

Microbial Carbon Capture Cell: Advanced Bio-electrochemical System for Wastewater Treatment, Electricity Generation and Algal Biomass Production



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1 Introduction

Water quality has been degraded due to receiving partially treated or untreated wastewater from domestic and industrial sources as well as from non-point sources. In recent years, exponential population growth and accelerated industrial development has resulted in increased quantity of generation of wastewater with high concentrations of diverse nature of pollutants. Hence, maintaining water quality in the water bodies has become an utmost important issue that needs immediate attention.

On the other hand, depletion of fossil fuel reserves has prompted the need of developing sustainable energy generation technologies. One such innovative and renewable technology is microbial fuel cell (MFC), which can simultaneously treat organic matter from wastewater as well as generate energy in the form of electricity for onsite applications. These bio-electrochemical cells convert chemical energy from wastewater used as fuel into electricity. Several researches are being carried out with a goal to facilitate and accelerate the development of MFC, which uses microorganisms to transform the chemical energy present in organic compound into electricity (Logan et al. 2006).

Generally, MFC is composed of an anodic and cathodic chamber, which is separated by a proton exchange membrane (separator). In the anodic chamber, the exoelectrogenic microorganisms, also known as electrogens, act as biocatalysts and oxidize organic matter into electrons, protons and carbon dioxide. The electrons are transferred to the cathode via external electrical circuit, and protons are transferred

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into cathodic chamber through membrane. Oxygen, or any another chemical oxidant, combines with electrons and protons on cathode to favour oxygen reduction reaction to form water, or other reduced compounds if alternate chemical oxidants are used. By this process, the energy stored in the chemical bonds of organic matter present in wastewater can be converted to electricity, which could be used directly. Thus, an efficient but easily available electron acceptor and PEM are prerequisite for good performance of MFC (Pant et al. 2010). The cost of external mechanical aeration in cathodic chamber for supplying oxygen and the high cost of ion exchange membrane need to be minimized for field scale application of MFC for wastewater treatment and electricity generation.

High oxidation potential and clean reduction product (water) make oxygen as the most common electron acceptor to be used in MFC. On the other hand, supply of oxygen in the cathodic side is, however, energy intensive mainly due to energy cost associated with external mechanical aeration. Microbial carbon capture cells (MCCs) nullify this challenge by using the ability of algae to produce oxygen with an added advantage of using harvested algae as a feed stock for production of emerging biodiesel as a fuel source. MCCs with different configurations (Elmekawy et al. 2014), different electrodes (Wang et al. 2010), various substrates (Wu et al. 2014; Ganesh and Jambeck 2013) and numerous algal species (Cui et al. 2014; Saba et al. 2017) have been widely studied. Microalgae employed in cathodic chamber should have high photosynthetic productivity and higher lipid content, which can qualify it as a good feedstock for biodiesel production (Morita et al. 2000).

MCC is a mix of employing different processes in two different compartments and hence, the performance of MCC rely upon individual efficiency of these two distinct processes occurring in anodic and cathodic compartments, depending on operating conditions and design parameters. The interrelationship of these dependable variables basically influences the overall performance of MCC. The present chapter provides a detailed knowledge on MCC along with an idea about the prominent and relevant parameters that influence its performance and efficiency.

2 Microbial Carbon Capture Cell

Carbon capture can be achieved in MFC by modifying it to MCC, for providing an encouraging solution of utilizing the CO₂ to synthesize the algal biomass in cathodic chamber, upon harvesting which can act as feedstock for biodiesel production, with simultaneous removal of organic matter from wastewater in anodic chamber and energy recovery in the form of electricity. The MCC consist of integration of MFC and algal species cultured in cathodic chamber for CO₂ sequestration and O₂ production to support cathodic reduction reaction (Fig. 1). The use of algal species in cathodic chamber generates oxygen during photosynthesis, making it available for cathodic reduction, thus reducing the cost of external aeration as required in aqueous cathode MFC.

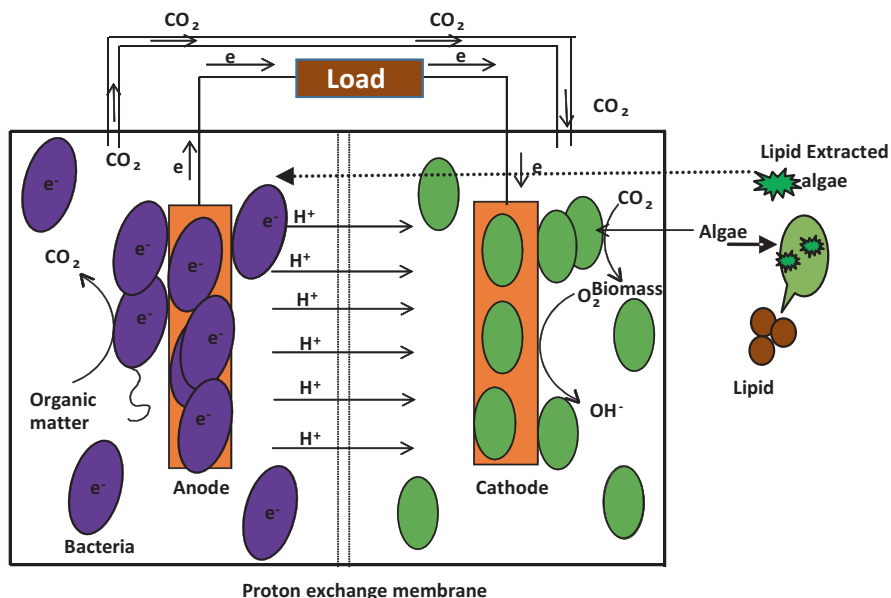
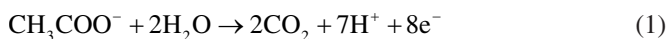


