Chapter 5
Algal Microbial Fuel Cells—Nature's Perpetual Energy Resource

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5.1 Current Scenario

The world's rapidly growing population is leading to increased energy demands worldwide. The population explosion and the rapid consumption of limited oil reserves is increasing carbon dioxide levels in the atmosphere, thus leading to global warming. Climate change is another, greater, threat to humans and the environment. Therefore, the demand for energy and its social consequences are leading researchers to look for substitutes for existing energy sources (Satyanarayana et al. 2011). Much wide-ranging research is being carried out to find possible energy solutions. The technology called microbial fuel cells (MFCs), where bacteria and other microbes generate electricity from waste and biomass, has gained the attention of researchers for its attractive features.

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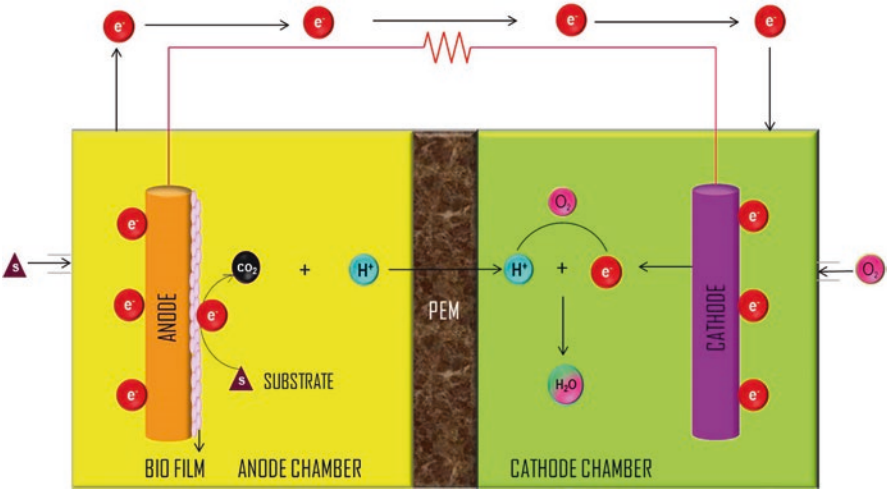


Fig. 5.1 Schematic diagram of basic microbial fuel cell (MFC)

5.1.1 Microbial Fuel Cells (MFCs)

Microbial fuel cells (MFCs) are a rapidly emerging technology, where electricity is generated from the microbial metabolization of substances; during this process oxidation-reduction occurs, releasing electrons through which the electricity is generated. MFCs contain two chambers, an anode and a cathode (Fig. 5.1), which are separated by a proton exchange membrane (PEM) (You et al. 2006). With this technology, microorganisms metabolize organic substances in the anode chamber, producing protons and electrons. The electrons migrate to the anode and reach the cathode via a circuit that is connected externally, while protons from the anode chamber are transferred to the cathode chamber via the PEM that is present between the anode and cathode (Oh et al. 2004).

The electrons and protons combine, with the reduction of oxygen to water taking place in the cathode chamber. MFCs have multiple gas inflows and outflows (Sevda et al. 2013). The cathode chamber has oxygen inlets that greatly affect the electricity output produced by the MFC. The oxygen source provided to the cathode chamber differs depending on the type of MFC used. For single-cell MFCs, atmospheric air is used, while mechanical aeration is used for dual-cell MFCs. Carbon dioxide is the main gaseous end product, and glucose and acetate or wastewater are used as a substrate (Freguia et al. 2007). The cathode chamber has an alkaline condition, which increases the absorption of carbon dioxide from the anode. This condition develops because of the accumulation of hydroxide ions, resulting from oxygen reduction at the cathode (Rozendal et al. 2006). In practice, there are limiting factors in the applications of MFC for oxygen gas delivery and carbon dioxide gas accumulation; these limitations can be overcome by the use of efficient and sustainable catalysts for the cathode reaction (El Mekawy et al. 2013).

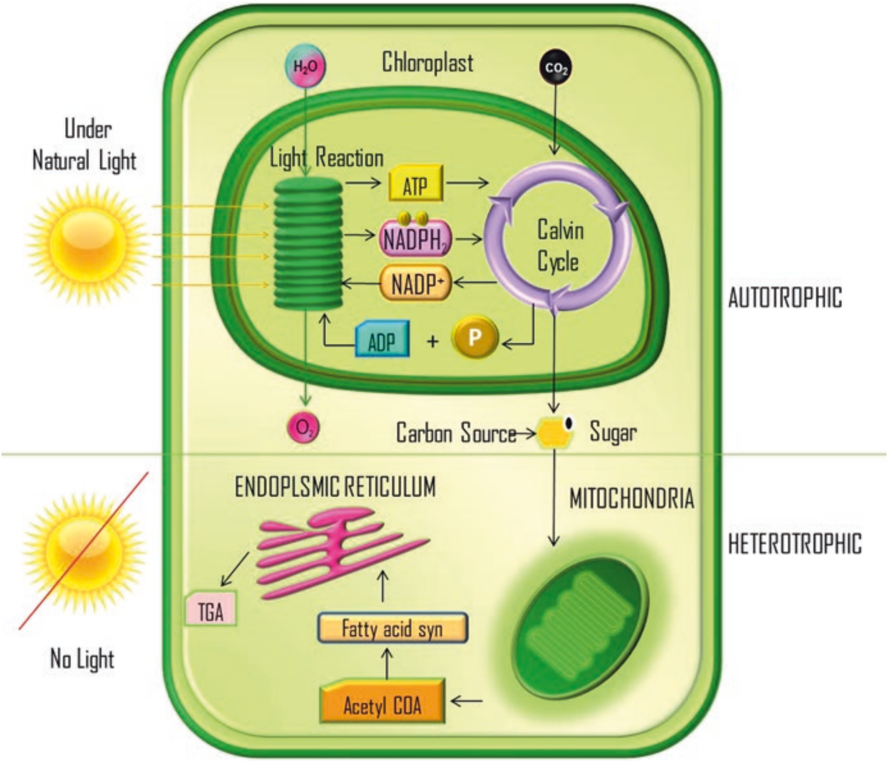


Fig. 5.2 Schematic representation of autotrophic and heterotrophic growth systems in algae

5.1.2 Algae

Algae are chlorophyll-containing organisms that range in size from microscopic and unicellular to very large and multicellular. Some algae are autotrophic in nature, deriving their own food from their surroundings in the form of sunlight. Algae have a distinctive role in maintaining the food chain and oxygen supply on Earth. Moreover, they have a high growth rate and high carbon dioxide fixation rate (Cheng et al. 2006a, b). Algae play a vital role in transforming solar energy into different forms of biochemical energy by their photosynthetic throughput (Mohan et al. 2011). Photosynthesis is the complex biological redox reaction that occurs in algae, by which they utilize solar energy to produce oxygen, carbohydrates, and other compounds. There are two different algal growth types, autotrophic and heterotrophic (Karube 1992). The growth system of algae that use carbon dioxide as a carbon source in the presence of light energy or in an illuminated environment is termed autotrophic (Fig. 5.2), while algae that grow in the absence of light, in photobioreactors (PBRs), by utilizing a carbon dioxide source from substrates provided in the culture medium, are heterotrophic.

Table 5.1 Different types of algae used as substrates in photosynthetic microbial fuel cells (PMFCs)

Algal species used in single-chambered PMFCs	
Species	Reference
Chlamydomonas reinhardtii	Nishio et al. (2013)
Chlorella vulgaris	Sharon B Velasquez et al. (2009)
Cyanobacteria	Yong Yuan et al. (2011) and Zhao. et al. (2012)
Ulva lactuca	Sharon B Velasquez et al. (2009)
Algal species used in dual-chambered PMFCs	
Microcystis aeruginosa	Huan Wang et al. (2012)
Chlorella vulgaris	Huan Wang et al. (2012)
Arthrospira maxima	Inglesby et al. (2012)
Scenedesmus obtusus	Rashid et al. (2013) and Cui et al. (2014)
Laminaria saccharina	Gadhamshetty et al. (2013)
Scenedesmus obliquus	Kondaveeti et al. (2014) and Hur et al. (2014)
Chlorella vulgaris	Lakaniemi et al. (2012)
Dunaliella tertiolecta	Lakaniemi et al. (2012)
Mixed algae	Strik et al. (2008), De Schamphelaire et al. (2009), and Huan Wang et al. (2012)

Autotrophic and heterotrophic modes can be combined to form a mixed culture (mixotrophic) growth mode, through which photosynthetic metabolism and respiratory metabolism function simultaneously to assimilate organic carbon and carbon dioxide (Lee 2004). Different types of algal species (Xiao et al 2014) used as substrates in photosynthetic MFCs (PFMCs) are listed in Table 5.1. The heterotrophic growth mode has an added advantage, since it allows the use of any type of bioreactor, with no specific design being necessary. In heterotrophic mode, the growth rate of the algal biomass is very high, along with the production of ATP. Also, the nitrogen yield and lipid content are very much higher than in the autotrophic mode. However, heterotophic algal cultures have several drawbacks in that the microalgal species used are limited. The energy expense is high when organic substrates are supplemented in a heterotrophic system are also subject to contamination with other microorganisms (Yang et al. 2000).

