Bioelectrochemical systems using microalgae − A concise research update

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Abstract

Excess consumption of energy by humans is compounded by environmental pollution, the greenhouse effect and climate change impacts. Current developments in the use of algae for bioenergy production offer several advantages. Algal biomass is hence considered a new bio−material which holds the promise to fulfil the rising demand for energy. Microalgae are used in effluents treatment, bioenergy production, high value added products synthesis and CO_2 capture. This review summarizes the potential applications of algae in bioelectrochemically mediated oxidation reactions in fully biotic microbial fuel cells for power generation and removal of unwanted nutrients. In addition, this review highlights the recent developments directed towards developing different types of microalgae MFCs. The different process factors affecting the performance of microalgae MFC system and some technological bottlenecks are also addressed.

Keywords: Microbial fuel cell, microalgae and cyanobacteria, double chamber algae MFCs, Integrated photo−bioelectrochemical system, Bioelectricity

Contents

1. Introduction

The global population is rising fast and it is estimated to be beyond 9 billion by 2050 (Hosseini et al., 2013). In addition, due to rising economic growth, there is also increased demand for energy and thus a more pronounced use of fossil fuels which then leads to more serious problems such as energy crisis and more consequential environment pollution. Combustion processes for energy production also produce toxic greenhouse gases such as CO_2, which in turn leads to global warming (GW) (Saratale et al., 2015). In the year 2010, the global energy−related CO_2 emissions into the atmosphere were estimated about 110 billion metric tonnes (bmt). It is now predicted that this amount will exceed 140 bmt in the year 2035 (Petroleum, 2014). To maintain energy and climate security, it is therefore very crucial to reduce and stop the emission of greenhouse gases into the environment to prevent the harmful impacts of GW (Singh and Ahluwalia, 2013; John et al., 2011).

Biofuels are being viewed earnestly as energy sources responding to the forthcoming demands (Brennan and Owende, 2010). First generation biofuels are usually obtained from food and oil crops but they are facing challenges due to crops for food usage. Also, at this moment, low conversion rate is one of the major limiting steps regarding second generation biofuels and which make the relevant process economically unfeasible (Saratale et al., 2013; Adenle et al., 2013). Fuels derived from algae are third generation biofuels. Algae are considered an alternative to land−based plants and biomass forms. From the primary investigations of biofuel production from algae at bench scale, algae appears to be one of the best possible alternative feedstocks which can aim to displace a fraction of fossil fuel (Najafi et al., 2011; Chisti, 2007; Khayoon et al., 2012). Based on their size variations and different morphologies, algae are either microalgae (phytoplankton) or macroalgae (macrophytes). Microalgae are microscopic, unicellular photosynthetic plants which are able to convert solar energy with an intake of CO_2 and H_2O by using nutrients to finally generate more biomass (Demirbas, 2010; Slade and Bauen, 2013; Alam et al., 2012). Macroalgae are comprised of multiple cells and are found near the seabed (Chen et al., 2009). Algae can transform solar power into biochemical energy via photosynthesis, have better growth rates compared to forest−derived biomass, agricultural residues and aquatic species (Brennan and Owende, 2010; Ndimba et al., 2013). Moreover, rapid growth rates and the ability to survive stringent environmental conditions make algae, as a whole new source of biomass, a potential alternative source of renewable fuel. Yet, the selection of the most appropriate and adapted species and providing the optimum environmental conditions are very essential aspects to be fully addressed before being able to achieve the accelerated rates of algal growth. Additionally, algae are capable of living in diverse environmental conditions with a relatively minimal nutrients requirement. Hence, algae cultivation is much feasible in areas where they are not habitually supported by mainstream agricultures (Ndimba et al., 2013; Slade and Bauen, 2013). Typically, algae are cultivated in photo−bioreactors (PBR) or in large open ponds producing biomass and are successively harvested to be processed for producing biofuels. Different aqueous systems like open ponds, closed ponds, hybrid PBR or PBR are widely used for the growing of microalgae. Microalgae also have a wide application in wastewater treatment and in thesequestration of CO_2 into potential biomass which can be considered as a potential feedstock for the production of renewable energy fuels such as biodiesel, biomethane, biohydrogen and bioethanol (Popp et al., 2014; Brennan and Owende, 2010; Chen et al., 2009; John et al., 2011).

2. Microalgae MFC systems

MFCs represent a novel and promising technology where microbial catalytic reactions at the anode end result in electric power generation from waste and renewable biomass (Inglesby et al., 2012; Rosenbaum et al., 2010). MFCs also assist in the bioremediation of specific pollutants and nutrients in wastewaters (Mathuriya and Yakhmi, 2014). Recovery of heavy metals, decolourisation of dyes, production of bioenergy such as biomethane, biohydrogen and even biomass are yet other applications of MFCs (Mathuriya and Yakhmi, 2014; Mohan et al., 2014a). Thus, MFCs have the dual benefits of power generation and wastewater treatment by which the process becomes as a whole more eco−friendly and economically feasible (Logan et al., 2006). The abiotic cathode reactions can catalyse the reduction of oxygen to form water. However, in such processes, the use of expensive elements namely platinum makes the process less economically unfeasible (Rosenbaum et al., 2010). Substantial research is being conducted to explore the potential of microalgae in different MFC systems for electricity generation. Bajracharya et al. (2016), Buti et al. (2016), Singh et al. (2012), Freguia et al. (2012) and Kelly and He (2014) have made excellent reviews on the different MFC types and discussed the main distinctive characteristics of each system. Algae in MFC systems become favorable because they may be used as efficient electron acceptors during the photosynthetic reactions at the cathodic end or as electron donors at the anodic end of the cell, and therefore are also capable in removing organic substrates (Wu et al., 2013;