Fig. 1 Schematic representation of CO₂ capture and cathodic reactions involved in MCC

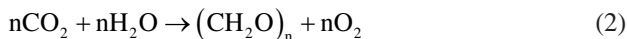
In MCC, the CO₂ generated during oxidative degradation of organic matter in the anodic chamber can be used for synthesis of the useful algal biomass with photosynthetic activity, attaining simultaneous electricity generation, CO₂ sequestration, wastewater treatment and biomass production. Thus, this addition of anodic off gases, produced during oxidation of organic matter, into cathodic chamber for favouring algae growth in cathodic chamber demonstrates an effective way for reducing CO₂ emission and in addition provides opportunity for simultaneous electricity generation without need of external aeration (Wang et al. 2010).

The overall biochemical reactions that occur at the anode and at the cathode of the MCC are as illustrated in Eq. (1) and Eqs. (2 and 3), respectively.

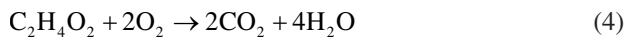
Anodic chamber:



Cathodic chamber (during exposure to light):



During light phase, algae carry out photosynthesis to produce oxygen and algal biomass, whereas during the dark phase, respiration occurs where the oxygen is consumed as per reaction explained in Eq. (4) (González et al. 2013).



Hence, there is a need to maintain the optimum light: dark period to get best possible performance from MCC.

3 Advancement in MCC

Research efforts on MCC mainly focused on the enhancement of performance and byproduct synthesis by optimizing the cathodic configuration and operating conditions, making favourable environment to support algal growth and enhancing cathodic reaction kinetics. Several aspects of MCC research have been discussed here.

3.1 Application of MCC

Wastewater Treatment

The organic matter present in the wastewater can be utilized as a carbon source for microbial communities in anodic chamber during oxidation, and, thus, wastewater can be effectively treated in MCC (Fig. 2). Pant et al. (2010) reviewed utilization of various substrates ranging from simple sugars (e.g. glucose, acetate) to complex wastewaters (e.g. starch processing wastewater, kitchen wastewater). The agricultural wastewater, domestic wastewater, effluent from food-processing industries,

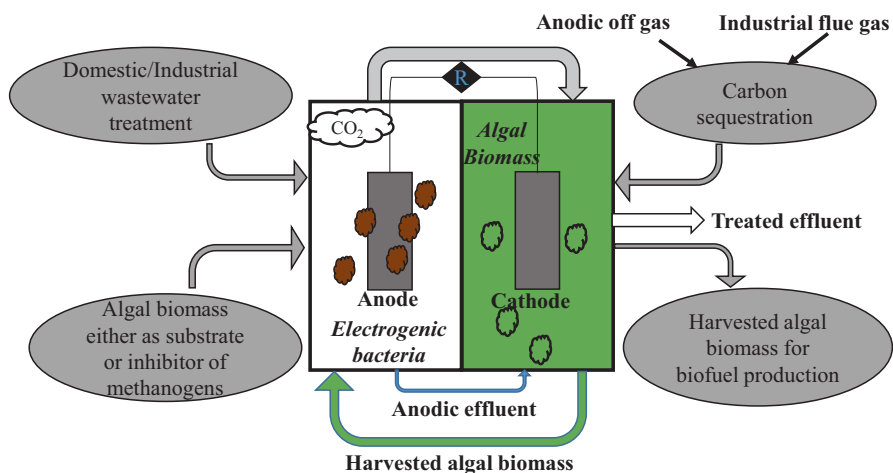


Fig. 2 Flow chart representing applicability of MCC

ligno-cellulosic waste, animal waste, waste activated sludge, etc. can be effectively treated in MFC, hence also in MCC, along with generation of bioelectricity. Hou et al. (2016) used *Golenkinia* sp. in cathodic chamber of MCC and achieved a power density of 6.3 W/m^3 along with chemical oxygen demand (COD) removal of 44%. Some of the researchers have even used algal biomass as a substrate for anodic oxidation and produced higher power output (Rajesh et al. 2015). Further, integrating microalgae with MFC (i.e. MCC) will provide an added advantage of removing nutrients from wastewater streams, if provided at cathodic side, along with carbon capture (Neethu and Ghangrekar 2017).