5.1.3 Experimental Setup of MFCs

For more than a decade it is has been believed that microorganisms could generate electricity, but only in recent years has the technique been instigated in the laboratory (Barua et al. 2010). MFCs are capable of utilizing microorganisms as a catalyst for converting the chemical energy of feed stocks into electricity (Aelterman et al. 2006). MFCs are complex microbial ecosystems where the redox reaction is part of

Table 5.2 Different types of donors and acceptors used in PMFCs

Donor at anode chamber	Acceptor at cathode chamber	Products obtained	Reference
Process: Oxidation	Process: Reduction		
Algal species	Potassium ferricyanide	Electricity	Strik et al. (2008)
Water	Potassium ferricyanide	Electricity	Thorne et al. (2011)
Water	Oxygen	Electricity	Zou et al. (2009)
Water and glucose	Potassium ferricyanide	Electricity	Yagishita et al. (1997)
Sediment material	Oxygen	Electricity	He et al. (2009)
Trypticase soy broth	Proton	Electricity	Qian et al. (2010)
Wastewater	Oxygen	Algal biomass + electricity	Xiao Z et al. (2012)
Marine sediment material	Oxygen	Glucose and oxygen+ electricity	Malik et al. (2009)
Organic acids and alcohols	Potassium ferricyanide	Hydrogen+ electricity	Rosenbaum et al. (2005b)
Succinate and propionate	Oxygen	Hydrogen+ electricity	Cho et al. (2008), Strik et al. (2010)

the microbial metabolism rather than being mediated by an inorganic catalyst (Gruning et al. 2014). Generally MFCs contain two chambers: an anode chamber and a cathode chamber, which are separated by a PEM. An anaerobic biofilm is formed on the electrode in the anode chamber, where oxidation of the substrate results in the release of protons and electrons. The protons are transferred from the anode to the cathode via the PEM. The electrons produced on the anode move to the cathode via an external circuit. The electrons reduce electron acceptor in the cathode chamber (Rabaey et al. 2005a, b). MFCs are constructed with different kinds of materials and with different configurations. Temperature and pH conditions vary depending upon the algal species used in the reactors. Other parameters, such as reactor size, electrode surface area, electron acceptors, and operating times, differ in each model. Different kinds of anodes and cathodes that act as donors and acceptors are listed in Table 5.2.

5.2 Electrode Materials

5.2.1 Properties of Electrode Materials

The performance of the MFC depends mainly on the choice of electrode material, as the adhesion of the microbes, transfer of electrons, and efficiency of the electrochemical substance depend on this material. To measure power production, carbon-based materials (carbon fiber, carbon felt, carbon cloth) are used. Logan (2010) reported that cathode materials should have the catalytic properties that are essential for oxygen reduction. Criteria for the selection of materials are different for anodes and cathodes, but there are certain properties that both should possess in general, as listed below.

Porosity and Surface Area The power output of the MFC is controlled by the surface area of the electrode. The loss in ohms is directly proportional to the electrode resistance. By decreasing the resistance the surface area can be increased, although the volume remains the same. This increase in surface area increases the efficiency of the MFC. Wang et al. (2011) and Rismani et al. (2008) reported that large numbers of reaction sites were provided by a large surface area; both these groups have also reported that electrical conductivity is greatly affected by the pore size of the electrode material.

Electrical Conductivity Biofilm present on the anode contains microbes that release electrons, and later these electrons travel through an external circuit. Electrode materials with higher electrical conductivity have lower resistance. To facilitate the transfer of electrons, the interfacial impedance has to be low. Natarajan et al. (2004) reported that a triple phase boundary reaction was facilitated by ionic conductivity at the cathode.

Durability and Stability Reduction and oxidation conditions in MFC increase the volume of material and results in decomposition. The electrode material's durability is increased when it has high surface roughness, but this might result in contamination. Hence, with an electrode that has high surface roughness, the MFC's long-term performance would be reduced. Mustakeem et al. (2015), reported that electrode materials should be durable in both acidic and basic media.

Accessibility and Cost The setup cost of an MFC depends on the cost of the electrode material used. When an MFC is about to be commercialized the cost of the material should be low and the material should be easily available. Platinum is an expensive metal that is non-durable and non-sustainable. Accordingly, in future, metal materials such as composites will be alternatives for expensive electrode material. The anode material should be biocompatible. Mustakeem et al. (2015) suggested that material with higher biocompatibility would adhere to the microbes, and consequently the life of the MFC would be increased.

5.3 Materials Used for the Anode

Anode materials should be very conductive, biocompatible, and chemically stable. The most versatile electrode material is carbon, which is available in different forms, such as graphite plates/rods/granules (Fig. 5.3) and fibrous materials in the

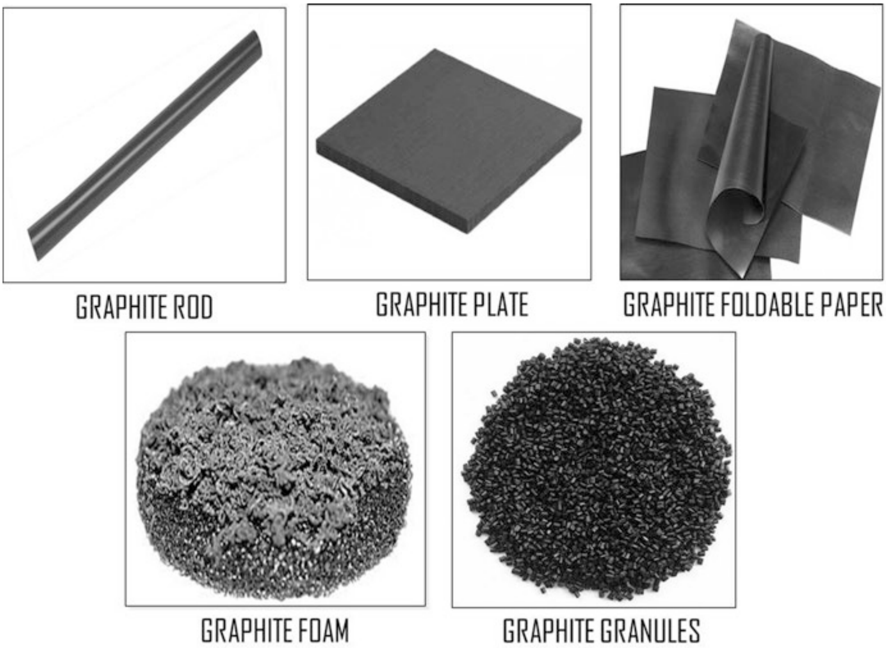


Fig. 5.3 Different types of graphite anode materials

form of carbon paper, carbon cloth, carbon foam, carbon felt and carbon fiber (Fig. 5.4). Graphite plates and rods are considered to be the simplest materials and the best anode electrode material because they are inexpensive, their handling is very easy, and their surface area is very defined. Park et al. (1999) and Gil et al. (2003) used graphite felt as electrodes because of its large surface area. He et al. (2005a, b) reported that even reticulate vitreous carbon material, which is very compact, can be used to achieve a greater surface area.

5.4 Materials Used for the Cathode

Park et al. (2003) reported that ferricyanide (K3 [Fe (CN) 6]) was the most popular electron acceptor used in MFCs owing to its good performance, and Rabaey et al. (2005a, b) reported that ferricyanide had lower potential than plain carbon when used for the cathode. However, the major disadvantage of ferricyanide is that oxygen cannot be sufficiently reoxidized, requiring regular replacement of the catholyte. In MFCs, the most suitable electron acceptor is oxygen, because of its oxidation potential and because it is easily available and free of cost and water is formed as an end product. The performance of an MFC may depend on the choice of cathode material, the selection of which is based entirely on the application required.

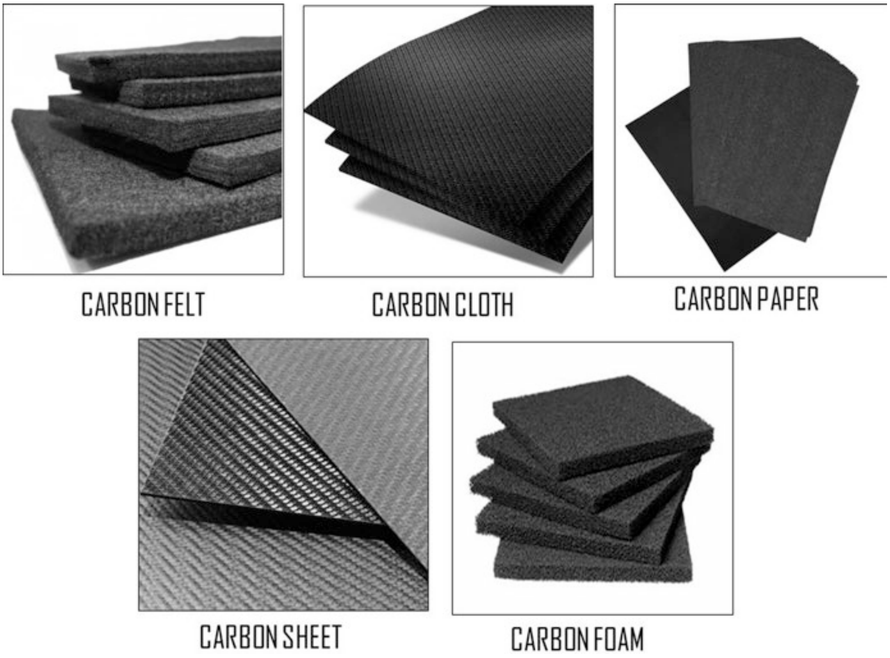


Fig. 5.4 Different types of carbon anode materials

5.5 Membranes

A membrane is essential for the transfer of protons and hydrogen ions from the anode to the cathode, inhibiting the electrons from hydrogen atoms; the PEM is such a membrane. There are different kinds of PEMs, such as bipolar membranes, cation exchange membranes (CEMs), and anion exchange membranes (AEMs). Reimers et al. (2001) reported that fluorinated polymer was the best base material for CEMs. With respect to optimum proton conductivity, sulfonic acid groups are used in membranes in proton-exchange membrane fuel cells. Owing to their lower thermal durability and low conductivity of hydroxyl ions, hydrocarbon polymer backbones and quaternary ammonium groups are the best base for AEMs.

