Chapter 5

Algal Fuel Cell

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Abstract

Algal Fuel Cells (AFC) are bioelectric devices that use photosynthetic organisms to turn light and biochemical energy into electrical energy. The potential of a fully biotic AFC still remains an unexplored area of research and hence it has led to rethink the prospective use of plant-based bioelectricity. AFC consists of an anode and a cathode connected by an external electric circuit and separated internally by a membrane/no membrane in which the growth of algae is assessed. The key parameters for evaluating the performance of AFC are electrodes, separators, oxygen supplement, nutrients and its configurations. By controlling these parameters, the electric power production can be optimized. This chapter discusses the recent trends examined by a number of researchers and are interpreted to gain a better understanding. It is stressed that a greater focus must be given for a complete comprehension of the algal processes required for the development of AFC applications. Thus, it can be concluded that a further development of AFC technology with reduced costs and improved performance is required for sustainable development.

Keywords: algae, algal fuel cell, photosynthetic electrode, photo bio-reactor, renewable energy

1. Introduction

Almost 80% of world energy consumption is from the combustion of fossil fuels. The depletion of these fossil fuels necessitates the importance of renewable energy synchronization. Fossil fuels on combustion pollute the environment by emitting huge amount of CO_2 to the atmosphere resulting in global climate change. The risks of over-dependence on fossil fuels can be avoided by using renewable and carbon-neutral energy sources in a large amount. The concern and awareness of the harmful impact of mineral-based fuels on the environment have pushed the research towards the production of eco-friendly energy from renewable sources. Renewable energy, which can be harvested from the sun either by photovoltaic energy or in the form of biomass energy as solar energy is considered as the mother of all energy, will play a predominant role in future. Globally, carbon neutral energy has been receiving the attention of extensive researches during last decades.

During the eighteenth century, the novel idea of generating electric energy from biological route emerged. The potential of using microorganisms that convert organic or inorganic compounds into electrical power was studied [1]. This process occurs through metabolic activity of microorganisms at ambient pressure and temperature [2]. Microbial fuel cells are the devices capable of producing bioelectricity from different sources of substrates [3, 4]. The substrate is regarded as one of the essential biochemical factors affecting power generation in microbial fuel cells. The consideration of microbial fuel cells as a marginal scientific issue has been catching up with other bioconversion concepts in recent years.

New designs have evolved and the operation has moved towards AFC for generating bioelectricity through the photosynthesis reaction by microalgae. Microalgae are considered as eco-friendly organisms having high photosynthetic efficiency and rapid reproduction and are also a good source of fuel with their neutral lipid content. Algae use energy from sunlight in the photosynthetic reaction in which they consume carbon dioxide to produce oxygen. The first creations of algae were cyanobacteria, the small sized blue green algae responsible for the early transformation of the earth's atmosphere. Algae play a significant role in the production of oxygen. In the current situation, there is need to reduce carbon dioxide and in this way algae convert carbon dioxide to oxygen where lights stimulate the CO_2 fixation by Calvin cycle. The photosynthesis reaction is considered as one of the complex biological redox reactions happening naturally and carried out by algae and plants in which they are able to use energy from the sun to produce carbohydrates and oxygen through multiple redox reactions. They also produce additional compounds during the process which may be utilized for energy or employed in the synthesis of other molecules [5, 6].

AFC is a promising technology which can capture CO_2 inexpensively with the help of algae. Generally, microalgae grow in a bioreactor or open pond where they can use the sunlight, CO_2 and nutrient. Therefore, new designs were employed for enabling the microalgae in a microbial fuel cell to generate electricity with different electrode materials.

2. Algal fuel cell configuration

AFCs are electro biochemical devices which have anode and cathode compartments enclosed with a photosynthetic microorganism. Here photosynthesis is carried out and they act as electron donors producing organic metabolites. The main objective of configuring AFC is to increases the power density and achieving high performance in order to create a cost effective system. Major configurations of AFC are a single chamber, two chambers, three chambers, coupled and sediment types.