Electricity Generation

Pandit et al. (2012) supplied CO_2 -air mixture to *Anabaena* sp. grown in cathodic chamber of MCC and generated a power density of 57.8 mW/m^2 . The electrical output from MCC varies with fluctuations in oxygen concentration synthesized by algal species. Jadhav et al. (2017) reported 1.5 fold higher power generation with use of *Chlorella pyrenoidosa* algal species over *Anabaena ambigua* sp., due to superiority in oxygen production rate of *Chlorella*. However, the electricity generated in MCC depends upon many physiological conditions that favour bacteria in the anodic chamber, which include pH of anolyte, electrode materials, design parameters as well as cathodic conditions such as algal concentration, CO_2 concentration, etc.

Carbon Capture and Algal Biomass Production

Large quantity of CO_2 , emitted from various conventional wastewater treatment methods for organic pollutant degradation, is added to the environment annually (Campos et al. 2016). Capturing and supplying this extent of CO_2 to the cathodic chamber of MCC will result in high algal biomass production by making the process sustainable with additional benefits (Kokabian et al. 2013). Additionally, microalgae have been recognized as one of the most productive biological systems for generating biomass and capturing carbon while treating the wastewater (Fig. 2). Considering properties of each algal species, the particular class of *Chlorella* sp. have high photosynthetic rate that favours high growth kinetics and results in higher biomass production. During MCC operation of 25 days, an algal biomass production of 66.4 mg/(L.day) was reported for *Chlorella* sp. and over 50.4 mg/(L.day) for *Anabaena* sp. grown in cathodic chamber due to variations in cell structure and growth kinetics (Jadhav et al. 2017). However, the carbon capture rate and biomass generation yield for individual algae depends upon the growth kinetics, nutrient availability for growth, operating conditions, light intensity and other environmental parameters.

Other Applications

Along with above discussed applications, the electricity generated from MCC can be capable to power the different electronic biosensors and electronic appliances. Additionally, algae in cathodic chamber are capable to remove nutrients from the anodic effluent and thus provide the polishing treatment before disposal of treated effluent (Fig. 2). The algal biomass harvested during photosynthesis can be further used as feedstock for synthesizing byproducts such as biodiesel, bioethanol, biohydrogen, methane, etc. (Wang et al. 2015). Also, while treating sewage, first it can be treated in anodic chamber for organic matter removal and then in cathodic chamber for removal of nutrient, and in this way higher pathogen destruction in cathodic chamber is also expected, producing superior quality treated water for desired onsite reuse.

3.2 *Photosynthetic Algal Microbial Fuel Cell*

Algae have been used commonly in MFCs to produce oxygen in the cathodic chamber so as to have oxygen reduction at cathode and harvested algal biomass, with or without oil extraction, can be utilized as a substrate for bacteria. However, sufficient electric current can also be generated at anode, where cytochromes help indirect shuttling of electrons generated in photosystem II of the algal cells and can be called as photosynthetic algal microbial fuel cell (PAMFC) (Shukla and Kumar 2018). He et al. (2014) reported a COD removal up to 92% with power density of 2.5 W/m³ in PAMFC having *C. vulgaris* in cathodic chamber. The immobilization of microalgal cells on polymeric or biopolymeric matrices can help in separation of algal cells together with enhancement of performance of MCC. Immobilization of microalgae provides additional advantage of increased cell density, resistance to toxic matter and stable operation with high metabolic activities over time.

3.3 *Prospective of Algae*

Algae as Substrate

Biomass is a good choice of feed stock to convert it to electrical energy, and algae are the most easily available source of biomass with high yield per unit area of land. The algal dry mass, considered as major pollutant vector in the streams, can be used as a potential substrate for electricity generation in anodic chamber of MCC (Cui et al. 2014). The algal biomass harvested during cathodic photosynthesis can be pretreated with heat treatment, enzymatic treatment or chemical treatment so that treated (or even untreated or live) algal mass can be utilized as a carbon source for anodic oxidation to produce the electrons (Shukla and Kumar 2018).

Algae as Biocathode

Since algae are photosynthetic microorganisms, the availability of light as well as the electron-donating anodic process may have significant effects on the performance of the biocathode. The phototrophic microorganisms can serve as biocatholytes in MFCs because the oxygen produced is an electron acceptor for the harvested electrons from the anodic chamber. Researchers used photosynthetic biocathode in sediment type MCC and achieved effective wastewater treatment (Commault et al. 2014; Neethu and Ghangrekar 2017). Previously, researchers also confirmed the advantageous use of algae as a viable biocathode in microbial desalination cells to supply electron acceptors in a sustainable manner (Kokabian and Gude 2015).