5.6 Integration of Algae in MFCs

During flow chain reactions, photosynthetic organisms undergo charge separation and discharge electrons and protons, with a synergic effect taking place between heterotrophic microorganisms and algae. The heterotrophic microorganisms metabolize the organic matter substrate, degrading it, and produce oxygen and bicarbonates, which are metabolized by the algae, using solar energy. Kruzic et al. (2009)

integrated an aeration system to replace a sustainable photosynthetic one. When algae are growing in the cathode chamber of an MFC, electricity is produced by a photosynthetic process (Juang et al. (2012)). McGowan et al. (2000) reported that the substrate is oxidized at the anode when the algae in the cathode are the electron source, and the carbon dioxide is reduced to biomass. For electron shuttling, a mediator is used in the cathode chamber through which the electrons flow from anode to cathode. The electrons from anode enters the catholyte to reduce oxidized state of mediator and enter the algae to release the electron and later gets oxidized again. The shuttled electrons are consumed by the algal cells that grow during the metabolic pathways by which carbon dioxide is transformed to biomass and oxygen. The oxidized mediator is released by the algal cell into the media and this cycle is repeated again were the mediator gets reduced again by the electrons within the catholyte Powell et al. (2009). When illumination was applied, a biochemical reaction took place in both the anode and cathode chambers, as explained by Zhou et al. (2012), and shown below:

$$C_6H_{12}O_6 + 6H2O \rightarrow 6CO_2 + 24H^+ + 24e \tag{5.1}$$

$$6CO_2 + 12H^+ + 12e \rightarrow C_6H_{12}O_6 \ \left(\text{biomass}\right) + 3O_2 \tag{5.2}$$

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \tag{5.3}$$

Under illumination, algal species undergo a photosynthetic process to produce biomass and organic matter. Oxygen consumption by algae takes place in the dark to oxidize the organic matter, through which energy is obtained (Del Campo AG et al. 2013a, b, c) (Eq. 5.3).

Certain photosynthetic bacteria, such as *Spirulina platensis*, are used as catalysts at the anode. Without the help of any mediator, electrochemical potential is maintained by the biofilm that is formed around the electrode; this biofilm can accept the generated electrons.

5.7 Different Types of PMFC Configurations

Technology using solar energy is now the focus of great attention with the ecological management of energy resources. In the past 10 years many innovative technologies have been developed to convert solar energy into bioelectricity with bio-electrochemical systems. In the absence of artificial mediators, photovoltaic devices can be used to separate photosynthetic and heterotrophic energy production. PMFCs consist of an anode and cathode; the cathode contains a biofilm surrounded by photosynthetic microorganisms in which photosynthesis takes place. At the end of photosynthesis these microorganisms act as electron donors and produce different kinds of metabolites, while carbon dioxide is removed. Increasing the power density is the most challenging task for improving the configuration of PMFCs.

5.8 Coupled PMFCs

A coupled PMFC is an integrated system consisting of a bi-anode-chamber MFC where carbon dioxide is pumped directly into the photo bioreactor that is coupled with the MFC (Fig. 5.5). This type of MFC functions in the absence of an ion exchange membrane; hence, it is very cost effective and simple in structure. Strik et al. (2008) constructed an MFC using two electrodes separated by a CEM. The MFC was connected to an illuminated PBR to grow algae by supplying air through a sparger. Algae grown under light illumination undergo photosynthesis, and energy conversion takes place to form a biomass of electrochemically active microorganisms in the anode compartment, through which electricity is produced. A photosynthetic algal MFC works on a principle based on the selected type of algae and microorganisms employed in an open system, without any toxic intermediaries. This model has generated electricity obtained as a result of catalysis for about 100 days.

Similarly to the results reported above, Powell et al. (2009) demonstrated a photosynthetic cathode as one part of an MFC employing *Chlorella vulgaris*; the other part of the MFC was an anode that employed yeast with a fermentative quality. This

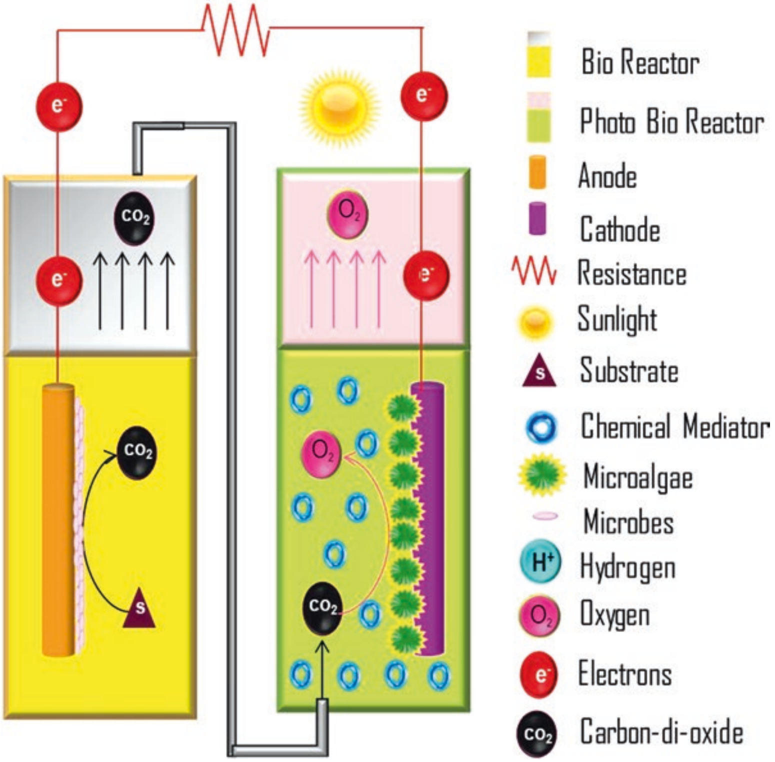


Fig. 5.5 Schematic diagram of coupled photosynthetic MFC (PMFC)

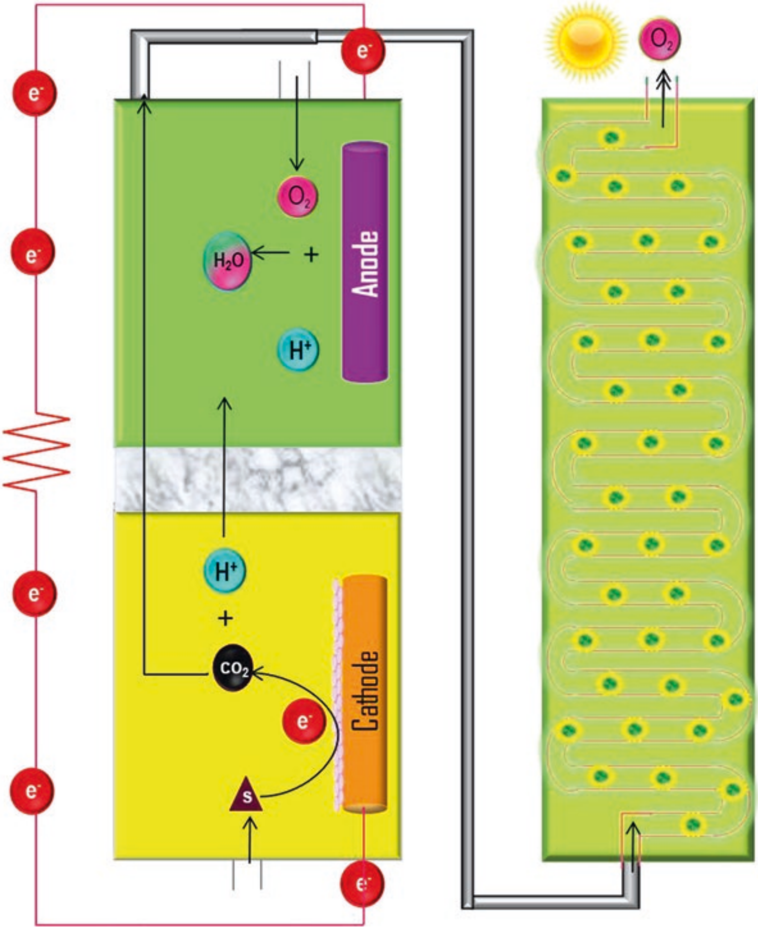


Fig. 5.6 Schematic diagram of coupled PMFC – upflow MFC-based design

model was said to be a coupled MFC. The cathode cell was designed to generate power and metabolize the carbon dioxide emission from bioethanol plants, whereas the anode cell was designed in such a way that it was illuminated by sunlight and aerated with feed and air consisting of 10% carbon dioxide passed to the cell cultures, with electron shuffle between the electrode and the yeast. Jiang et al. (2013) proposed a similar design for a coupled MFC using a PBR and an upflow MFC where the effluent was pumped continuously into the PBR (Fig. 5.6). Microalgae under continuous illumination were employed for this experiment. The coupled MFC was made using plastic cylinders, and the electrode was a carbon fiber brush. The anode and cathode chambers were separated using glass and wool beads. This model of an integrated PBR and MFC was designed for wastewater treatment and power generation.

Silvaggi (2016) proposed an MFC system integrated with an algal bioreactor in which synthetic wastewater was fed into the anode compartment, where organic compounds were biologically degraded to generate electrons. The generated electrons moved from the anode electrode (carbon brush) to the cathode electrode (carbon cloth), where oxygen reduction occurred to complete the electrical circuit. The treated wastewater was discharged into a transitional beaker, and this solution was then supplied to the cathode compartment (algal bioreactor), where algae grew and produced dissolved oxygen to support the cathode reaction. The final effluent (containing suspended algal cells) was discharged from the cathode compartment.

5.9 Single-Chambered PMFCs

In a single-chambered MFC, photosynthetic microorganisms were employed, as these microbes have the ability to shuttle electrons to the electrode with no mediators; this design was said to be a membrane-less single-chambered MFC (El Mekawy A et al. (2014).

Fu et al. (2009, 2010) proposed a design similar to the one noted above, using blue green algae (Fig. 5.8). This proposed design was to be used for power generation. The design consists of a non-membrane single chamber with an anode and electrode. The algae act as a biocatalyst and form a biofilm, which creates electropotential. Under light illumination, photosynthesis takes place and in dark conditions a respiration reaction takes place, by which electric current is generated.

Chandra et al. (2012) and Venkata Subhash et al. (2013) proposed another type of single-chambered PMFC, termed a photobiological fuel cell. This type of PMFC has dual chambers, an anode and a cathode, separated by a PEM. These authors used mixotrophic microalgal cultures. In the mixotrophic culture medium, where both autotrophic and heterotrophic metabolism take place, these algae form a biofilm, utilizing carbon dioxide, and they act as a carbon source.

