it is not cost effective [36]. Thus, bacteria based MFC systems can be replaced with biomass based ones such as algae. This will greatly reduce the cost as there will be no restriction for anaerobic condition and further, utilization of algal biomass for biofuels and other value-added product formation. Utilization of solar energy by photosynthetic algae in a microbial fuel cell for bioelectricity production is a remarkable step in sustainable current production. Algae have already been used in MFC either at cathode to provide oxygen or at anode as substrate for the growth of bacteria. These studies have been observed for increasing power generation during dark phase. However, the oxygen production from algae reduces the power generation during light phase [38]. In the ex-situ photo MFC systems, a separate photobioreactor is needed for optimal algae growth and less complicated dark MFC system for optimal electricity generation. However, there are limitations of feeding a complex organic matter to a mixed heterotrophic bacterial community in MFC due to low columbic efficiency. Therefore, improvised strategies like development of photobioreactor with immobilized cyanobacteria to generate and degrade metabolic products in series with a dark MFC to increase the columbic efficiency are in trends. The development and performance of photosynthetic microbial fuel cell (PAMFC) for power generation have been demonstrated [39]. The continuous current output of 539 mA/m^2 for 150 days was established by developing solar powered PAMFC by designing photobioreactor coupled to MFC [40,41]. Several researchers have made prominent endeavor in improvising the performance of cathode system by increasing oxygen level by growing blue green algal immobilized in beads [42] or without immobilization [43] and directly growing *Chlorella* at cathode [44], which enhances the power output due to increased concentration of oxygen as electron acceptor liberated during photosynthesis. A combination of electrochemical and fluorescence techniques is helpful in understanding the mechanism and predicting the maximum quantum yield (Fv/Fm), alpha (α), light saturation coefficient (E_k) and maximum rate of electron transfer (rETRm) [45]. The present review aims to explore the possibility of electricity generation during algal growth through photosynthetic algal microbial fuel cell (PAMFC). The utilization of wet algal biomass for different

Table 1
Power generation capacity using microbial fuel cell.

Anode	Cathode	Reactor type	Substrate	Maximum power density (W/m^3)	Ref.
Carbon paper	Air cathode	Two chamber	Primary clarifier overflow	0.98	[16]
Carbon cloth	Packed bed air cathode	Single chamber	Preacclimated bacteria from an active MFC	46	[17]
Carbon mesh	Air cathode	Single chamber cube	Preacclimated bacteria from an active MFC	45	[18]
Activated carbon cloth	Air cathode	Single chamber	*D. desulfuricans* strain Essex 6	51	[19]
Granular graphite	Catholyte: $K Fe(CN)_6$	Tubular MFC	Preacclimated bacteria from an active MFC	90	[20]
Graphite felt	Catholyte: $K Fe(CN)_6$	Two chamber MFC	Preacclimated bacteria from an active MFC	386	[21]
Granular activated carbon	Air cathode	Single chamber	Domestic wastewater	5	[22]
Carbon Brush	Air cathode	Single chamber	Preacclimated bacteria from an active MFC	73	[16]
Pt coated Ti metal	Graphite felt	Dual chambered flat plate MFC	Anaerobic sludge from paper mill	144	[23]
Activated carbon	Stainless steel mesh	Single chambered	Anaerobic sludge	0.852	[24]
Graphite felt	SS mesh-air cathode	Single chambered	Domestic waste water	24.9	[25]
Millilayer graphene anode	Air cathode-carbon cloth	single chambered	acetate	8	[26]
Graphite fiber brush with Ti	Graphite fiber brush with Ti and graphite granules	One anodic and two cathodic chambers	Dairy manure	14.11	[27]
Packed granular graphite	Packed granular graphite	Constructed wetland MFC	Alum-sludge	0.168	[28]
Carbon felt	Carbon felt	Dual chambered	Waste activated sludge	8.7	[29]
Graphite brush	MCNT Pt air	hybrid microbial fuel cell membrane bioreactor (MFC-MBR)	Wastewater	14.5	[30]
Granular graphite	SS mesh biocat	bioelectrochemical membrane reactor (BEMR)	Wastewater	4.35	[31]
Graphite brush	Ni-HFM	Ultrafiltration microbial fuel cell (UF-MFCs)	Wastewater	6.6	[32]
Graphite felt	Graphite felt biocathode	EMBR (Electrochemical membrane bioreactor)	Effluent from lab scale MFC	7.6	[33]