Algae as Inhibitor of Methanogens

Considering the varieties of microbial populations present in the mixed anaerobic sludge inoculum used in anodic chamber, major substrate is consumed by methanogenic consortia for methane production and other non-electrogenic reactions. To reduce the substrate consumption by non-electrogenic bacteria and recover maximum coulombs from the substrate, researchers have used algal powder to suppress the growth of methanogens and also to serve as a substrate for anodic oxidation (Rajesh et al. 2015, 2014). Hexadecatrienoic acid, a long-chain saturated fatty acid, present in the marine algae *Chaetoceros* was found to inhibit the growth of methanogenic *archaea* by the process of adsorption as well as disruption of cell membranes and achieved the Coulombic efficiency (CE) of 45.18% with a power density of 21.43 W/m³ (Rajesh et al. 2015).

Algae for Wastewater Treatment

Along with carbon capture, microalgae can assist in effective removal of nutrients present in wastewater by utilizing these elements during their cell metabolism (Elmekawy et al. 2014). Electro-migration along with diffusion of ions from anodic to cathodic chamber concurred for recovery of nutrients from the wastewater (Colombo et al. 2017). Recently, Huang et al. (2017b) reported maximum PO₄³⁻-P removal up to 37.2% using *C. vulgaris* biocathode in MFC. Nitrogen is utilized as nutrient source for algal cultivation and can be effectively treated in MCC at loading of 2 g/L of nitrate (Neethu et al. 2018). However, additional photo-bioreactor coupled with MFC is reported to be capable of removing about 92% phosphorous and 99% NH₄⁺-N. Moreover, Kokabian and Gude (2015) proposed coupling of algae in cathodic chamber of microbial desalination cell and achieved complete salt removal in such system. Single-chambered air cathode MFC was capable of removing COD, colour and heavy metals (Zn-98%; Cr-80%) from wastewater (Logroño et al. 2017).

Algae as a Carbon Source for Electrode Material

Harmful algal blooms, including blue-green algae, can act as a promising electrode material for sodium-ion batteries and can be used for fuel cell applications. The algae carbonization helps to develop low-cost green electrode material for high-capacity batteries and also contribute to solve the issue of harmful algal blooms (Meng et al. 2015). Also, nanoporous carbon having large specific surface area can be synthesized from microalgae as a promising composite electrode material (Zhou et al. 2012).

Microalgal Biorefinery

Microalgae contains high concentration of proteins, lipids and carbohydrates, and its biomass after harvesting can be utilized as a potential feedstock for biodiesel production, lipid extraction and other applications. In microalgae biorefinery applications, CO₂-neutral MFC was developed for producing feedstock for bioethanol production, algae oil extraction and bioelectricity generation simultaneously during treatment of fermented beer yeast in the anodic chamber (Powell and Hill 2009). However, some algal species requires pretreatment to release carbohydrates stored in the cells. In addition, photobiological and fermentative ways of biohydrogen production from algal biomass employing *S. obliquus* and *Chlamydomonas reinhardtii* in cathodic chamber of MCC are well established.

4 Factors Governing the Performance of MCC

4.1 Algal Biocathode

Oxygen is one of the most widely recognized electron acceptors utilized within the cathodic chamber of MFC owing to its high oxidation potential (0.8 V vs. SHE), and certainly it produces a clean end product, i.e. water, after reduction (Ucar et al. 2017). In any case, most investigations demonstrated that supply of oxygen to the cathodic chamber consumes energy. Microalgae may provide a viable alternative to cathodic oxygen supply; however, its efficiency as an eminent biocathode depends on various factors which are discussed briefly here. The oxygen that is given away during photosynthesis originates from water and not from the part of CO₂. The light reaction responsible for oxygen production occurs at the thylakoid membranes of the cell chloroplast, thus rate of oxygen evolution is believed to be dependent mainly on cell type and concentration, light intensity and operating conditions (Perrine et al. 2012).

Algal Species, Type and its Concentration

Performance of MCC is reliant on algal species as the photosynthesis rate and cell multiplying time are diverse for different types of microalgae communities (Sun et al. 2016). An investigation by Jadhav et al. (Jadhav et al. 2017) showed the dominance of *Chlorella* over *Anabaena* for capturing CO₂ and generation of photosynthetic oxygen that encouraged the cathodic reduction. The *Chlorella sp.* is the most preferred biocathode on account of their resistance for high level of CO₂, higher tolerance to municipal wastewater and reasonable lipid content. A study utilizing diverse types of *Chlorella* in cathodic chamber showed that a superior performing MCC was acquired with *C. vulgaris* as biocathode to demonstrate higher biomass yield and CO₂ fixation rate (Hu et al. 2015).

Gautam (2016) reported that biocathode with mixed algae collected from natural pond performed better over pure culture of *C. pyrenoidosa* biocathode in MCC under natural sunlight conditions and it can be suitable option for practical application of MCC at large scale. In this way the power yield is, by implication, dependent on the biomass concentration, which in turn relies upon algal species used and cell doubling time. Equally important is the cell concentration; lower cell concentration infers less oxygen (electron acceptor) availability, thus resulting in reduction in performance of MCC. Power can be enhanced with increment in concentration of algal biomass up to a certain concentration; however, beyond certain concentration of algae, the efficiency decreases due to self-shading of algae where cells close to the surface utilize a portion of the light and shade those more deep in the water (Ugwu and Aoyagi 2008). Another critical unfavourable impact of higher cell concentration is the metabolic loss because of formation of excess metabolites. Algae used in MCC serve as feedstock for biodiesel production as well as sequesters the anodic off gas introduced into the cathodic chamber. Hence, while choosing the algal species, it is crucial to choose species that have high photosynthetic efficiency to capture CO₂ and also that can yield lipid having proper unsaturated fats for biodiesel synthesis.