Similarly, Nishio et al. (2013) used a synergetic approach, by introducing a mixed culture of bacterial and microalgal cells, which improves the performance of single-chambered PMFCs. Their design used a general MFC with a portable biobattery. This system has the ability to produce certain organic byproducts, such as acetate, as a result of assimilation carried out by the bacteria, with electricity produced at the end. The highlight of their work was to recharge the MFC and extend the operation time. Photosynthetic reaction was achieved by illuminating light and dark conditions, which seems to be a reversible process that recharges the MFC to prolong the operation time.

Lin et al. (2013) designed an MFC with no membrane or mediator. Different materials were used for the anode and cathode. Gold mesh was used as the anode and carbon cloth as the cathode. They used *Spirulina platensis*, which aggregated in the anode and formed a biofilm. The biofilm was tested for chlorophyll content, which seemed to be very high; this high chlorophyll content was an added advantage for generating high voltage and high power density.

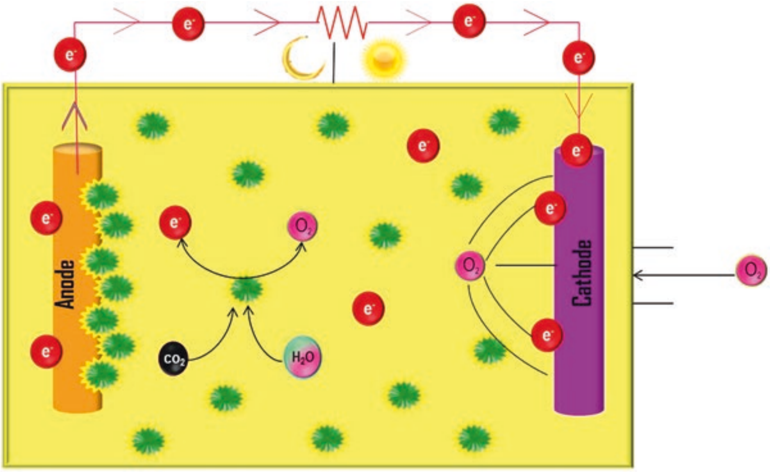


Fig. 5.7 Schematic diagram of a single-chambered MFC

Hai-ming and Jiang (2016) proposed a combination of MFCs with microalgal cultivation for bioelectricity generation and domestic wastewater treatment, using a device (Fig. 5.7) in which bacteria were employed as catalysts to oxidize organic matter as well as to generate electrical current. A sediment MFC (SMFC) was constructed with an anaerobic tube glued to the top of the chamber. The tube was sealed with a butyl rubber stopper and a perforated plastic screw cap. A platinum-coated carbon cloth and carbon fiber brush were used as the cathode and anode electrodes, respectively, for the SMFC, and the electrodes were connected to a copper wire through an external resistance. A stainless steel sheet was used in the cathode as a current collector. The brush anode was placed on the other side of the chamber with its end located 1 cm from the cathode (Fig. 5.8) Hai-ming and Jiang (2016).

Cylindrical-chambered MFCs are very effective for chemical oxygen demand (COD) removal from wastewater, but are not effective for nitrogen and phosphorus removal. Alternatively, microalgae can effectively remove nitrogen and phosphorus from wastewater. To improve the efficiency of wastewater treatment, a combined system consisting of an MFC and microalgal cultivation was developed, and the effectiveness of the system for wastewater treatment and electricity generation was evaluated Hai-ming and Jiang (2016).

5.10 Dual-Chambered PMFCs

A dual-chambered PMFC that uses algae for the synthesis of oxygen in the cathode chamber is the most preferred design. This design contains an ion exchange membrane to separate the two chambers. Different kinds of experiments have been carried out using these dual-chambered PMFCs, as described below.

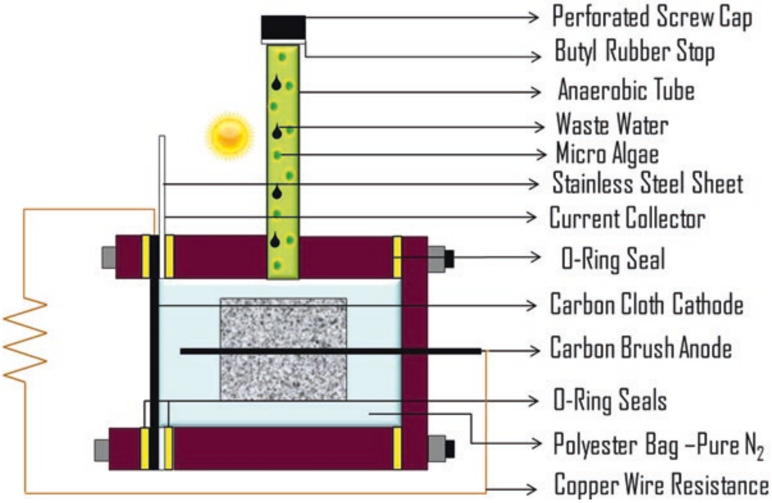


Fig. 5.8 Schematic diagram of single-chambered photosynthetic microbial fuel cell (SC-PMFC)

Rodrigo et al. (2009) designed a model dual-chambered PMFC (Fig. 5.9) in which microalgae, under illumination for 12 h per day, were used in the cathode chamber. The anode chamber, which contained bacteria, emitted carbon dioxide. In this design a vent is constructed at the top of the two chambers and connected with a pipe. The emitted carbon dioxide travels through this vent from the anode to the cathode and the microalgae utilize this carbon dioxide for growth during photosynthesis. As a result, biomass production of microalgae is also achieved.

Powell et al. (2009) used *C. vulgaris* for a comparative experiment. The algae were employed in the cathode chamber as an electron acceptor. They were also responsible for carbon dioxide removal. To determine biomass production, a sealed glass bulb was filled with a known volume of nutrient medium and carbon dioxide, along with the *C. vulgaris*. Evaluation of the cell yield was calculated by using the concentration of *C. vulgaris* cells and carbon dioxide. These authors' experiment resulted in very high cell growth, at the rate of 3.6 mg/L-h, and a reasonable power density was achieved.

Yadav (2009) constructed a dual-chambered MFC using a cylindrical plastic jar of 500 ml capacity, with 450 ml of synthetic wastewater being fed into the anode chamber; the same volume was fed into the cathode chamber. The two chambers were connected with a tube and separated by a PEM (Nafion 117; Manufacturer: Sigma Aldrich, USA). The whole experimental setup was placed under continuous illumination with fluorescent light (Philips spiral fluorescent light lamps, 15 W) to provide light for photosynthesis by algal beads. The preliminary investigation showed that the entrapped algal beads underwent constant photosynthesis and maintained the dissolved oxygen concentration in the cathode chamber solution at

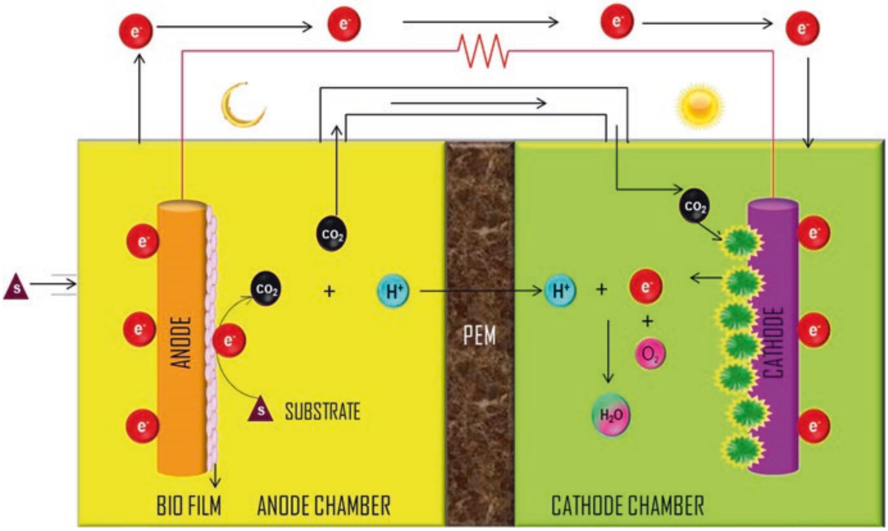


Fig. 5.9 Schematic diagram of dual-chambered photosynthetic microbial fuel cell (DC-PMFC)

around 4.0 mg/l, which is reasonably good for a successful MFC. This MFC produced power in the range of 3.97.53E × 10^{-6} W, power density in the range of 0.238 mW/m^2, and current density in the range of 1.05 mA/m. 48% reduction in COD was also observed after 5 days of experimentation.

Ramanathan et al. (2011) proposed a dual-chambered PMFC for studying nine marine microalgae: *Isochrysis sp.*, *Nannochloropsis sp.*, *Dicrateria sp.*, *Chaetoceros calcitrans*, *Pavlova sp.*, *Synechocystis sp.*, *Dunaliella sp.*, *Chlorella salina*, and *Tetraselmis gracilis*. These algae were used for generating electricity directly from biodegradable compounds.

Mitra and Hill (2011) proposed an MFC design consisting of an autotrophic cathode with *C. vulgaris* and an anode consisting of fermentative *Saccharomyces cerevisiae*, and they evaluated this system for electricity production. The system was connected with various levels of resistance to characterize and evaluate the power generation capacity and study the voltage dynamics. To study the effect of algal cell density and energy production, a recycle system was introduced into the cathode. The experimental output with respect to the cell density was 437 to 2140 mg/L. Higher the cell density resulted in higher power production of about 0.6 mW/m^2 with 5000 Ω as loading resistance.