Gude et al., 2013; Commault et al., 2014). Algae−based MFCs make up a syntrophic interaction between bacterial populations and algal biomass and this system functions with a minimal net energy input. The mechanism of algal MFC involves the oxidation of the biodegradable substrates and generating electrons at anode and the evolution of CO_2 at the cathode (He et al., 2009; Powell et al., 2011). It was observed by some workers that oxygen production at cathode mainly depends on the oxygenic photosynthesis for the transfer of electrons from water to $NADP^+$ using the PSI, PSII and cytochrome b_6f complex and by small plastoquinone and plastocyanin mobile molecules (Juang et al., 2012; Wu et al., 2013; Commault et al., 2014). In the cathode chamber and in the presence of sunlight, algae carry out photosynthesis and convert CO_2 to generate different types of organic matter, oxygen and biomass; whilst in the dark stage, they use up oxygen and produce energy by direct oxidation of the previously produced organic materials (Commault et al., 2014; Wu et al., 2013). In some cases, as reported by Mohan et al. (2014b) and Rosenbaum et al. (2010), it has been observed that certain photosynthetic cyanobacteria could act as s bioanode catalyst for yielding higher electrogenic activity without producing O_2 (Parlevliet and Moheimani, 2014).

Ma et al. (2017) designed a photosynthetic microbial fuel cell (MFC) for the production of *Chlorella* biomass by utilizing wastewater and reported that the system was sustainable for both biomass and energy production. Zhu et al. (2016) studied the potential of MFCs for nitrification/denitrification and found that nitrogen removal efficiencies were much improved using MFCs. Salar-Garcia et al. (2016) reported that the use of catholyte from ceramic MFCs enhanced lysis of microalgae under light/dark cycle conditions and increased electricity generation. Saba et al. (2017a) reviewed MFCs for energy generation as well as wastewater treatment and biomass production and also discussed the effects of several parameters on energy production from MFCs. Likewise, Xu et al. (2016) reviewed different emerging technologies integrated with MFCs as well as their development while also proposing a direction for further research. Later, Baicha et al. (2016) reviewed the utilisation of microalgae for bioenergy production from MFCs while also highlighting the use of CO_2 for biomass cultivation in the cathode chamber of the MFC. Besides MFC, other studies have investigated the use of algae in microbial desalination cells (MDCs) and bioelectrochemical systems (BES). Saba et al. (2017b) compared the use of *Nannochloropsis salina* and $KFe(CN)_6$ as catholyte for power generation from MDCs and reported highest desalination efficiency with *Nannochloropsis salina* as catholyte and highest power generation with $KFe(CN)_6$ as catholyte. Using a similar system, Zamanpour et al. (2017) evaluated the effects of salt concentrations on power density, salt removal rate and algal growth and reported that higher salt concentrations resulted in maximum power density with higher salt removal rates and algal growth. Khalfbadam et al. (2016) reported the use of a BES for removal of soluble chemical oxygen demand with and without current generation and obtained highest removal of soluble chemical oxygen demand with the system without current generation. Luo et al. (2016) reviewed the application of integrated photobioelectrochemical system for wastewater treatment and bioenergy production by highlighting the challenges with this system and proposing collaboration between the different experts for further progress in this field. Wu et al. (2016) studied the effects of light sources viz. incandescent and fluorescent on the growth rate, productivity and chlorophyll α content of *Desmodesmus* sp. A8 prior to electricity generation from a BES inoculated with the microalgae and found that incandescent light was more suitable for biomass production as well as energy production. Given the rising interest and constructive research efforts in this field of bioenergy generation, this review will revisit selected research findings and provide a concise update on algal MFCs and their key features of operation and performance.