Light, CO₂ Supply and Oxygen Concentration

Different environmental parameters influence algal growth kinetics either directly or in a roundabout way, these include light/irradiance/temperature, CO₂, pH, blending/aeration, salinity, etc. Keeping in mind one of the end goals, i.e. to improve the microalgal growth in cathodic chamber of MCC, the light prerequisite is a standout among the most vital parameters; hence, proper intensity, duration and wavelength of light should be provided with extreme care. Extreme intensity may prompt photo oxidation leading to growth prevention, while reduced light intensity will lead to growth restrictions. There have been a few advancement in the utilization of light by using changed light sources, such as texturized optical filaments and LEDs with

particular wavelengths and proper lens to collimate light beam (Carvalho et al. 2011). The part of incident light that isn't utilized gets changed over into heat energy; consequently, utilization of red and blue light is ideal to keep up the survivable temperature for algal cultivation (Michael et al. 2015). Thus, the utilization of internally illuminated LED can bring out different favourable circumstances of less heat energy scattering along with avoidance of self-shading. Low temperatures increase the solubility of CO₂, and this indeed promotes the high growth rate and yield of microalgae.

Equally important is the presence of carbon source, especially CO₂. Some green algae are accounted for to effortlessly grown at high CO₂ concentration, and *Chlorella* are one of the known species that are used for carbon sequestration having high photosynthetic efficiency to convert CO₂ to O₂ (Singh and Singh 2014). Enhancement in power generation, quantity of biomass and lipids with increase in CO₂ concentration were reported earlier by many authors (Wang et al. 2010; Sato et al. 2003; Andersen and Andersen 2006; Tang et al. 2011). Optimum concentration of CO₂ varies with species as evident in the case of *C. vulgaris* with a carbon fixation rate of 6.17 mg/L.h (Bhola et al. 2011) unlike *Scenedesmus* species having the optimal CO₂ consumption rate of 59.19 mg/L.h (Ho et al. 2012). When CO₂ is consumed in the presence of light due to cell metabolic reactions, O₂ is liberated, which acts as electron acceptor in MCC. One of the significant limitations of algal growth in a photo-bioreactor is that high oxygen concentration suppresses the growth, which is not an issue in MCC as oxygen released constantly get reduced by means of oxygen reduction reaction (ORR) for cathodic reduction. In MCC, a voltage of 706 mV was observed with a DO concentration of 6.6 mg/L in cathodic side, hence making algae as a suitable candidate for production of O₂ that is necessary for stable performance of MCC (Kang et al. 2003).

Nitrate Concentration

Different microalgal species will respond differently to concentration of nutrients provided depending on their quota flexibility. Microalgae expel nutrients from wastewater essentially by utilizing it for algal metabolism (Aslan and Kapdan 2006). Nitrogen has a key impact in deciding the productivity of microalgae as far as biomass and lipid production is concerned. Neethu et al. (2018) reported that power generation was increased with increase in nitrate concentration from 0.5 to 2.0 g/L and further increase in nitrogen resulted into decrease in power output of MCC. Also, Converti et al. showed that decrease in concentration of nitrogen in the medium can expand the lipid portions of biomass dry weight (Converti et al. 2009). Hence, it is important to have an optimum concentration of nitrogen at which biomass and lipid content can be boosted. For this situation, the domestic wastewater, which contains moderately less inorganic nutrients, can permit appropriate development of microalgae alongside the accumulation of lipid content in algal cells.

4.2 *Operating Conditions and Anodic Constraints*

Performance of MCC is highly determined by the operating condition as discussed earlier. Thus, if the condition is unfavourable to the exoelectrogenic bacteria (on anode) and algal community (in cathodic chamber), the overall performance of MCC will be adversely affected. For optimum COD removal and power production, operating conditions such as organic loading rate (OLR), hydraulic retention time (HRT), inoculums, substrate, anodic environment and anolyte pH ought to be rightly chosen. The OLR mainly depends on the substrate concentration (i.e. COD loading) and flow rate, which is again dependent on HRT. Substrate fed in MFC can range from complex molecules of starch to simple acetate (Pant et al. 2010). Complex substrates have to be broken down to simple organic molecules before being used as carbon source in MFC for easy metabolism by bacteria (Pant et al. 2010). In a study, when acetate was compared with butyrate, propionate and glucose as substrate in MFC, the acetate-fed MFC gave the highest CE (Chae et al. 2009). Similar results proving the higher efficiency of MFC by usage of simple compounds were reported by Liu et al. (2009), which compared the efficiency of acetate-induced consortia and protein-rich wastewater as substrate. Operation mode can be either batch mode or continuous mode, where the later one is preferred in practical application for continuous generation of electricity. Also, the HRT to be provided depends mainly on the complexity or degradability of the substrate, the influence of which on performance of MFC being reported in several literature (Sharma and Li 2010; Akman et al. 2013; Rahimnejad et al. 2011). Hence an optimum HRT should be fixed, which gives the best result in the prevailing environmental, bacterial as well as other operating conditions.