Lakaniemi et al. (2012) carried out a similar experiment with other algae in a dual-chambered PMFC; they used freshwater microalgae (*C. vulgaris*) and marine microalgae (*Dunaliella tertiolecta*). This experiment evaluated the production of algal biomass to be used as a feed stock for the production of the electricity within a dual chamber at a temperature of 37 °C. The inoculum for the anode chamber was obtained from the sewage waste of a municipal sludge digester. Inoculums were nutritionally maintained for two different algal cultures. Maximum power was generated by continuous subculturing of enriched anaerobic organisms. Butanol was obtained from the algal biomass of the anode. The level of power generated and the butanol obtained from *C. vulgaris* were very high compared with the results for *D. tertiolecta.* In the slurry of marine algae some calcium and magnesium precipitates were found on the sides of the cathode. The authors concluded that their results indicated that their combined methodology could achieve high bioenergy production from an algal biomass.

Juang et al. (2012), Zhou et al. (2012), and Gajda et al. (2015) constructed a general dual-chambered MFC with the chambers separated by a PEM. The inoculum for the anode chamber was obtained from a wastewater treatment plant. Activated sludge was used for this experiment. Light illumination was excluded to avoid the growth of algae. However, microalgae were employed as a catalyst in the anode.

Raman K et al. (2012) and Lan JC et al. (2013) used dual-chambered MFCs in a different stratergy. They planned a three level of process to be carried out. The first process was the production of microalgae and bacterial cultures. In the second process, mechanical aeration was applied to the microalgal culture. Finally, MFCs illumination was increased mildly. All these three stratergies were experimented to evaluate the power generation obtained through each condition.

Singhvi et al. (2013) proposed a dual-chambered salt bridge MFC for a detoxification process. They studied the effects of algae in detoxifying water contaminated with chromium VI. The device they used for the experiments showed great efficiency for chromium removal, with 98% removed within 96 h at pH 2. The acidic pH condition helped in removing the chromium and in COD removal, as well as aiding open circuit potential and power density. This system proved to have high efficiency for bioremediation as well as power production.

Wu et al. (2013a, b) developed a tubular PBR, using *C. vulgaris* in the cathode compartment to produce oxygen. Two different types of cathode materials were used in this experiment. To evaluate the efficacy of the MFC with algae in the cathode, the MFC was tested with both light and dark cycles. Their results indicated that the algae they used could be effective oxygenators. The lifespan of the algae seemed to be reduced when they were continuously illuminated.

Luimstra et al. (2013) proposed a PMFC design that could be used for algal screening and electricity generation. Disposable polystyrene bottles were used to prepare the anode chamber, where simple carbon coating was applied. This chamber was utilized for algal growth. This design has unique features, such as screening the algae and analyzing and isolating the microorganisms that have electrogenic activity. Several types of bacteria that were isolated were shown to possess electrogenic activity.

Using a photosynthetic algal MFC, He et al. (2013a, b) employed *C. vulgaris* as an immobilized culture in the cathode compartment to treat wastewater and aid in the generation of electricity and biomass production. The conditions with respect to the immobilization of the algae, as well as the matrix concentration and the inoculum concentration, were studied in detail.

Campo et al. (2013a, b, c) proposed a design of MFC assisted at the cathode. Mechanical aeration was not provided to the cathode chamber. Hence, there was a requirement for oxygen, which was achieved by using *C. vulgaris*. The cathode was illuminated for 12 h every day. It took about 25 days to reach the standard conditions required for the evaluation. The rate of dissolved oxygen and the cell voltage were evaluated daily. The results indicated that the dissolved oxygen rate was not constant throughout the day, with the maximum being reached when the process was carried out in the dark. The cell voltage and the oxygen profile remained the same throughout the experimental period. Half an hour was required for the supply of carbon dioxide to be stabilized and for the system to begin working. In the acclimation stage, the power density seemed to be increased by about 13.5 mW m^2.

Gajda et al. (2013) showed that oxygen was produced in an illumination-dependent manner in photosynthetic organisms which helped to raise the generation of power by 42%. Further studies revealed that the use of a biotic cathode showed a response to light and raised the generation of power by 48% compared with that for an abiotic cathode.

Gadhamshetty et al. (2013) used a dual-chambered MFC for a batch-fed method, employing *Laminaria saccharina* as an electron donor, with mixed cultures acting as a biocatalyst in the anode chamber. The cultures were studied with three pre treatment conditions such as, 1. autoclave treatment 2. microwave irradiation and 3. No-Treatment. To control the performance of the dual-chambered MFC, a control set up was used to fix the baseline of the MFC.

Rashid et al. (2013) generated electricity using activated sludge and an algal biomass. The MFC anode was inoculated with the activated sludge. Different concentrations of the algal biomass were dried and tested. The concentration of algal biomass required to produce a voltage higher than 0.89 V was 5 g/L, and the power density was found to be 1.78 W/m^2. The output was found to be comparatively low without pretreatment. The algal biomass was tested as a substrate after oil extraction, but power output was very low. Hence, this work shows that using the whole algal biomass enhances energy production.

Kondaveeti et al. (2014) used a renewable algal biomass, *Scenedesmus obliquus*, as a substrate for generating electricity in dual-chambered MFCs. From a polarization test, it was found that the maximum power density with the pretreated algal biomass was 102 mW/m^{-2} (951 mW/m^{-3}) at a current generation of 276 mA/m^{-2}. The main organic compounds in the algal oriented biomass were lactate and acetate, and these were mainly used for electricity generation. Other byproducts, such as propionate and butyrate, were formed in negligible amounts.

Hur et al. (2014) utilized the spectroscopic changes observed in algal-derived organic matter to evaluate MFC function. Technically, variations were found in less dense component and proteins comprised in large-size. During the period of electricity generation fluorescent compounds decomposed. These authors have also reported that extracellular organic matter shows a very low ultraviolet (UV) absorption rate. Smaller-sized compounds that absorb UV seemed to decompose by themselves in the initial stages, as found by the performance of size exclusion chromatography. The protein and polysaccharide substrates were examined by Fourier transform infrared spectroscopy, which showed two structures that are very dominant in algal-derived organic matter in the microbial fuel system.

Kakarla et al. (2014) proposed a dual-chambered MFC that used algae as an oxygenator. Plain carbon paper was used as anode electrode. A carbon fiber brush and plain carbon paper were used as cathode electrodes for a comparitive study. The carbon fiber brush in the MFC cathode exhibited a voltage of 0.21 ± 0.01 V, whereas the plain carbon paper cathode had an output voltage of 0.06 ± 0.005 V. The carbon fiber brush showed a higher power output than that of the plain carbon paper.

Gouveia et al. (2014) were determined to extract pigments from microalgae. They used *C. vulgaris* in the cathode compartment and a bacterium in the anode. This study was done under different light intensities, and maximum power was attained when the light intensity was 96 lE/ (m^2 s), for which the power generated was about 62.7 mW/m^2. The authors reported that increasing the light intensity tended to increase the power production. The impact of light intensity also showed positive potential for carotenogenesis with respect to the pigments produced by the microalgae.

Cui et al. (2014) attempted to grow microalgae simultaneously in the two chambers of a dual-chambered MFC. The substrate used at the anode was a dead microalgal biomass. The carbon dioxide generated at the anode was utilized for the growth of microalgae at the cathode. This was a comparative study between an algal-fed MFC and an acetate-fed MFC. For 0.5 g/L microalgal powder, the maximum power density was 1926 ± 21.4 mW/m^2 and a coulombic efficiency of 6.3 ± 0.2% was achieved. Microalgal growth could not be sustained in the acetate-fed MFC, which lacked a carbon dioxide supply.

Gajda et al. (2015) described the potential of algal biomass production along with the treatment of wastewater and power generation, using a complete biotic MFC. Current was generated by an anaerobic biofilm that was present in the anode half-cell. Biomass was formed by the oxygen reduction reaction that took place with the help of phototrophic biofilm. Algal growth in the cathode chamber was monitored and parameters for power production were assessed and comparatively analyzed. The generation of electricity activated the crossover of cations and helped in the formation of an algal biomass. Later the harvested algal biomass was reused in a closed system.

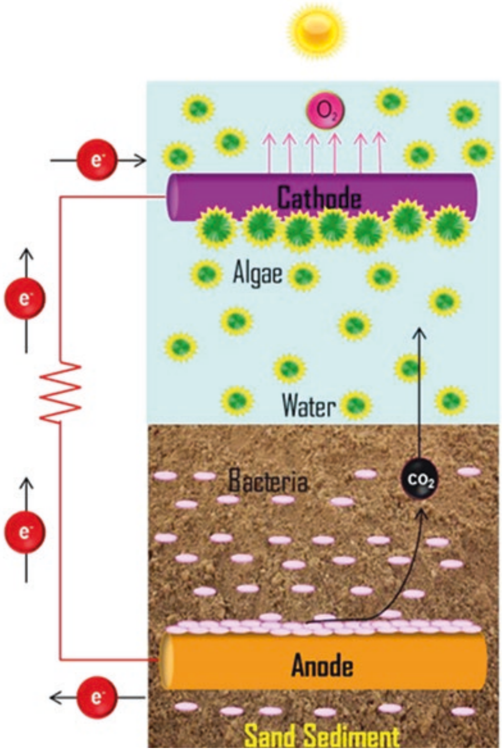
Chang Xu et al. (2015) demonstrated two different MFC models using algae. Their system was constructed with graphite or carbon electrodes and had no mediators. The first model had an anode chamber inoculated with microalgae and the cathode chamber was filled with potassium ferricyanide. In the second model, microalgae were inoculated in both anode and cathode at various conditions. *Chlorella pyrenoidosa*, which acts as an electron donor, was used in both chambers. The results indicated that higher electricity production was achieved using the first model, under low light intensity. The high algal density in ? limited the production of electricity. 4-Nitroaniline was used to increase the permeability of the algal cells, thus increasing the open circuit voltage in return. Proton leak-promoting agents such as resveratrol and 2,4-dinitrophenol acting on the mitochondria of the algal cells increased the bioelectricity production of the algal MFCs.

5.11 Sediment MFCs (SMFCs)

In SMFCs, power generation can be produced naturally by employing an anode in the sediment, while the cathode is immersed in the water and lies above the sediment. This kind of experimental setup is defined as an SMFC (Fig. 5.10). Reimers et al. (2006) and Schamphelaire et al. (2008) have called this type of system a benthic MFC. Two kinds of reactions take place in SMFCs—redox reactions and cathodic reactions. Organic molecules are oxidized by microorganisms in the sediment in what is called redox reactions, whereas the reduction reaction of electron acceptors is similar to that of oxygen dissolved in water.