2.1. Single-chamber algae−MFCs

Single chamber (membrane−less) MFCs have been studied very well so far. The photosynthetic biocatalysts have shown the ability to transport electrons to the electrode surface without having to resort to “electron shuttle mediators” (Lin et al., 2013). *Spirulina platensis*, a type of blue−green microalgae, has been studied without using membranes. This MFC system produced electric power in the presence of light with a power density output of 0.132 mW m^{-2} and with an output of 1.64 mW m^{-2} in dark conditions (Fu et al., 2009). The electric power thus generated under the dark conditions more than that of generated under light condition. Due to these properties of being functional with better yields of power under extreme conditions of light, single-chambered MFC can operate for longer periods of time. This type of MFC design is also useful for the better attachment of microalgae on the surface of the electrodes and could be hence utilized as a photosynthetic biocatalyst for bioelectricity generation (**Figure 1**). Typically, single-chamber MFC configurations have both electrodes (the anode and the cathode) connected through an electric circuit. Moreover, some workers have designed single-chamber algal MFCs wherein bacteria and algae were added and their synergistic actions increase the efficiency of the process. In this type of system and in the presence of light, microalgae produce organic acids which are used as substrates by the bacteria to produce electricity (**Figure 2**). Nishio et al. (2013) have used "*single chamber MFC bioreactors*" consisting of algae utilizing *Lactobacillus* and *Geobacter* for producing electricity from *Chlamydomonas reinhardtii* grown phototosynthetically, and observed that their system could give a power density in the tune of 0.078 W m^{-2}. Yuan et al. (2011) have studied a blue-green algae powered single chamber MFC and this system showed significant chemical oxygen demand (about 78.9%), and total nitrogen (about 96.8%) removal efficiencies with an ultimate power density yield of 114 mW m^{-2} of maximum power density. This system also was found effective for the removal of algal toxins such as microcystins released from blue−green algae. The results from Yuan et al. (2011) hence suggested that single-chambered algal MFC have the capability for the remediation of contaminated environments with a simultaneous production of electricity. Caprariis et al. (2014) have developed bio−photovoltaic cells for the production of clean energy using the photosynthetic activity of green microalgae *Chlorella vulgaris*. In the system of Caprariis et al. (2014), the anode was dipped in the broth and the cathode left exposed to the surrounding air, and thus no organic substrate and mediators were required. Alongside, Caprariis et al. (2014) observed that there was no net CO_2 production. Due to exo−electrogenic activities of *Chlorella vulgaris* in this system, the production of electricity at a power density of 14 μW m^{-2} was possible and it meant as a whole that there was a major scope for research in developing this type of system for power production.

2.2. Double-chamber algae−MFCs

In this type of system, two compartments are separated by a "*proton exchange membrane*" (**Figure 3**). Recently, Gajda et al. (2015) demonstrated that an MFC consisting of anaerobic biofilms at the anode could generate current, whilst the phototrophic biofilm at the cathodic end had produced oxygen through the oxido−reduction reaction and algal biomass production. This system had achieved both wastewater remediation and power generation along with biomass production. Few microalgae strains such as *Chlorella vulgaris* (Zhang et al., 2011; Zhou et al., 2012; Wang et al., 2010), *Spirulina platensis* (Fu et al., 2009) and *Pseudokircheneriella subcapitata* (Xiao et al., 2012 have been used in a double-chamber MFC. Some investigators have demonstrated that mixed algal cultures could also be used in the development of MFC cathodes (Jiang et al., 2012; Chandra et al., 2012; Strik et al., 2010; He et al., 2009). Strik et al. (2008) have utilized mediator-less photosynthetic algal microbial fuel cell in an open system for 100 days to generate electricity, and reported a maximum power production performance of the MFC at 110 mW m^{-2} of photobioreactor surface area. Mitra et al. (2012) have developed a MFC system based on *Chlorella vulgaris* at the cathodic end and *Saccharomyces cerevisiae* and which was operated under continuous flow regimes. Mitra et al. (2012) reported a peak power density of 0.6 mW m^{-2}. Similarly, Zhang et al. (2011) have used green algae in the cathodic chamber and demonstrated both good nutrient removal and electricity production at 68±5 mW m^{-2} with a 1000 Ω resistor. In some cases, MFC systems show a poor performance with relatively small power generation and especially so when the oxygen supplied by algal growth becomes a form of inhibition/limitation to further use the system for long term operation (McCormick et al., 2011; Zhang et al., 2011). Some investigators have developed micro MFC (µMFC) to undertake the screening of *Rhodopseudomonas palustris* using acetate and *Arthrospira maxima* feedstock. The µMFC system showed power developed by Inglesby et al. (2012) had a power density output of 10.4 mW m^{-3} and it was also found that the power generation was independent of *R. palustris* concentrations and growth patterns. Nevertheless, micro MFC devices could be revamped and thereafter used for high−throughput screening and as well as in carrying out sensitivity analysis of the different process parameters involved in the complex bio−electrochemical reactions. This could be an avenue of research whose outcomes will probably prioritize the process parameters and allow research efforts to focus on optimization studies and simulations.

2.3. Photosynthetic sediment MFCs (PSMFC)

Photosynthetic−sediment MFC is made up of an anode arranged in the sediment and a cathode compartment filled with microalgae and which is present on the top of sediment. The anodic bacterial activity produces CO_2 which then gets consumed at the cathode compartment by the algal cells therein. Oxygen is then produced and power generated. He et al. (2009) have constructed a "*sediment−type self−sustained phototrophic MFC*" which produced a maximum current of 0.054 ± 0.002 mA at a resistance of 1 kΩ in a system which had been operated for over 145 days. Commault et al. (2014) recently developed a membrane−less sediment−type MFC consisting of a photosynthetic biocathode containing a complex microbial community along with microalgae and cyanobacteria which were able to produce a maximum power density 11 mW m^{-2} over 180 days with no feeding.