In single chamber AFC, bacteria and microalgae are grown together in one chamber which is membrane less wherein micro-algae forms a biofilm on the anode and some are usually configured with an air cathode [7, 8]. Carbon dioxide generated by autotrophic and heterotrophic organisms are consumed simultaneously by algae in the same chamber. In single chamber AFC, bacterial co-cultures are grown synergistically with algal co-cultures [9]. Single chambers are easy to manage in lab when compared to other configurations. Single chamber AFC are easy to operate, cost effective in scaling up and can be used commercially.

Dual or two chambered AFC consists of two separate chambers in which microalgae and bacteria are separated by a membrane [10, 11]. In two chambered configuration, cathodic compartment contains microalgae that are illuminated for photosynthesis reaction. The anodic compartment is also illuminated making the algae to cover the bacterial compartment in most of the studies. Highly relative internal resistance and crossover of the membrane are some issues are associated with this system.

Three chambered MFCs are an additional chamber containing salt water that gives stress to the production of power. The third chamber is in between the cathode and anode chambers. Partial desalination is observed in the middle chamber where cations move towards cathode and anion towards anode [7].

In sediment AFC, an anode is buried in sediment and a cathode is on the top of sediment immersed in the water having microalgae. The differences in existing electro-potentials generate energy [12, 13]. During this process the released electrons are captured by the anode and current is generated in an electrical circuit. In this configuration, cathode compartment was changed to biogenic one.

3. Bio-active organisms

Microalgae are one of the best bioactive metabolites for a microbial fuel cell which can mitigate CO_2. The mechanism of donating an electron and accepting it is still uncertain. The understanding of the mechanism is important for improving the performances of AFCs. Some studies predicted that dumping of cells in a certain environment causes the reduction of power against oxidative stress. Researchers have explained these mechanisms by using specific inhibitors of electron transport chain in microalgae [14, 15]. Another prediction has reported that microorganisms use electrical signal for communicating and this is explained in many complex communities containing autotrophic and heterotrophic, eukaryotic and prokaryotic organisms where electrogenic microorganisms exist [16]. Many researchers have reviewed and recommended microbial fuel cells using microalgae for the right selection of the type of algal strain to maximize power production [17, 18]. The study to determine the method of screening the right strain is few in number. A recent study has made an effort for cost-effective photosynthetic microbial fuel cell design with highly reproducible electrochemical characteristics that can be used to screen algae and cyanobacteria for photosynthetic electrogenic activity. *Paulschulzia pseudovolvox* (*Chlorophyceae*) is identified as good electrogenic qualities among several cyanobacteria [19].

4. Interactions between algae and electrodes

4.1. Anolyte

The anolyte used in AFC is rich in carbon source such as glucose formate and acetate being similar to other prepared sources like LB medium, *Scenedesmus* algae in powder form, fruit industry liquid waste and wastewater [9, 11, 20–24]. The factors affecting the generation of power depends on the types of anolytes used and their internal resistance. The efficiency and power production of AFC depend on the resistance of membrane on anolyte, high ion generation in the anodic chamber and oxygen crossover through the membrane. Some of the problems faced by AFC are membrane fouling, high COD and low pH of anolyte. To overcome these problems, membrane pretreatment and continuous monitoring of the internal conditions of the anodic chamber is necessary.

4.2. Catholyte

The commonly used catholyte in AFC is microalgae. Microalgae in cathode help in reducing the CO_2 emitted from bacterial metabolism, respiration providing economic and environmental sustainability. Blue green algae, *Chlorella vulgaris*, *Desmodesmus sp.*, etc. are some of the microalgae used in the cathode compartment of AFC. *Chlorella vulgaris* is one of the common microalgae which have been studied extensively as a catholyte by many researchers. It is influenced by several factors such as electron consumption by methanogenesis, aerobic respiration by the cathodic biofilm and oxygen crossover which is hindered during COD removal [25]. Moreover, algal biofilms can limit the diffusion of oxygen affecting the performance of AFC [26]. Researchers have reported 92% of COD removal and 90–80% removal of inorganic components with 2.2 mW^{-3} of power density [27]. The yielded biomass from AFC can be used as animal feed or for energy and bio-product generation [28].

