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The Microbial Fuel Cell: The Solution to the Global Energy and Environmental Crises?

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Abstract

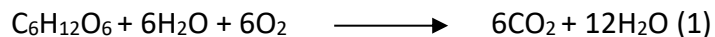
The current climate change threat by green house gas emissions from the combustion of fossil fuels has necessitated a search for alternative non-polluting, reliable, renewable and sustainable sources of energy such as solar energy and its derivatives. During anaerobic microbial metabolism of small carbohydrates, protons and electrons are generated together with carbon dioxide gas. After the electrons are donated to the anode by the microbes (or with the aid of chemical mediators), these electrons can be channelled through a circuit bearing a load to the cathode, where the atmospheric oxygen is reduced, first to its divalent ions and subsequently to water. Unlike other biomass-to-energy conversion techniques such as torrefaction and gasification, no emissions are produced and the process is carbon neutral. There is no need for expensive conversion techniques such as transesterification, thermal or catalytic cracking or catalytic liquefaction. It is also non-destructive; the energy is harvested in-situ and is guaranteed as long as feedstock is available, can be implemented using industrial waste water, can be used in desalination or remediation and has application potential in wetlands and erosion sites which are prevalent in Sub-Saharan Africa, reducing competition with food supply and other conventional sources of bio-energy.

Keywords: Plant-Microbial Fuel Cell, Alternative Energy, In-situ Energy, Zero Emissions, Electrigens

Introduction

A microbial fuel cell is a bio-electrochemical system which derives electrical current from the catalytic action of electrigenic microbes on organic compounds and/or metals (Aelterman, 2009;

Clauwert, 2007; Cheng et al, 2007; Min and Logan, 2004; Morozan et al, 2007). The microbial decomposition of sugars in aerobic conditions produces carbon dioxide and water (Scott and Murano, 2007).



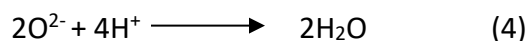
However, in anaerobic conditions, carbon dioxide, protons and electrons are produced since oxygen is not available to take up the electrons.



To utilize them in electricity generation, the electrons produced have to be moved from the electron transport chain of the cell and be deposited on an electrode. This can be achieved in two ways. Inorganic mediators such as thionine, methyl blue, methyl viologen and humic acid tap into the electron transport chain and channel electrons produced via the lipid membrane and the outer cell membrane and liberates the electron at the electrode which becomes negatively charged (Strik et al, 2008). Microorganisms which require a mediator usually do not possess electrochemically active surface proteins to transfer electrons to the anode electrode (Strik et al, 2008; Scholz et al, 2003). Alternatively, certain electrochemically active bacteria (including those with pili, which are tiny hair-like extensions on their external membrane) can be utilized as they can directly transport electrons from respiratory enzyme to the anode in anaerobic conditions since the difference in free energy between it and the electrode is larger than other available acceptors [10]. Examples include *Shewanella putrefaciens*, *Aeromonas hydrophila*, *Rhodospirillum rubrum*, *Clostridium botulinum*, *C. butyricum*, *Desulfotomaculum reducens*, *Rhodobacter capsulatus* and *Thiobacillus ferrooxidans* (Clauwert et al, 2008; Schampelaire et al, 2008; Walker et al, 2010; Logan and Logan, 2006). The electrons flow through a load to the cathode where oxygen is readily available to be reduced (Bergel et al, 2005).



The protons generated at the anode also flow to the cathode by means of a proton or cation exchange membrane. Subsequent reduction of oxygen ions by protons produces water (Mohan et al, 2007; Min and Logan, 2004).



To produce sufficient oxygen reduction rate, a catalyst (mostly platinum) is used. Other novel catalysts that have been proposed include iron-tetra methoxy phenylporphyrin (Kim et al, 2011). The water produced is pure and thus the process can also be used for remediation and water purification while generating electricity (Min and Logan, 2004; Lee et al, 2008; Logan et al, 2006; Scott and Murano, 2007).

The potential difference between the anode and the cathode, together with the flow of electrons results in the generation of power. The power output is relatively low and variable (Clauwert et al, 2008; Lee et al, 2008). However, up to 90% columbic efficiency can be achieved (Lee et al, 2008). Function and efficiency is dependent on the nature of carbon source used, the design and configuration of the fuel cell, the nature and type of electrodes and proton exchange membrane in use, presence of electron acceptors such as mediators and nature of inoculums (Cheng et al, 2007; He et al, 2005; DiBucci and Boland, 2011).