2.4. Algae-based microbial carbon capture cells (MCC)

Recently, some investigators demonstrated the performance of algae–based microbial carbon capture cell (MCC) under illumination. Liu et al. (2015) utilized such a system in both light and dark condition where they observed a peak power density of 187 mW m^{-2} under light illumination, and this output was relatively higher than that of 21 mW m^{-2} obtained under dark conditions. The results from Liu et al. (2015) supported that algal photosynthesis is crucial in such systems. Recently, Pandit et al. (2012) evaluated the MCC performance with *Anabaena* biocathode sparged with a CO_2–air mixture, and they reported a peak power output which was higher in comparison to the biocathode that had been sparged with air only. Wang et al. (2010) had earlier developed an MCC using *C. vulgaris* to reduce CO_2 emissions and reported significant CO_2 reduction and a peak power density of 5.6 W m^{-3} (Wang et al., 2010). Some investigators proved that the application of immobilized cells as compared to suspended cells could increase the columbic efficiency up to 88% (Zhou et al., 2012).

2.5. Anode-catalyzed microalgae MFCs

There are few reports where microalgae or photosynthetic bacteria have been utilized for electron production in the anode compartment and have ability to transfer to the anode without electro mediators. ––

Chang et al. (2015) utilized live *Chlorella pyrenoidosa* in the anode of a MFC where this species had acted as an electron donor. Under optimized conditions of oxygen levels, the density of algal cell populations and the intensity of incident light, a peak power density of 6030 mW m^{-2} was obtained. In addition, it has also been seen that some bacteria such as *Rhodopseudomonas* and other purple non–sulphur bacteria can also effectively utilize biomass found in the anode compartment of an MFC (Xing et al., 2008). Highlights of other studies which probed the performance of anode-catalyzed microalgae are summarized in Table 1.

2.6. Algae as substrate supplier in dark MFCs anodic end

The literature shows that algal biomass consists of adequately high carbohydrates, proteins and lipids contents for electricity generation in MFCs, including live algae and dry algae biomass at the anode compartment (Li and Zhen, 2014). Utilization of microalgae biomass showed dual benefits including pollution control and cost effective feedstock in MFC processing. Some microalgae have very high cellulose and hemicellulose content and pretreatment of the algal biomass is often obligatory to increase the efficiency of the process−Additionally, dry algae biomass has been assessed as a substrate in MFC for the growth of oxidizing bacteria at the anodic end (Gouveia et al. 2014, Velasquez−Orta et al. 2009; Rashid et al. 2013; Cui et al. 2014).

Velasquez−Orta et al. (2009) − have tested *Chlorella vulgaris* and *Ulva lactuca* feedstocks in dry powder at the anodic end of the MFC system they designed, and subsequently recorded a peak power density of 0.98 W m^{-2} from the *Chlorella vulgaris* and 760 mW m^{-2} for the scenario of *Ulva lactuca* −. Rashid et al. (2013) have used activated sludge and *Scenedesmus* algal biomass as a nutrient source at the anode, and then observed that sonication and thermal pre−treatment of algal biomass had enhanced the microbial digestibility of the algae and also increased the overall performance of the MFC test unit. In other studies, e.g. Nishio et al. (2013), formate produced by green algae e.g. *Chlamydomonas reinhardtii* and *Geobacter sulfurreducens* have also been assessed for its influence on electricity generation in MFC environment. Lakaniemi et al. (2012) have used *Chlorella vulgaris* and *Dunaliella tertiolecta* in MFCs and recorded a peak power density of 15 mW·m^{-2} at the cathode with *Chlorella vulgaris* in comparison with *Dunaliella tertiolecta* which yielded almost thrice a lower power density of 5.3 mW m^{-2}. Wang et al. (2012) have studied raw algal sludge and alkaline pre−treated algae sludge in MFC and reported a peak power density was 2.8 and 4.0 W m^{-3}, respectively. In this same work, the removal efficiency for the full quantities of oxygen demands was 33% and 57%, respectively (Wang et al., 2012). These specific results inferred that pretreatment of biomass may be envisaged as a useful step to enhance the bioelectrokinetics in the MFC for higher power generation.

2.7. Integrated photo−bioelectrochemical systems

Some investigators have developed integrated photobio-electrochemical systems by incorporating an MFC within an algae−based bioreactor. Such a system has been found to be useful in the generation of electricity and algal biomass. Xiao et al. (2012) reported significant removal of COD of up to 92%, ammonium nitrogen removal of 98% and phosphate removal of 82% with a concomitant peak power density yield of 2.2 W m^{-3}. Strik et al. (2008) developed an integrated system by annexing a glass photobioreactor to an MFC for electricity generation and for algal biomass production. Similarly, Jiang et al. (2013) demonstrated that an up flow MFC- photobioreactor coupled system could bring about the generation of electricity and remediation of the effluents. De Schamphelaire and Verstraete (2009) have constructed a closed−loop system to transform sunlight into biogas. In this work of De Schamphelaire and Verstraete (2009), the algal biomass generated was employed as feedstock in an anaerobic tank, and under the specific experimental conditions, an algal biomass production of 24–30 tonnes VS ha^{-1} $year^{-1}$ and a biogas production of 0.5 N m^3 kg^{-1}algae were reported. Hence, there is evidence to support the suitability of integrated systems for the simultaneous production of different types of biofuels at a relatively low cost and with low environmental impact.