In addition to the previously mentioned parameters, electrolyte pH is likewise as vital as it governs the performance of MFC. Majority of researches arrived at a conclusion that the consortia best performs in alkaline condition (Zhuang et al. 2010; Puig et al. 2010; Behera and Ghangrekar 2009). The reason for this conclusion is differently addressed in various studies. Certain work demonstrated the higher internal resistance at lower pH (Behera and Ghangrekar 2009), whereas Yuan et al. focused on the effect of anolyte pH on electrocatalytic activity of anodic biofilms (Yuan et al. 2011); alongside Zhuang et al. explained this by more negative anodic potential as a result of alkaline pH (Zhuang et al. 2010).

4.3 *Design Parameters*

Proper design of MCC can lower the overall internal resistance and improve efficiency of organic matter oxidation and TDS removal. Design parameters that affect the performance include the electrode spacing, electrode material, membrane thickness and area, mixing, size of chambers and reactor layout. The reactor configuration is a critical parameter that influences the power generation and algal production

in MCC (Table 1). Algae are generally cultivated in photo-bioreactor (PBR), and subsequently while incorporating algae in MFC system, it can take two configurations – the PBR externally connected to the MFC and the PBR incorporated inside the MFC components (Fig. 3). The first configuration can be a photo-reactor bottle connected using peristaltic pump to the MFCs, where complete recirculation occurs in a closed-loop system (Gajda et al. 2015; Jiang et al. 2013) or PBR kept separately without PEM wherein CO₂ generated in anodic chamber is directly released into the photo-bioreactor (Powell et al. 2009). In case of later, among the diverse reactor designs proposed by researchers, the generally adopted design is dual-chambered MCC.

In a two-chambered MCC, anolyte (anodic chamber) and catholyte (cathodic chamber) are separated by a membrane (proton exchange membrane), and electrodes are linked by an external circuit. In this type of MCC, the CO₂ produced in anodic chamber is generally transferred to the cathodic chamber through a vent made at top of each chamber (Khandelwal et al. 2018). Apart from dual-chambered system, certain studies were carried out using single-chambered MCC, where the electrodes were placed in a single chamber without separators and algal bacterial symbiosis was observed in such MCC (Fu et al. 2010). Aside from this, an airlift MCC system, established by Hu et al. (2015), simultaneously achieved the high level of carbon sequestration along with wastewater remediation.

Design of algal chamber of MCC is one of the major technical aspects that should be given importance for the production of microalgal biomass in cathodic chamber. In contrast to the usual MFCs, there must be a transparent surface keeping in mind the end goal to guarantee the light is received by the algal cells in cathodic chamber of MCC. For the most effective utilization of incident light, several studies have been carried out in terms of reactor design and its architecture. While designing the cathodic part of MCC, no light should be lost, and no dark area ought to happen in which algae don't grow. So light capturing, channelling and scattering play an important role while considering the design of MCC. Scientists have explored the utilization of Fresnel focal points and light guides to focus, carry and deliver direct light into the algae suspension (Zijffers et al. 2008). Also, few studies were conducted to enhance the horizontal dispersion to an expansive stretch out by roughening the surface of the illuminating surface of the distributor (Csögör et al. 1999). Hence, while planning the lighting arrangement to MCC, importance should be given to the following: (i) enough light is available as required for the growth of species used, (ii) light intensity that can be adjusted accordingly, (iii) light wavelength (blue, red) that can be shifted to support the algal growth, (iv) light frequency should be variable, which can match the prevailing condition of region, (v) uniform distribution of light throughout the media and (vi) proper mixing can help in uniform distribution of incident light.

Biocompatibility of carbon-based material such as graphite rod, carbon felt, carbon cloth, etc. makes it the most suitable material to be used as electrodes in MCC (Table 1). Surface area and its roughness are two major factors that determine the adhesion of bacterial or algal biofilm on electrode surface. Compared to other electrode materials, graphite felt provide the desired surface area and texture required