Another SMFC model was proposed by Jeon et al. (2012) (Fig. 5.11). Their design has an anode and a cathode placed on opposite sides of a cylindrical plastic chamber made of poly acrylic plastic. Graphite felt is placed in both the anode and the cathode. The electrodes of both chambers are externally connected using a copper wire. The setup of the anode chamber was fixed, as follows. Initially the sediment was placed in the chamber where the anode was fixed to the middle of the sediment. Later, the anode was covered using sterilized sand. To collect the gas that is generated from the anode placed in the sediment, a funnel-shaped glass collector is fixed on the sediment surface and connected to a fixed sample bag for gas collection.

Fig. 5.10 Schematic diagram of photosynthetic sediment microbial fuel cells (PSMFCs)



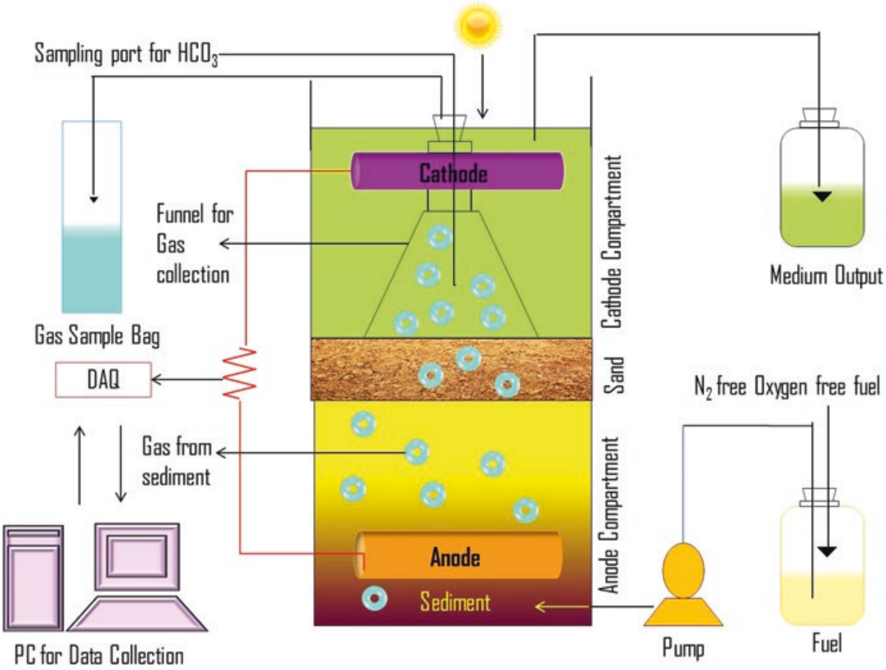


Fig. 5.11 Schematic diagram of algal culture system using PSMFC

Another parameter to customize the production of an algal biomass in an SMFC was evaluated using *C. vulgaris*. Generally, the current generated was considered to be an important factor for the rate of increase of carbon dioxide generation. Also, the production of methane was inhibited as a result of power generation. Hence to evaluate the similar efficacy *C. vulgaris* was employed in the cathode chamber were the power was generated under10 Ω resistance. Of note, the biomass production rate was associated only with the power generated through the SMFC. In this experiment the algal dry weight was reported to be 420 mg/L and the current generated was 48.5 mA/m^2. Hence, this SMFC model was considered for the production of an algal biomass, utilizing the carbon dioxide produced by the oxidation reactions as a result of power generation.

5.12 Twelve-Reactor Algal Fuel Cells

Electricity production was investigated using single-chambered MFCs in which different types of algae were used. The algae were used in powder form in the MFC to obtain energy with different power densities. Sharon B Velasquez et al. (2009) used a 12-reactor MFC, with each reactor having a volume of 25 ml. The 12 MFCs were operated according to different strategies. Four of the MFCs functioned as closed circuit systems, four functioned as open circuit systems, and the other four were constructed as anaerobic reactors with an end-plate sealing. Logan and Regan (2006) used a graphite fiber brush in the anode in both MFCs and anaerobic reactors. Cheng and Logan (2007) used ammonia gas at high temperature to treat a graphite fiber brush, and constructed the cathode following the methodology of Cheng et al. (2006a, b), in which method the cathode was prepared using platinum as a catalyst, with four layers for diffusion. Although the materials in a mixed culture are in a non-sterile condition, the materials that were used by Cheng et al. (2006a, b) were sterilized in an autoclave at 121 °C for 15 min. Comparatively, *Ulva lactuca* was completely degraded, whereas *C. vulgaris* generated more power with respect to the mass substrate. The power density obtained by *C. vulgaris* was 277 W/m^3 and *U. lactuca* produced a power density of about 215 W/m^3. A linear sweep voltammetry method was used to obtain the polarization curves to interpret the power densities obtained through the different cycles. At the end of the process, the microbes grown in the reactors were evaluated for fingerprint analysis, which reported that only 11% of these microbes were similar to the cultures that had been inoculated. Finally Cheng et al. (2006a, b) suggested that these types of multiple MFC reactors help in producing a renewable source of energy.

5.13 Nine-Cascade Algal Fuel Cells

X.A. Walter et al. (2015) used a design comprising nine MFCs. A sequential mode of operation was carried out using the nine cascades. A downstream mode was used to feed the output to the consecutive cascades. The results of this setup mode were also studied by Ioannis Ieropoulos et al. (2008) and Winfield et al. (2012), who reported that this downstream feeding setup provided excellent utilization of the organic substrate and generated a higher current density, because of the shorter diffuser distance. The construction design is explained in detail as follows. Black acrylic material was used to construct the anode compartment. This specific material was selected to avoid the growth of phototrophic microorganisms. The connecting tubes were constructed using the same material, for the same reason. The anode and cathode were both made of carbon fibers; the anode compartment had a volume of 4.5 ml and the fiber material measured 64 cm^2, whereas the cathode fiber material measured about 160 cm^2. Continuous flow of tap water at 5 ml/min acted as a catholyte. The anode and cathode electrodes were submitted to a three-dimensional transformation, exposing a surface area of 3.3 cm^2.The terracotta membrane used in this design has a hard surface area of about 6.8 cm^2 and thickness of about 2 mm. The amount of water absorbed (% of weight) by terracotta membranes was 9.1% ± 0.3% Winfield et al. (2013). Each MFC was connected with light - tight - gas-gap drippers. This method was used to avoid current conduction via the fluids from each unit and to keep the whole unit free from electricity for manual monitoring. The anode compartment consisted of continuously grown *Synechococcus leopoliensis* culture. Phototrophs are digested using a pre-digester, which produces oxygen in return. This nine-cascade MFC system, with the help of a fresh culture, could produce a power voltage of 42 W/m^3. Certain parameters of this system, such as its long-term stability, will have to be optimized in future.

5.14 Anode Assistance with Phototrophic Microorganisms

Zou et al. (2009) and Pisciotta et al. (2011) reported that PMFCs which employ photosynthetic microorganisms in the anode chamber undergo a photocatalytic water reaction by which electrons are generated. Generally, PMFCs differ from the normal type of MFCs, which produce electricity as a result of the oxidation of organic compounds. Algae-assisted anodes have an electrochemical catalytic capacity that is used to generate electricity. A simple schematic representation of an algae-assisted PMFC is shown in Fig. 5.12). Different algal species employed in anodes are listed in Table 5.3.

5.15 Anode-Assisted Electrochemical Catalysis

Anode-assisting phototrophic microorganisms such as heterotrophic bacteria use organic carbon as a carbon source. Different types of bacteria employed in anodes had different outcomes (Xing et al. 2008). *Rhodopseudomonas palustris* is a

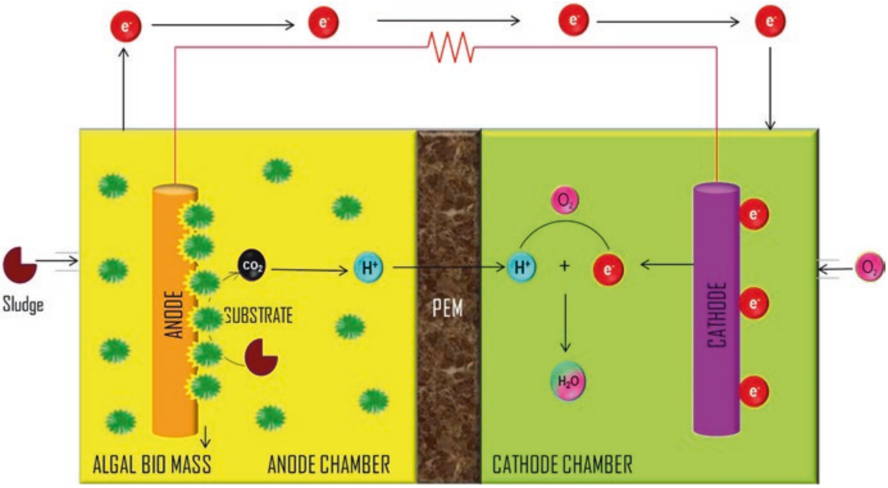


Fig. 5.12 Schematic diagram of phototrophic microorganism assisting the anode process. From Rashid et al. (2013), with permission from?