3. Effects of process parameters

Different process parameters such as illumination, light intensity, electrode material, air sparging and concentration of CO_2 may affect the overall performance of microalgae−MFCs. However, a detailed investigation of these parameters is limited in the literature. Light illumination and the intensity of the light has been so far found to significantly influence the algal biocathode reactions and the performance of MFCs. Lan et al. (2013) have investigated the effects of different types of light and light intensities in photo MFCs containing *Chlamydomonas reinhardtii transformation* F5 and reported that higher light intensities gave better performance whereas red light illumination showed significant power density production (12.95 mW $m^{-2}_{cathode}$) as opposed to blue light illumination. Similarly, Wu et al. (2014) investigated the influence of different light intensities on *Desmodesmus* sp. A8 assisted biocathode in which the anode and cathode resistances were strongly affected by changes in light intensity. Moreover, several other workers have studied the effects of illuminated and non−illuminated cycles on algae biocathode-assisted MFC systems where under dark conditions no power was produced (Xiao et al., 2012;Wang et al., 2010, ; Chandra et al., 2012; Strik et al., 2010; Zhang et al., 2011). When assessing the mode of operation of the MFC, Gonzalez del Campo et al. (2013) achieved a higher power output with continuous mode operation as compared to sequencing−batch mode operation. On another note of parameter influence, Kakarla and Min (2014) have demonstrated the influence of cathode materials on MFC performance in devices that included algae−assisted cathodes. In this study of Kakarla and Min (2014), carbon fiber brush and plain carbon paper were used as materials for the *Scenedesmus obliquus* assisted biocathode reaction. In addition, also in this study, it was observed that oxygen supply was beneficial for algal biocathode reactions as compared to mechanical aeration.

4. Direct electron transfer in microalgae and cyanobacteria assisted MFCs

Extracellular electron transfer is an important mechanism which helps to understand and then develop new functions in bioelectrochemical systems. In MFC, the electron transfer mechanism for exo−electrogens namely *Geobacter sulferreducens* has been studied very well (Malvankar et al., 2012). According to Gorby et al. (2006), the electron transfer mechanisms can be carried out by "*indirect transfer via flavin*", by direct transfer in proteins and in some rare instances, the cytochromes of terminal reductases have participated in the pathways. In algal MFC, the majority of research has been devoted for improving current outputs using potential algal strains and by employing engineering approaches to some extent. In cathodic microalgal MFC, mediators are required and this is a major limitation for scalability to higher scale of production with regards to sustainability, cost and toxicity considerations. Moreover, these mediators may influence intracellular components and electrobiochemical mechanistic pathways of algal system (Wu et al., 2013). However, the electron transport or electron flow pathway between the microalgae and electrode system has not been studied well, and hence there is a very limited information of the functions and characteristics of the electrode−microalgae interactions (Rosenbaum et al., 2010). Very few reports describe the electrode−microalgae interactions. Wu et al. (2013) have isolated nine green microalgae from wastewater and studied their electron transport capacity between the cells and electrodes. Wu et al. (2013) reported that the *Desmodesmus* sp. demonstrated its capability of direct electron transport via the "*membrane−associated proteins"* and *"indirect electron transfer via secreted oxygen*" (Wu et al., 2013). The study of Wu et al. (2013) was a first in its kind to have givenan elementary model which could be further made comprehensive to study the mechanistic pathways bringing about electron transports. In a study by Cereda et al. (2014), mediatorless biophotovoltaic devices consisting of cyanobacterium *Synechocystis* sp. PCC6803 were shown to have the ability for direct electron transfer through conductive nano−wires at the anode chamber under excess light and CO_2 limiting condition (Cereda et al., 2014).

Upon scaling-up MFCs from a 170 mL single chamber open air cathode treating spent wash to a 100 L chamber, Dimou et al. (2014) observed that COD removal efficiency had risen to 90% and electricity production had been optimized from 0.4 V to 0.65 V. Dimou et al. (2014) also reported that the robust microbial community had effectively treated large volumes of anaerobically generated digestate, thus showing a high potential for MFCs to be scaled-up to industrial application. Mohan et al. (2014c) have also indicated that in-depth analysis of any biocatalyst performance, electron transfers and redox mechanisms and technology scale-up aspects are crucial to further promote the integration of MFC as viable energy and environmental solution. Indeed, according to a number of studies and lastly from Li and Sheng (2012), Liu and Cheng (2014), Butti et al. (2016) and Bajracharya et al. (2016), the potential for scalability of MFCs is a key challenge which needs to be comprehensively addressed with more adapted research and development efforts. In particular, the scalability issues which demand more work are related to (i) the synthesis and use of more efficient, effective and less costly materials, (ii) the design of more energy efficient reactor configurations, (iii) developing mechanistic strategies which will augment the recovery of power and enhance power density yields, (iv) reducing the impacts of low selectivity, (v) and finally limiting the risks from unwanted microbial contaminations which in turn hamper the overall mass-transfer coefficients. In addition, the reproducibility of effective laboratory scale investigations to pilot scale systems need to be also looked into for making the algal MFCs technology economically viable and environmentally workable.