Table 1 Effect of various design parameters on performance on MCC

Anode material	Cathode material	Reactor configuration	Substrate	Algal biocathode/catholyte	Power/current density	References
Carbon felt	Carbon felt	Double chamber	Synthetic wastewater (SWW)	<i>C. Pyrenoidosa</i>	6.4 W/m ³	(Jadhav et al. 2017)
Graphite felt	Graphite felt	Dual chamber	SWW	<i>C. vulgaris</i>	2.7 W/ m ³	(Khandelwal et al. 2018)
Carbon felt	Carbon felt	Dual chamber	Sediment (inoculums) + SWW	<i>Chlorella</i>	202.9 ± 18.1 mW/m ²	(Zheng et al. 2017)
Carbon felt	Carbon felt	Dual chamber	UASB (inoculums) + SWW	<i>Chlorella</i>	158.2 ± 15.1 mW/m ²	(Zheng et al. 2017)
–	Stainless steel	MBR-MFC	SWW	<i>C. pyrenoidosa</i>	1.2 W/m ³	(Yang et al. 2017)
Carbon cloth	Carbon cloth	Dual chamber	SWW	<i>Cyanobacteria</i>	1.48 mA	(Rago et al. 2017)
Carbon cloth	Carbon cloth	–	–	<i>Scenedesmus sp</i>	–	(Angelaalincy et al. 2017)
Carbon brush	Stainless steel	Tubular	SWW	<i>Chlorella</i>	200 mA/m ²	(Ma et al. 2017)
Carbon cloth	Carbon cloth	Two chamber	SWW	<i>Spirulina</i>	0.85 W/m ²	(Colombo et al. 2017)
Graphite rod	graphite rod	Two chamber	<i>C. pyrenoidosa</i>	K ₃ [Fe(CN) ₆]	6030 mW/m ²	(Xu et al. 2015)
Carbon paper	carbon paper	Two chamber	<i>C. pyrenoidosa</i>	<i>C. pyrenoidosa</i>	2.5 mW/m ²	(Xu et al. 2015)
Graphite rod	Graphite rod	Two chamber	SWW	<i>C. vulgaris</i>	0.6 mW/m ²	(Mitra and Hill 2012)
Carbon brush	Carbon felt	Two chamber	SWW	<i>C. vulgaris</i>	187 mW/m ²	(Liu et al. 2015)
Graphite felt	Graphite felt	Two chamber	SWW	<i>Desmodesmus sp.</i>	64.2 mW/m ²	(Wu et al. 2014)
Carbon fibre	carbon paper	Two chamber	SWW	<i>Microcystis aeruginosa</i>	58.4 mW/m ³	(Cai et al. 2013)

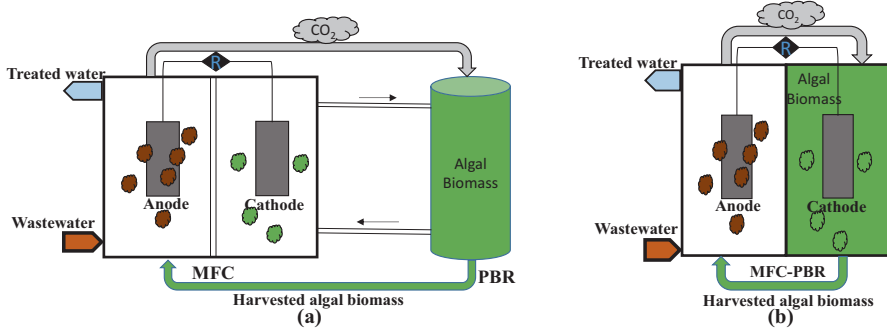


Fig. 3 Configurations of microbial carbon capture cell (a) PBR connected to MFC and (b) PBR within MFC

for uniform biofilm formation and colonization of bacteria. An enriched biofilm formation on anode surface will help in easy transfer of electrons to anode. Another major design factor that determines the performance of an MCC is the spacing between anode and cathode. Though utilization of appropriate material can diminish the activation losses (Mustakeem 2015; Zhou et al. 2011), bringing the anode and cathode closer can bring down the ohmic losses (Doherty et al. 2015). The power generation decreases with an increasing electrode spacing; whereas, keeping the electrodes too close can quicken substrate and oxygen diffusion, bringing about fast biofouling of the cathodes (Tartakovsky and Guiot 2006). To overcome these unfavourable impacts on performance of MCC, there should be an ideal separation between the electrodes. Electrode spacing could be related with different factors in controlling efficiency of MFC. Previous studies showed the effect of external resistance (Ghangrekar and Shinde 2007), where a maximum power density was observed at lower spacing of 20 cm between the electrodes, apart from this certain studies proved that the control over electrode spacing for improving power generation is dependent on substrate concentration (Lee and Huang 2013). Ahn et al. have tried different electrode configurations to optimize the performance of a multi-electrode MFC; a better power and coulombic efficiency was attained by separator electrode assembly configuration, whereas better wastewater treatment efficiency was achieved in configuration with closely spaced electrodes (Ahn et al. 2014).