4.3. Electrode material

Electrode materials play a vital role in AFC because of its overall cost effectiveness and the performance in power generation. Properties such as good electrical conductivity and low resistance, strong biocompatibility, chemical stability and anti-corrosion, large surface area and appropriate mechanical strength and toughness are to be considered in the selection of an electrode material. Commonly used anode materials are graphite plates and rods, carbon fiber brushes, carbon cloth, carbon paper, carbon felt, carbon nanotubes and granulated graphite [17]. Carbon electrode is used extensively due to its low cost when compared to other electrodes. Biofilm helps in trapping the electron with the help of electrode and algal substrate. Therefore, cathode graphite felt coated with platinum, 10% Teflon coated on carbon paper, etc. are preferred to increase biofilm formation on the cathode.

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5. Membrane

The membrane is the heart of this system which is highly expensive. This results in the increase of the overall cost of AFC. Membranes act as a separator for the anode and cathode compartments. The substrate that is used in this system tends to produce electrons and protons which are passed through the membrane for the separation of specific ions. Though the membranes are used as a barrier, it has some issues. The motion of ions from the anode to cathode chamber slowly increases the protons in the anode chamber and the negatively charged ions in the cathode chamber. This results in low and high pH in anode and cathode.

The overall performance of AFC can improve by a membrane separator having micellar porous structure separating the specific ions from anode chamber to cathode chamber. Proton exchange membrane and electron exchange membrane are the most preferred membranes due to their superior conductivity properties. But these are unsuitable for high power scale application due to their need for hydration and high cost. Some of the studies have explored the use of alternative membranes of low cost which are: cation exchange membranes such as sulfonated polyether ether ketone, sulfonated polystyrene-ethylene-butylene-polystyrene, CMI-7000 and Hyflon ion, anion exchange membranes such as AMI-7000, salt bridges and porous materials such as J-Cloth, glass fiber filters, nylon, nonwoven cloth, earthenware pot, ceramic, terracotta, compostable bags and latex glove. The use of these inexpensive membranes occasionally causes difficulties like high internal resistance.

6. Influence of carbon dioxide

The healthy growth of algae in AFC is essential for efficient power production which is influenced by growth media, nutrient supplement and CO_2. The optimal growth of microalgae is achieved when the cathodic chamber is bubbled with CO_2 or by diverting CO_2 produced in the anodic chamber which concludes that the microalgae is able to fix CO_2 by consuming the inorganic carbon in cathodic chamber and CO_2 produced in the anionic chamber which permeates through the membrane [23, 29]. The micro-algae also prefer to use CO_2 in the presence of light and organic carbon the result of which is the production of daytime electricity depending on the organic loading rate and light irradiation. In some cases, a higher concentration of CO_2 causes adverse effect on algae during the early stages of growth. The dissolved CO_2 eventually decreases the pH of the electrolyte and this pH of the algal inoculums must be high initially to overcome. Apart from this, CO_2 concentration also affects the lipid content of microalgae. The cells produce polyunsaturated fatty acids under high CO_2 concentrations. A 6% lipid content increase was observed accompanied by a 10–15% increase in CO_2 supply [30].

7. Influence of light source

Algae and higher plants contain two major photosynthetic systems in thylakoid membrane. They are classified as photosystem I and photosystem II containing chlorophylls and carotenoid pigments respectively for light energy absorption [31, 32]. The chlorophyll pigment adsorbs wavelength between 650 and 750 nm in the red region while carotenoids pigment absorbs wavelength between 450 and 500 nm in the blue region. This mechanism of transferring excitation energy by both chlorophyll and carotenoids results in higher efficiency of photosynthesis over a wide range of wavelengths [32]. However, the absorption of wavelength by the pigments depends entirely on the type and history of microalgae [33].

During photosynthesis, light energy absorbed by chlorophyll induces the transfer of electrons and hydrogen ions from water to an acceptor called NADP+ where they are temporarily stored. The light reactions use solar power to reduce NADP+ to NADPH by adding a pair of electrons along with a proton from which electrical power may be generated [34].