5. Concluding remarks

This short review has addressed the key aspects related to the use of some new types of algal biomass-based microbial fuel cell systems for the generation of electric power. The main types of the microbial fuel cell reactor designs using algae have been surveyed and are namely the single chamber algae−MFC, double chamber algae−MFC, photosynthetic sediment MFC (PSMFC), algae based microbial carbon capture cells, anode catalyzed microalgae MFC, live algae or algal biomass as substrate in dark anode compartment of MFC and integrated photo−bioelectrochemical systems. Most of the MFC systems have their own specific merits and shortcomings, but are all able to bring about the sought energy generation patterns and performance to different extents of complexity and yields of power intensity. However, the exact mechanistic pathways which are essentially a complex mix of biological reactions taking place in an electrochemically controlled medium are not yet fully elucidated. Once these mechanisms may be understood and modeled in simple mathematical forms, the optimization of the different reactor configurations may be undertaken using a comprehensive design of experiments approach. All the more, the many environmental parameters which are inherent to each of the latter MFC systems play a crucial and synergetic role in determining the quality of power production and the effectiveness of the configuration to deliver the actual performance recorded. Once more, there is a need to isolate the more sensitive parameters and optimize them in their influence on the power production regimes. As of the present state, the use of algal biomass constitutes a clean and green bioenergy research niche which is receiving more and more interest. It is envisaged that in the coming decade, following more applied research and process intensification, algal biomass will have become a substantial player in the microbial fuel cell research and development field. Research and development should not only be related to small−scale MFC systems, but there is also a wide need to assess the suitability of the specific MFC system at the different points of use and energy delivery it may best fit in. Such an assessment should be well designed from a complete lifecycle perspective, both technically and from an economic angle. The harmonization of the use of a single type of algae−based MFC or a combination of algal MFC designs for one type of energy production and application will equally demand research and development efforts to be streamlined and concentrated towards more field scale experimentation and validation.

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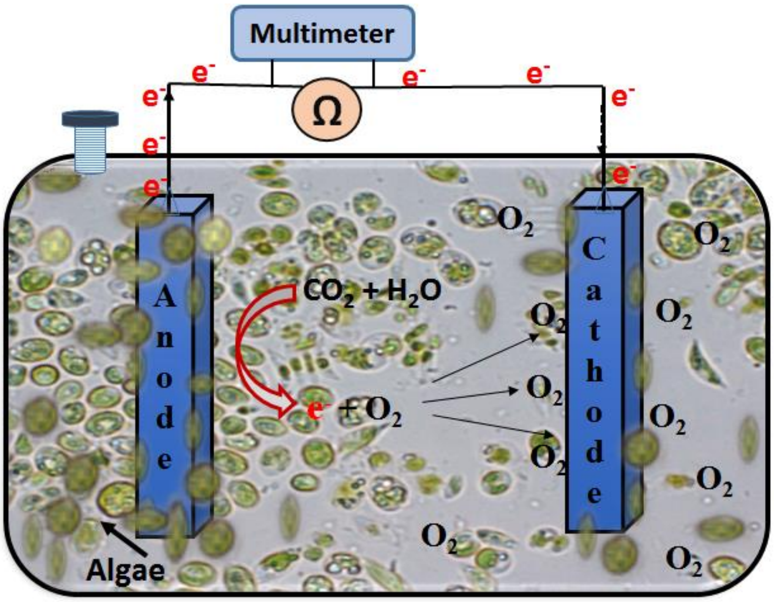
Figure Captions

Fig. 1 Schematic diagram of a single chamber co−culture (microalgae and bacteria) catalysed MFC.

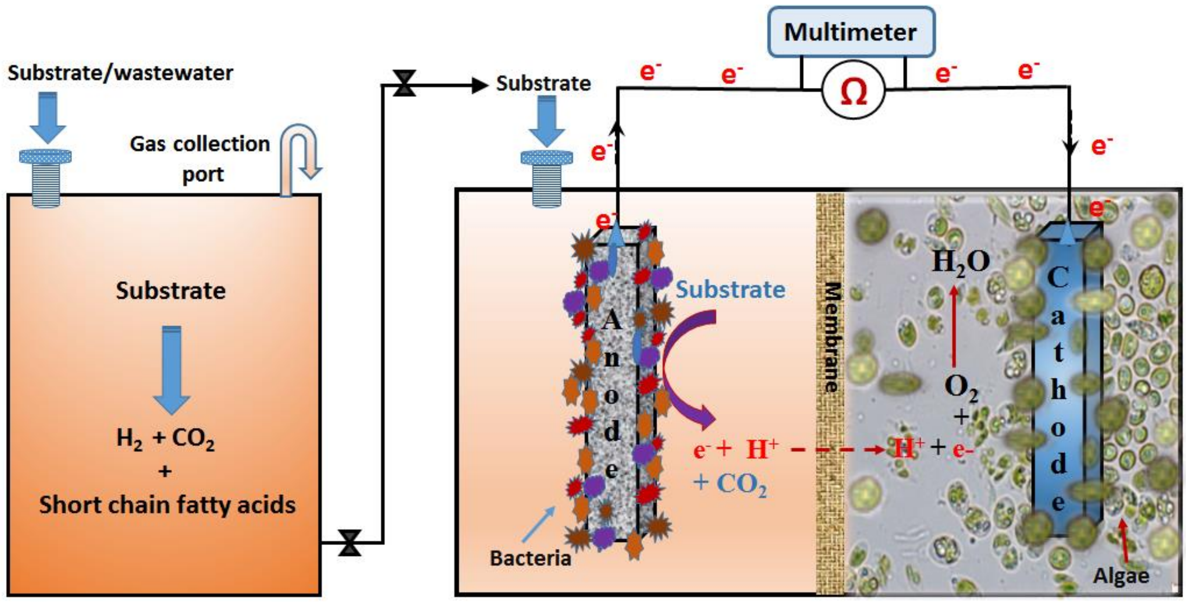
Fig. 2 Schematic diagram of a double chamber MFC (bacteria in anode and microalgae in cathode) integrated with wastewater treatment/hydrogen producing bioreactor