Table 5.3 Algal species assisting in the anode chamber

Algal species used in single-chambered PMFCs	
Species	Reference
Rhodobacter sphaeroides	Cho et al. (2008)
Rhodopseudomonas palustris	Xing et al. (2008)
Chlamydomonas reinhardtii	Nishio et al. (2013)
Mixed algae	Chandra et al. (2012), Subhash et al. (2013), and Malik et al. (2009)
Algal species used in dual-chambered PMFCs	
Chlorobium limicola	Badalamenti et al. (2013)
Rhodopseudomonas palustris	Inglesby et al. (2012)
Mixed culture	Cao et al. (2008) and Badalamenti et al. (2013)

phototrophic non-sulfur bacterium. When this bacterium assists in the anode it shows high activity, and electron transfer to the anode electrode is executed indirectly. This strain is used widely because of its utilization of various organic compounds in wastewaters and domestic wastes. Compared with *Rhodobacter, Rhodopseudomonas* is considered to be the dominant type of bacteria for producing electricity when soluble electron mediators are used to assist in the anode chamber. Cao et al. (2008) observed that illuminating the chambers had a positive effect on the production of electricity. Inglesby and Fisher (2012) revealed that *R. palustris* consumed the whole cell of the cyanobacterium *Arthrospira maxima* to generate electricity in two types of MFCs. Morishima et al. (2007) reported that hydrogen was obtained as a product of organic oxidation in anode assisted MFC, which affected the electricity production. So they carried out gene manipulation in such a way that a gene-manipulated *R. palustris* suppressed the production of hydrogen, resulting in a high-performance MFC with higher electricity production. Chandra et al. (2012) evaluated the efficacy of the application of mixed phototrophic bacteria by using these bacteria to assist in an anode chamber. They revealed that, in mixotrophic PMFCs, electricity production was higher in illuminated than in dark conditions, since the oxygenic phototrophs were dominant. Similarly, Subhash et al. (2013) generated electricity using mixotrophic microalgae in the anode as a biocatalyst. They reported that this kind of mixotrophic system generated electricity at a low output. Badalamenti et al. (2013) reported *Chlorobia* as very dominant phototrophs that assisted in the anode chambers. With reference to these various results, it is clear that different kinds of phototrophic bacteria can assist in the anode, where they act as key factors responsible for electricity generation.

5.16 Substrates as End Products

As a result of the phototrophic activities in MFCs, energy-rich compounds are produced by these phototrophic microorganisms and are later converted to electricity. He et al. (2005a, b) used *Rhodobacter capsulatus* as a substrate in a dual-chamber MFC linked with a PBR. This approach was further investigated and simplified by Rosenbaum et al.(2005a, b) and Cho et al. (2008), who used phototrophic microorganisms to assist in an anode-based fuel cell. Further, Rosenbaum et al. (2005a, b) used *Escherichia coli* in dark fermentation and *R. sphaeroides* in photo fermentation to utilize the organic compounds by which these microbes produce hydrogen, which later generates electricity. However, the hydrogen produced seemed to be very low compared with the amount of oxidized hydrogen. Hydrogen pressure in the chamber will decrease the production of hydrogen. The oxidation of hydrogen is carried out by using platinum as a metal catalyst. Without using platinum as a catalyst, electricity can be generated using *Rhodopseudomonas spp*., rather than *R. sphaeroides* (Cho et al. 2008). Malik et al. (2009) generated electricity using cyanobacteria that produce glucose, which is utilized by the microbes present in the anode. Nisho et al. (2013) used *Geobacter sulfurreducens* in a phototrophic MFC where the microbe utilized the formate produced by *C. reinhardtii*, which aids in generating electricity. Badalamenti et al. (2014) used two different bacteria—*Chlorobium* and *Geobacter*—both bacteria were used as monocultures and co-cultures for electricity generation.

5.17 Cathode Assistance with Phototrophic Microorganisms

Using photosynthetic microorganisms in the cathode chamber of an MFC has many benefits, such as biomass production, carbon dioxide reduction, and the supply of oxygen. Algal species assisting in the cathode chamber are listed in Table 5.4.

5.18 Oxygen Production

An attractive feature of the cathode process is the oxygen production that occurs owing to mechanical aeration, which utilizes a large amount of energy. Xiao Z et al. (2012) and Wu et al. (2013a, b) undertook research on MFCs with light illumination that generated electricity using photosynthetic microorganisms. Compared with results for mechanical aeration, the dissolved oxygen concentration remained high were as the dissolved oxygen concentration was affected by the illumination condition (Campo et al. 2013a, b, c). Kokabian et al. (2013) reported that a method of desalination at the cathode, using *C. vulgaris* microalgae, had better results than the use of an abiotic cathode. He et al. (2013a, b), for their studies, utilized a pure

Table 5.4 Algal species assisting in the cathode chamber

Algal species used in single-chambered MFCs	
Species	Reference
Chlorella vulgaris	Fei Zhang et al. (2011)
Algal species used in dual-chambered PMFCs	
Chlorella vulgaris	Gouveia et al. (2014), Campo et al. (2013a, b, c), Huan Wang et al. (2012), and Powell et al. (2009)
Desmodesmus sp. A8	Wu et al. (2014)
Microcystis aeruginosa IPP	Cai et al. (2013)
Mixed culture	Xiao Z et al. (2012), Lobato et al. (2013), Juang et al. (2012), and Cao et al. (2008)
Algal species used in three-chambered PMFCs	
Chlorella vulgaris	Kokabian et al. (2013)

culture of *C. vulgaris* which produced oxygen in the cathode electrode; this oxygen was accepted by the electrons from the cathode electrode. Powell et al. (2009) employed *C. vulgaris* in the cathode and concluded that, in the presence of an electron mediator, *C. vulgaris* exhibited the property of an electron acceptor. Cao et al. (2009) and Lyautey et al. (2011) used a mixed culture to investigate electrochemical activities. They were unable to differentiate the electron transfer roles shown by different phototrophic microorganisms.

5.19 Carbon Dioxide Utilization

Photosynthetic microorganisms use carbon dioxide as a carbon source. Reduction of carbon dioxide takes place via photosynthesis. Wang et al. (2010) designed an MFC called a microbial carbon capture cell. This microbial carbon capture cell employs photosynthetic microorganisms at the cathode to utilize the carbon dioxide produced from the anode region as a result of the oxidation of organic compounds. The carbon dioxide generated at the anode is absorbed by the cathode for *C. vulgaris* growth, with no evidence of carbon dioxide shown in the headspace of the cathode compartment. Cui et al. (2014) used *C. vulgaris* for their study in the cathode compartment. Their studies revealed that the carbon dioxide supply was affected by the concentration of organic compounds in the anode. They suggested that developing microbial carbon capture cells would help to propel new MFC technology that could neutralize carbon. Zhou et al. (2012) also used *C. vulgaris*, in the form of sodium alginate and calcium chloride beads . They reported that 88% maximum power density was achieved by the algae immobilized on the beads than the suspended algae. Similarly, He et al. (2014) used an immobilization technique, using a matrix and optimized conditions such as cross linking time and initial innoculum concentration resulted in a 258% increase of power density compared to the previous optimization by which maximum power density obtained was 88% only.

5.20 Production of Biomass

MFCs are also used for biomass production, employing a photosynthetic cathode with an electrode and biomass suspended in the cathode solution, but quantification of the biomass produced is very challenging. Cao et al. (2009), in their studies, focused on the biomass that is suspended in the cathode compartment. Their study revealed that the biomass on the cathode electrode contained a high level of lipid. Gouveia et al. (2014) used a dual-chambered MFC and achieved a greater biomass concentration than the previous method with 2800 mgL^{-1}, but it was affected by the hydraulic retention time (HRT), with a long HRT helping to accumulate more biomass. Hyeon Jin Jeon et al. (2012), using a multiple-feed batch-operated MFC, achieved a high algal biomass with an HRT of 410 days. Xiao Z et al. (2012) used a continuous-feed batch system, but they integrated the photo-bioelectrochemical system with an HRT of 3 days, which resulted in a low biomass concentration. Gouveia et al. (2014) extracted pigments from the algal biomass, which is very rich in carotenoids. The pigment composition is affected by the light intensity. Christi (2007) produced photosynthetic microorganisms that were used for energy production. Fei Zhang et al. (2011) achieved a high algal biomass concentration using a single-chambered SMFC. Energy production from an algal biomass, using an MFC, is very attractive. Many new strategies have to be developed to evaluate the factors that consume energy during the process and during algal biomass production (Fig. 5.13).

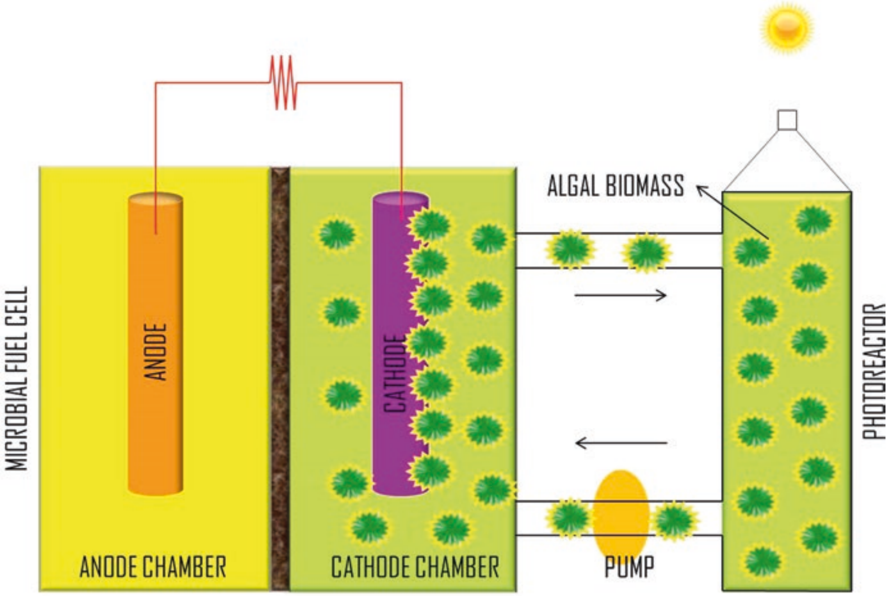


Fig. 5.13 Schematic diagram of phototrophic microorganism assisting the cathode process

5.21 Treatment of Wastewater

One important factor in choosing an MFC is selection for wastewater treatment, especially to remove contaminants, as well as to evaluate the performance of the MFC. Some MFCs have a cathode containing an organic solution that mimics wastewater fed into the anode, and the removal of organic compounds has been successfully achieved with such MFCs. Detailed studies are not reported with regard to the removal of organic compounds using algae at the cathode. Hyeon Jin Jeon et al. (2012) used an upflow-type MFC for growing algae in the cathode, but sufficient information about the algae employed for contaminant removal was not reported. Another study, by Li Xiao et al. (2012), reported the reduction of phosphorus and nitrogen concentrations with a cathode-assisted MFC. Subhadra et al. (2011) identified a large water foot print which was a key challenge for commercialized algal bioreactors. Olguín (2012) reported that growing algae would have dual benefits, such as biomass production and contaminant removal. Generally, treating wastewater in the cathode will certainly stimulate heterotrophic bacterial growth, although the organic compounds will be electron donors, reacting with the cathode electrode, a factor that would impair the generation of electricity. Generally, wastewater treated at the anode is fed into the cathode, where nutrients for the growth of algae are provided by the treated wastewater; these nutrients are also associated with the removal of organic residues.