Photosynthesis rate can be increased by proper light source and light intensities leading to higher cell growth and generation of electrons. As a result, higher bioelectricities might be observed with an optimized light source installed in photo microbial fuel cells. However, only a few studies focusing on the influence of specific light supply or intensities upon power generation and cell growth of photosynthetic microorganisms have been carried out. Xing et al. [35] found that the exposure of AFC to incandescent light increased power densities by 8–10% for glucose fed reactors and 34% for acetate fed reactors when compared to the reactors operated under dark condition. But, Fu et al. [36] obtained a higher power density and open-circuit voltage when AFC was operated under dark condition by using *Spirulina platensis* as biocatalyst. Yeh et al. [37] had investigated the effect of the type and light intensity of artificial light sources on the cell growth of microalgae *Chlorella vulgaris*. They found that fluorescent light source was effective in indoor cultivation of these microalgae with an overall productivity of 0.029 g dry cell weight $L^{-1}d^{-1}$ and it was obtained by using light source having a light intensity of 9 W m^{-2}. Similarly, *S. platensis* and *H. pluvialis* cultivated under red LED light condition showed better growth profile [35, 38, 39]. On the other hand, *Nannochloropsis sp.* showed a maximum specific growth rate of 0.64, 0.51, 0.54 and 0.58 d^{-1} when exposed to blue, red, green and white light respectively [40].

8. Influence of fouling

8.1. Membrane fouling

The most important component of AFC is a membrane which acts as a physical separator and ion selective in passing protons. Moreover, it also hinders the passage of other materials and prevents the crossover of oxygen from the cathode to the anode. Microbes grow on the surface of the membrane causing membrane fouling when AFC is operated for a long term. Membrane fouling occurs when organic foulants such as extracellular polymeric substances aggregate on the surface of the membrane. The negatively charged sulfonate groups in the membrane are prone to this type of fouling especially at low pH [41]. This bond eventually contributes to the formation of a strong biofouling layer on the membrane.

8.2. Biofouling

Oxygen reduction reaction occurs on the exposed area of catalyst and its framework present in three-phase boundaries. Over potential of this is efficiently reduced by commonly used

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expensive catalyst. The latest development in low cost catalyst like carbon based cathode delivers equivalent performance due to abundant pores and larger specific area. However, the main drawbacks of this porous structure are their low resistance to biological fouling. Therefore, ionic membranes and separators are used in AFC to reduce this effect on proton exchange layers.

Biofouling is caused by the bacteria attached to the surface of catalyst layer that releases extracellular polymeric substances. Biofouling on catalyst layer is similar to biofilm on membranes and separators. It is a thick layer developed on carbon based cathode that increases the diffusion resistance responsible for the declined performance during the long term. Further, it also decreases the activity of dopants on the surface of catalyst layer by the combined effect of biofilms with salt deposition. This was evident from the research of Zhang et al. [42] in which improved power density of cathode increase up to 29% was observed after removing the fouling by weak hydrochloric acid. But there are not clear and sufficient demonstrations regarding the individual effect of biofouling located on the surface of the catalyst layer and inside the layer.

9. Energy analysis

Economic success of AFC is directly related to power generation, algal biomass production in combination with other application in a fully biotic cell. Even though there is enormous progress in the research in this area, there are still difficulties in practical applications. The overall power output of the system decreases with the increase in the dimension of AFC. This is mainly due to poor mixing and deprived configuration of electrodes. Laboratory scale reactors having a capacity less than 50 mL relatively generate high power densities greater than 500 Wm^{-3} whereas configurations having larger than 2 L normally produce a power density less than 30 Wm^{-3}. The energy data of AFC are generally expressed in normalized energy recovery expressed in kilowatt hours per cubic meter based on the volume of reactor. Simple anode substrate produces more electricity than complex substrate due to easy degradation pathways. For instance, acetate produce much higher power densities than glucose (<0.03), sucrose (–< 0.01) and wastewaters (<0.01) which are complex. Similarly, average normalized energy recovery with acetate, glucose and wastewater are 0.25, 0.18 and 0.04 kWh m^{-3} respectively [43].