Fig. 3 Schematic representation of a double chamber MFC with algae/autotrophs acting as biocatalyst in the anode compartment to then provide H^+ and electrons to the cathode compartment where bacteria/heterotrophs utilise them to produce hydrogen.



Single chamber Algae−MFC

Fig. 1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Gas collection port
Substrate
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+
Short chain fatty acids
Substrate
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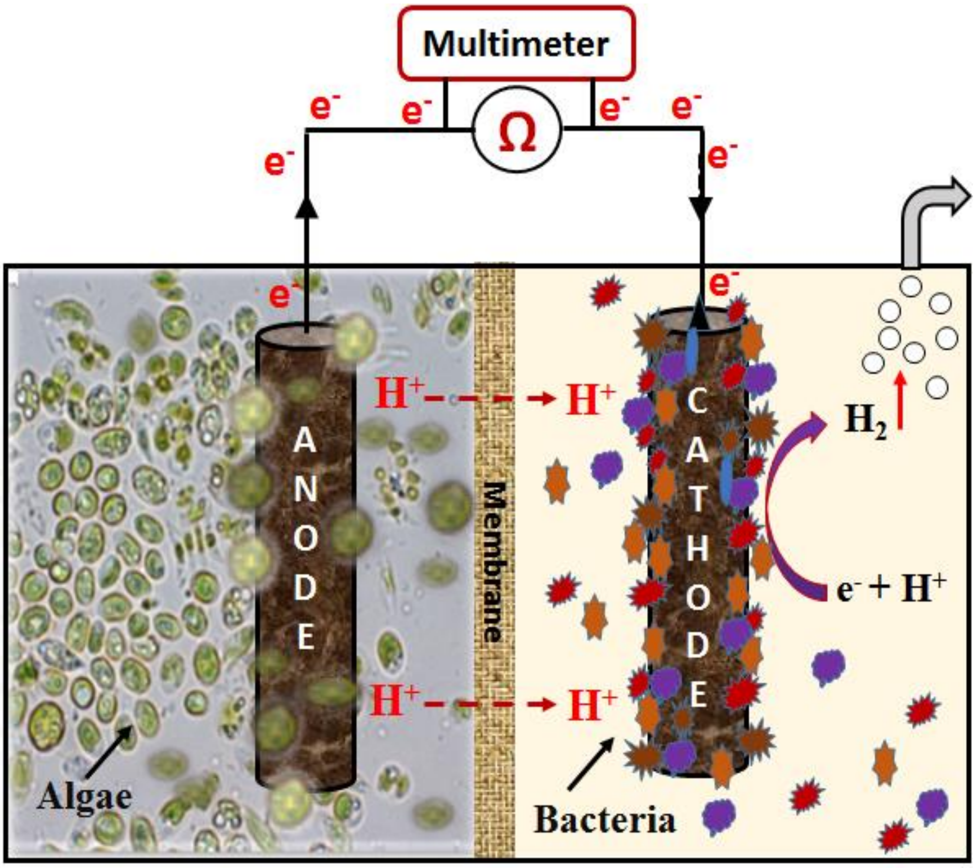
e- + H+
+ CO_2
H+ + e-
H_2O
O_2
Cathode
Bacteria
Algae

Fig. 2


Multimeter
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H2
e- + H+
Algae
Bacteria

Fig. 3

Table 1: Microalgae MFC systems and their corresponding process highlights

Algal and cyanobacteria used	Type of MFC	Electrode	Maximum power density	Process highlights	Reference
Chlorella vulgaris	Single chamber	Anode: Carbon paper Cathode: Carbon paper containing Pt	0.068 W m^{-2}	Produce electricity and algal biomass. Sequester carbon, nitrogen and phosphorus	Zhang et al. (2011)
Chlorella vulgaris, Dunaliella tertiolecta	Double chamber	Anode: Graphite plate electrodes Cathode: Graphite plate electrodes	0.015 W m^{-2}	Peak power density higher with *C. vulgaris* than *D. tertiolecta*	Lakaniemi et al. (2012)
Scenedesmus obliquus	Double chamber	Anode: Plain carbon paper Cathode: platinum coated carbon paper	153 mW m^{-2}	Microalgae sustained MFC processes and development of an algal biofilm enhanced direct oxygen transfer	Kakarla and Min (2014)
Chlorella pyrenoidosa	Double chamber	Anode: Graphite rod Cathode: Graphite rod	30.15 mW m^{-2}	Higher current generated and denser algal biomass produced	Xu et al. (2015)
Scenedesmus obliquus	Double chamber	Anode: Toray carbon paper Cathode: Toray carbon paper	102 mW m^{-2}	74% COD removal; lactate and acetate produced from algal biomass during power production	Kondaveeti et al. (2014)
Arthrospira axima (Spirulina	Double chamber	Anode: Graphite Cathode: Graphite	20.5 mW m^{-2}	63% TCOD removal with 10.4% energy capture	Inglesby and Fisher (2013)