5.22 Illumination Effects

Photosynthetic microorganisms grow with the help of illumination, depending on factors such as the intensity and duration of the illumination. Wu et al. (2014) and He et al. (2013a, b) have reported that electricity generation increases when there is an increase in illumination, with an associated increase in dissolved oxygen production. Xiao Z et al. (2012) performed a comparative study, of light and dark conditions, showing that the dark period significantly decreased electricity and biomass production; these authors also explained the important factors of the dark period for PMFCs. Juang et al. (2012), in their research, reported high electricity production with low light intensity. Their studies also suggest the importance of light intensities, photosynthetic microorganisms, and the protocol for operating conditions using algae assisted at cathodes in MFCs.

5.23 Challenges and Prospects

Production of electricity with MFCs has been achieved by using phototrophic microorganisms. In-depth knowledge about the challenges with respect to the application of MFCs will help to define the research and focus on the reported issues. The most challenging aspect of algal MFCs is to solve the technical problems of microalgal processing in the MFC. In the cathode chamber of the MFC algae require a large surface area for illumination.

It is challenging to use photosynthetic products such as hydrogen and organic compounds for the generation of electricity by MFCs, where biomass production is very much higher than the energy produced. As a result of photosynthesis, oxygen is produced in algal-assisted MFC anodes, with illumination and the design and operation of the reactor presenting great challenges. Photo hydrogen production utilizes organic compounds that act as substrates. Mixed cultures may affect phototrophic activity in MFCs.

As yet, there are no scientifically proven procedures for the large-scale production of energy by MFCs. Sediment MFCs can be employed for remote sensor powering, where the intensity of light inhibits the cell growth. When the density of the algae is too high, light penetration is too low, and this can disturb cell growth. Bombelli et al. (2011) reported that algal MFCs can produce electricity through biological pathways by converting light energy into electrical energy. The biomass thus obtained is organic and has zero carbon. Carbon dioxide, oxygen, and biomass production, as well as consumption, has to be balanced in the system.

Researchers are making efforts to enhance the power generation output of MFCs, and very high output could also increase the efficiency of algal cultivation. Using photosynthetic microorganisms directly for electricity production is not the best option, as the cell walls are resistant to hydrolysis. With anaerobic digestion, more energy is recovered was as MFCs which has less advantage compared to the aerobic digestion. The carbon dioxide supply inside the MFC has reduced the cost of aeration for algae. Further studies need to investigate the illumination effects in anode-assisted electrochemical catalysis.

Xing et al. (2008) reported that illumination in MFCs was not required for current generation, although research by Cao et al. (2008) reported that illumination improved the generation of electricity. Microalgae grow under various conditions where carbon dioxide recovery requires the self-growth for algae cultivation which is limited with the supply of light resources. Lin et al. (2015) experimented with a large eight-chamber photocathode with varied light intensity, and they have also employed an open cultivation method where light variation is not required.

For algal MFCs, both biomass cultivation and electricity generation are strategies employed. Compared with suspended algae, algal bead cultures increase the supply of oxygen, but the growth of algal bead cultures is slow and these cultures produce a very low biomass compared with that produced by suspended algae. These limitations enhances a high production reduces the costs for algal MFC. At the anode, substrate is utilized, and consistency of the performance of algal MFCs is low. The biofilm at the anode has great efficiency with low density in surface. The biofilm is resistant to the transfer of electrons; many research studies of biofilms have been reported, but only those with pure cultures of photosynthetic microorganisms have been noted. However, mixed cultures are generally used for the treatment of wastewater and they are applied practically. The power output of algal MFCs cannot be higher than the value afforded by the biofilm on the anode, which is only a few hundred milliwatts per square meter. The anode biofilm produces carbon dioxide, which is consumed by algal cells in the cathode chamber in the presence of light. The oxygen thus yielded acts as an electron acceptor for the cathode chamber.

Algal MFCs are considered to be a platform for biochemical and biofuel production utilizing wastewater organic substances. The design of some MFCs with PBRs is advantageous. The PBR can be in any configuration, such as flat or tubular. Much research is being carried out to implement algal MFCs as technical devices for algal biomass production and for electricity generation. Future perspectives of algal-MFC systems are described in the following section.

5.24 Future Perspectives of PMFCs

To address some of the challenges described above, Li and Zhen (2014) have proposed models of MFC technology that employ phototrophic microorganisms as a substrate in the anode and oxygen supply in the cathode. They expect that these models will lead to further investigations of photosynthetic microorganisms and MFCs.

The first proposed model involves a system where the algal biomass is degraded by using light energy and converted to electric energy. The model consists of three units: an MFC, an anaerobic digester, and a PBR (Fig. 5.14). The PBR is used for algal biomass production by photosynthesis. The produced biomass is placed in the anaerobic digester, which produces biogas. The algal cells are digested and then they are imported into the anode in the MFC. Bioenergy is produced from this system, where anaerobic digesters produce biogas that is further used by the MFC and directly produces electricity.

The second proposed model focuses on the cathode-assisted photosynthetic microorganisms that are used for wastewater treatment. These organisms are placed in either a closed or an open tubular bioreactor (Fig. 5.15). MFCs are integrated in the algal bioreactors (Xiao Z et al. 2012). Wastewater is fed into the MFC for degradation and the degraded effluent is discharged through an outlet to the algal bioreactors, which support the growth of algae. Closed tubular reactors seem to be more efficient, but are costlier than open channel reactors, which provide very low algal production but are easy to maintain. Closed tubular reactor systems are used for small-scale applications, whereas open-channel reactor systems are used for large-scale production.

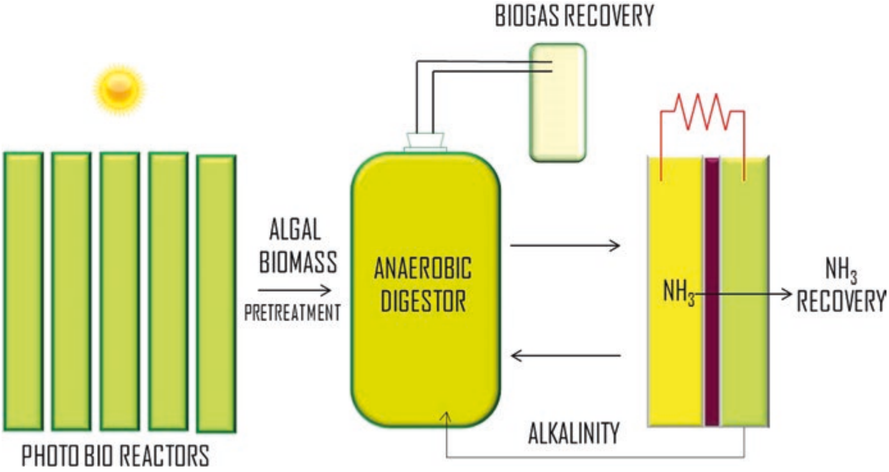


Fig. 5.14 Photo-MFC paradigms

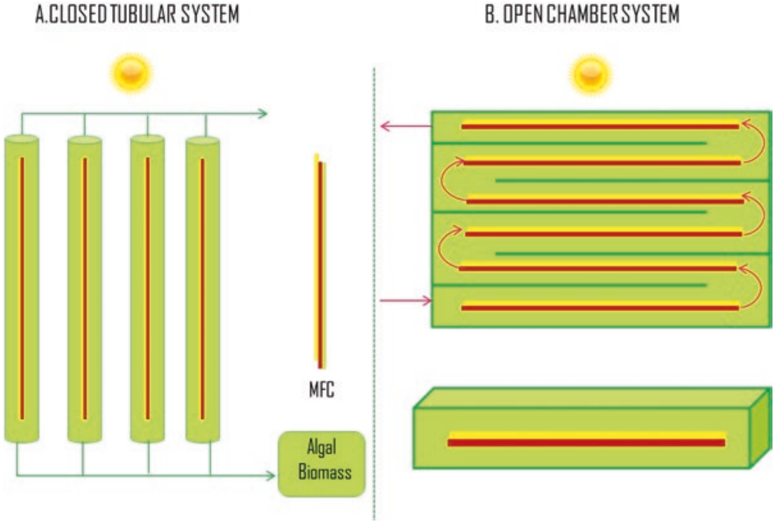


Fig. 5.15 Algal bioreactor paradigm—open and closed MFC systems

5.25 Conclusion

There have been significant developments and technological advances in MFC processes using microalgae. The advantage of incorporating PMFCs is to generate electricity. Owing to the low conversion efficiency, in certain systems algae are used as a substrate. Advances in algal MFC applications will lead to the development of a device that links microalgal cultivation, using a cathodic chamber and a conventional anodic chamber, and employs electron donors as fuel, providing a new pathway for converting light energy into electrical energy, with the production of less carbon dioxide. Oxygen production is an added advantage in the cathode reaction where biomass accumulation takes place. Wastewater treatment is accomplished by using MFCs, and, with further upgrades to MFC systems, photosynthetic microorganisms should be developed that show synergistic cooperation similar to that occurring with anaerobic digestion, and MFCs will be integrated with algal bioreactors, similar to algal ponds. In future, the development of algal fuel cells will have a substantial effect on the production of algal biomass, which can be utilized for commercial benefit in various fields.

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