A good separation between the electrodes is necessary to prevent interaction between oxygen diffusion, anolyte, catholyte and other materials. This is facilitated by a solid electrolyte or an oxygen gradient. The commonly used solid electrolytes include cation exchange membrane, anion exchange membrane, proton exchange membrane and other materials like textiles, woven fabrics, eggshell, papers, glass wool, etc. [44]. These materials greatly affect energy recovery, performance and capital cost of AFC. Some of the researches show that ion exchange membranes have a lower normalized energy recovery 0.14 ± 0.40 kWh m^{-3} when compared to the membrane-less system which has 0.23 ± 0.46 kWh m^{-3} ($p < 0.05$) [43].

Stacking AFC in parallel or series configuration helps to achieve preferred voltage and current output [45]. This shows some encouraging results for the technical feasibility of operating multiple AFCs. It is proven that a stack consisting of 40 identical 20 mL units can achieve an open-circuit voltage of 13.03 V [46]. Similarly, by shuffling the parallel and serial electric connections in a stack an external power management system can extract a power of ~200 mW which can drive a 60-W DC motor [47].

The information on energy recovery helps to establish an overall energy balance. The improvement of energy recovery through optimizing configuration, operation, microbiology and materials will make AFCs more attractive. On the other hand, adopting proper strategies to reduce the energy requirement of operation may compensate for low energy recovery. Incorporating other energy producing processes such as biogas production, algal biomass harvesting, biohydrogen etc., will increase the energy independency. Further, modifying the process for desalination, nutrient recovery and production of valuable chemicals will also maximize the benefits of AFC.

10. Application and adaptability

AFC has attractive properties that ensure further development and applications of this technology. It can be easily combined with green roofs to create electricity where photosynthetic and electrochemical reactions are carried out by a continuously growing population of microorganisms in living solar cells. This makes the system capable of self-repair, giving long lifetime and low maintenance. Moreover, using these reproducing organisms living in solar cells does not require any special catalysts that in solar cells are costly and toxic. Therefore, it can be used in natural surroundings with no risk of pollution. AFC also has organic material as intermediate energy carriers between the photosynthetic and the electrochemical portions of the cell which help them in generating electricity at night [48]. Closed loop AFC systems can preserve nutrients for the organisms which enable long-term, low-maintenance power production. Integrated AFC will add value to other applications such as food, agriculture, biomass for bio-energy production etc. [49, 50]. Similarly, it can be coupled with wastewater and surface water treatment to supply extra organic matter for energy production and in turns providing treated water [51].

11. Challenges

Algae fuel cells are not without limitations. They need high cost infrastructure and energy for harvesting and growth. Another problem associated with microbial fuel cells is the pH membrane gradient which reduces cell voltage and power output. This problem is caused by acid production at the anode, alkaline production at the cathode and the nonspecific proton exchange through the membrane. The high cost of membrane commonly used in laboratories as a proton-permeable membrane would also limit the applications [52]. In addition, the slow rate of oxygen reduction at cathode electrodes is also a major limiting factor for power generation.

Need for improved engineering on downstream algae biofuel processing from AFC for sustainable energy production is another challenge. It includes effective strategies for nutrient circulation and light exposure in designing photo-bioreactors that are reasonably cheap for large-scale deployment in low-cost systems. The secondary challenge related to this is the extraction of crude algae oil which is mostly addressed from the engineering side. The extraction technologies which are successfully demonstrated are relatively expensive. On the other hand, challenges associated with the management of algae bio-oil conversion to usable liquid fuels need improved catalysts similar to petroleum crude.

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12. Conclusion

AFC is a developing technology with a huge potential to capture solar energy and convert it to electricity. Similarly, the regenerated biomass during the process can be converted into secondary biofuels like solid biomass, bioethanol, biogas, etc. which is an added advantage. This technology also remediates wastewater, removes heavy metals, dye decolorizes, etc. Even though various studies have focused on increasing the performance parameters, physical and catalytic parameter variations, improvement of power generation, cost effective electrode materials, selection of bioactive organisms and finding out an alternative membrane to give cost effective solution need to be addressed. In near future, algae will become a sustainable technology and development in this research area. The possibility of using bioengineering, molecular biology, biotechnology and electrical engineering together to improve the efficiency of AFC is not a farfetched idea. Some studies like life cycle analysis based on commercial-scale, increasing power density, optimization technological methods on AFC configuration need special attention and investigation.

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