maxima)					
Chlorella vulgaris	Single chamber	Anode: glassy graphite rods Cathode: glassy graphite rods	2.7 mW m^{-2}	Successful removal of CO_2	Powell et al. (2009)
Chlorella vulgaris	Double chamber	Anode: Toray carbon cloths with 10% Teflon Cathode: Toray carbon cloths with 10% Teflon	13.5 mW m^{-2}	Polarization resistance more significant at cathode	Gonzalez del Campo et al. (2013)
Cyanobacteria (*Synechococcus*) and Green alga (*Chlorella vulgaris)*	Single chamber	Anode: Indium tin oxide‒coated polyethylene terephthalate	10.3 mW m^{-2}	Exoelectrogenic activities took place in photosynthetic microbes and gave pronounced electricity production	McCormick et al. (2011)
Mixed microalgal culture	Double chamber	Anode: Graphite plate electrodes Cathode: Graphite plate electrodes	57 mW m^{-2}	MFC reactions in spring season yielded higher bioelectrogenic activity (57.0 mW m^{-2}) over summer (1.1 mW m^{-2})	Mohan et al. (2014b)
Spirulina platensis	Single chamber	Anode: Platinum electrodes Cathode: Platinum electrodes	6.5 mW m^{-2}	Higher power density from PMC under non illuminated conditions	Fu et al. (2010)

Chlorella vulgaris	Double chamber	Anode: Carbon felt Cathode: Carbon fiber cloth	8.79 mW m^{-2}	There was a very high COD removal reaching 84.8% and the corresponding peak power density recorded was 2485.35 mW m^{-3} at 7.9 A m^{-3}. The Coulombic efficiency equaled 9.40%	Zhou et al. (2012)
Chlorella vulgaris	Single chamber+sediment	Anode: Graphite felt Cathode: Multi−walled carbon nanotubes	21 mW m^{-2}	Power density from sediment microbial fuel cells with an algae−assisted cathode system reached 21 mW m^{-2}. This power density performance was enhanced to 80.95% when coating material in the form of carbon nanotube was applied to the cathode	Wang et al. (2014)
Chlorella vulgaris	Double chamber	Anode: Carbon fiber brush Cathode: Carbon cloth	19.45 mW m^{-2}	The peak power densities varied from 4.1 to 5.6 W m^{-3}. The interesting feature of this work was that the complete amounts ofCO_2 produced from the anodic region was fully consumed by the catholyte, and the soluble fraction of the inorganic carbon was transformed to algal biomass	Wang et al. (2010)
Chlorella vulgaris	Double chamber	Anode: Carbon fiber brush Cathode: Carbon cloth	1926 mW m^{-2}	In this work, the maximum power density reached 8.77 Wm^{-3} and the corresponding Coulombic efficiency topped at 6.5% for a COD of 2500 mg COD L^{-1} of microalgal biomass. The microalgal biomass equally sequestered CO_2	Cui et al. (2014)

Chlorella vulgaris	Double chamber	Anode: Plain Graphite Cathode: Plain Graphite	62.7 mW m^{-2}	In this work, it was shown that higher light intensity varied from 26 to 96 μE m^{-2} s^{-1}) had enhanced the extent of power density up to nearly 600%	Gouveia et al. (2014)
Desmodesmus sp. A8	Double chamber	Anode: Plain graphite felt Cathode: Plain graphite felt	99.09 mW m^{-2}	Microalgae–microbial fuel cells are specifically designed configurations which allow the effective and efficient conversion of solar energy to electrical power using certain complex biological mechanisms	Lee et al. (2015)
Escherichia coli	Single chamber	Anode: Mn^{4+}graphite Cathode: Fe^{3+} graphite	91 mW m^{-2}	Electron mediators may be integrated into graphite electrodes to significantly enhance electricity production	Park and Zeikus (2003)
H. praevalens and Marinobacter hydrocarbonoclasticus.	Single chamber	Anode: Activated carbon electrodes Cathode: Activated carbon electrodes	47 mW m^{-2}	Coupling of MFCs with capacitive deionization will sustain desalination and reuse of hypersaline effluents.	Monzon et al. (2017)
Geobacter spp.	Double chamber	Anode: Graphite Cathode: Graphite	0.16–1.14 A m^{-2}	*G. sulfurreducens* enhanced the performance of MFCs	Bond and Lovley (2003)
Klebsiella pneumonie L17	Double chamber	Anode: Carbon felt Cathode: Carbon felt	1.2 (A m^{-2})	*K. pneumoniae* biofilms induced the direct electron transfers from fuels to electrodes	Zhang et al. (2008)

Sludge wastewater	Double chamber	Anode: Graphite carbon electrode Cathode: Graphite carbon electrode	125 mW cm^{-2}	Enhanced power density of florescent light limits electricity output of MFCs	Juang et al. (2012)