Maintaining the anaerobicity of anodic chamber is a prerequisite for the growth of exoelectrogenic bacteria in anodic chamber of MCC. Hence, it is necessary to set apart the anodic chamber from the cathodic chamber rich in oxygen, and here separator plays a major role in design of MCC. An ideal separator should have higher proton conductivity, ion transport number, ion exchange capacity, water absorption along with minimal oxygen diffusion, resistance, acetate crossover and biodegradability (Tanaka 2015). Among the different cation exchange membranes commonly used, Nafion is most popularly used membrane (Huang et al. 2017a); however, bipolar membranes (Kim et al. 2017), chitosan-graphene oxide mixed-matrix membrane (Holder et al. 2017), glass wool (Venkata Mohan et al. 2008), SPEEK membranes

(Ghasemi et al. 2016), ceramic membranes (Daud et al. 2018) and clayware membranes (Ghadge et al. 2015) were also used. The mostly used membrane separator in MFC is the Nafion membrane; however, it has few limitations, for example, oxygen diffusion, cation accumulation, substrate loss, durability and high cost. These confinements have prompted tremendous attempts in the advancement of a suitable material that can viably fill in as a low-cost PEM, and the researches are still going on in search of suitable replacement.

4.4 Other Factors

Along with major factors, other parameters such as mixing conditions, immobilization of biomass, etc. affect the performance of MCC in terms of electricity generation and wastewater treatment. Turbulence (mixing) affects the growth positively by increasing rate of mass transfer between nutrients and algal cell; it also helps in removal of metabolites (e.g. oxygen) from the growth media. Similar studies also suggested immobilization of microalgae on glass beads or polymeric or biopolymeric matrices are capable of producing high algal cell concentration, resistance to hazardous matter, stable and flexible operation and longer period of operation with stable voltage due to longer logarithmic growth phase (Jin et al. 2011; Bashan and De-Bashan 2010). The rate of cathodic reactions was enhanced by concentration of oxygen as terminal electron acceptor, and hence growth kinetics of algal culture under given operating conditions is important to overcome the cathodic limitations.

5 Bottlenecks and Perspectives

Even though remarkable progress is evident in the field of MCC research, there are still certain challenges that need to be overthrown in order to commercialize this technology. Integrating algae in MFC will make MFC a complex system, whose performance will depend on several factors most of which have been already discussed in this chapter. Since in MCC the oxygen produced by the microalgae plays a major role, increasing the photosynthetic efficiency of algal species is of utmost importance. As discussed earlier, different microalgae strains respond differently to different growth conditions provided, and hence it is difficult to optimize these conditions to a specific species. Also, in MCC the algae relies upon the CO₂ received from the anodic chamber; hence, studies need to be done to quantify the flow of anodic off gas towards the algal chamber, and further anodic oxidation will be limited by the O₂ released by photosynthesis; hence, its role is important. MCC developed must be able to treat wastewater having different strengths and compositions; handle variations in pH, temperature, etc.; and operate without any adverse impact to the environment. Modelling studies and optimization of various factors affecting

the performance of MCC are of great importance. For enhancing power generation, development/synthesis of low-cost cathode catalyst that is not toxic to algae is yet to be investigated.

Design parameters including the materials used and MCC configurations are equally important in increasing the efficiency of MCC. Configuration of MCC should be such that it gives no or minimal loss of CO_2 while moving from anodic chamber to cathodic chamber. Along with transport of CO_2 , transport of protons from anodic chamber to cathodic chamber is equally important to complete the redox reactions. A low-cost membrane separator with minimal oxygen and acetate diffusion along with high proton conduction is prerequisite for efficient performance of MCC, which is yet to be synthesized. Similarly, the voltage generated has a positive correlation with the dissolved oxygen concentration of catholyte (Neethu et al. 2018), which fluctuates with the day and night cycle. This can come out as a great challenge faced by MCC, when thought to be operated under natural sunlight condition, which needs an immediate solution. Considering the complication of MFC system alone, coupling or integrating algal system to MFC makes overall process complex for commercialization. The high capital cost for fabricating MCC, considering all dependable components and their lower efficiencies, is also by far the major factor contributing to the limited commercialization of MCC technology. In order to compete realistically with other prevailing feedstock yield for biodiesel production and power generation technologies, as well as offering wastewater remediation, MCC should turn out to be more powerful from the viewpoint of both effectiveness and cost.

6 Summary

Application of MFC in wastewater treatment and bioelectricity generation is a well-known concept in present scenario; however, utilization of algae for oxygen supply, biomass production and other product synthesis along with providing polishing treatment to wastewater for removing nutrients is a major breakthrough in BES research domain. The performance of the system as a whole depends on the electrochemical reactions that occur between substrate oxidation to the final electron acceptor. Factors including algal growth kinetics, density, light intensity, CO_2 supply and other operating conditions govern the performance of MCC. Proper selection of these parameters and finding optimum condition for these for the algal species being cultivated in cathodic chamber of MCC can take forward this technology to an advanced level for its real-life applications. Moreover, presence of algae in cathodic chamber of MCC, apart from providing oxygen for cathodic reduction, also can serve as a substrate for anodic oxidation, a methanogen inhibitor to enhance the CE, harvested algal biomass for biodiesel production and other byproduct recovery, which can make MCC a cost-effective and sustainable solution for wastewater treatment as compared to conventional wastewater treatment methods.

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