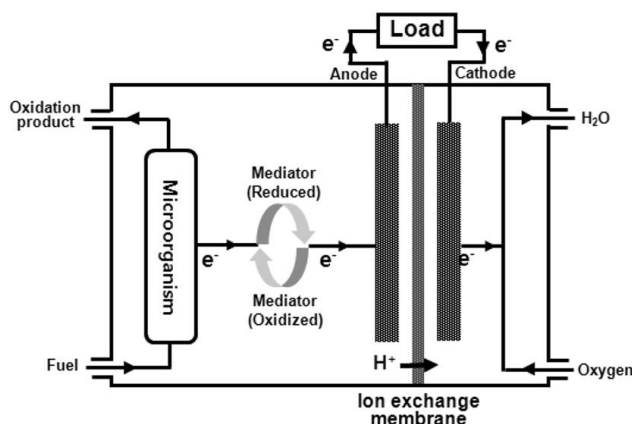


Fig. 1 A schematic diagram of the Microbial Fuel Cell (Source: Kim et al, 2011)

The remainder of this paper is organized as follows. Section 2 describes the different feedstocks in use for microbial fuel cell technology. Different variants of the microbial fuel cell are described in Section 3. The characteristics, applications and advantages of microbial fuel cells are discussed in Section 4. Section 5 discusses major factors limiting efficient electricity generation in microbial fuel cells. Finally, Section 6 draws the main conclusions of the paper.

Feed Stock

Different feedstock can be used for the production of electricity using the microbial fuel cell including organic acids, alcohols, amino acids, proteins and even inorganic sulphides (Lee et al, 2008; Scholz et al, 2003). Acetate can also be used effectively (90% columbic efficiency) since it is resistant to alternative microbial conversion such as fermentation and methanogenesis at room temperature and anaerobic environment (Lee et al, 2008). Also, industrial effluents (waste water) such as paper recycling sludge, brewery effluents and food processing liquid effluents are suitable for use (Min and Logan, 2004; Mohan et al, 2007; Schamphelaire et al, 2008).

Types of the Microbial Fuel Cell

Various types of the microbial fuel cell exists, differing majorly on the source of substrates, microbes used and mechanism of electron transfer to the anode. Based on mechanism of electron transfer to the anode, there are two types of microbial fuel cell which are the mediator-microbial fuel cell and the mediatorless-microbial fuel cell.

Mediator-microbial fuel cells are microbial fuel cells which use a mediator to transfer electrons produced from the microbial metabolism of small chain carbohydrates to the anode (Logan et al, 2006). This is necessary because most bacteria cannot transfer electrons directly to the anode [Scholz et al, 2003]. Mediators like thionine, methyl blue, methyl viologen and humic acid tap into the electron transport chain and abstract electrons (becoming reduced in the process) and carry these electrons through the lipid membrane and the outer cell membrane (DiBucci and Boland, 2011; Kim et al, 2011). At the cathode, oxidation of the mediators takes place as the electrons are released to oxygen, which is a more powerful electron acceptor (Saito et al, 2011; Kim et al, 2011). The redox reactions undertaken by the mediator leave it unchanged at the end of each cycle. It can thus be recycled back to the anode for another cycle (Logan et al, 2006). Requirements for good mediators include that all oxidation states of the mediator be chemically stable in electrolyte solution in order to adsorb adequately on the bacterial cells and electrode surface (Logan et al, 2006; Rozendal et al, 2008; Scholz et al, 2003). The mediator also should not interfere with other metabolic processes going on in the cell (Rozendal et al, 2008). The mediator should not be reduced or decomposed by the cell reactions (Bergel et al, 2005). The reduced state of the mediator should escape freely from the cell via the membrane. The oxidation process of the mediator should be fast and electrochemically reversible (Logan et al, 2006; Kim et al, 2011). The mediator's redox potential should be fast enough to provide rapid electron transfer from the metabolites but slow enough to prevent significant loss of potential. The oxidized state of the mediator should easily access the membrane-bound redox active complexes to be reduced and oxidized states of the mediator should easily penetrate the bacterial membrane to reach the reductive species inside the bacteria (Scholz et al, 2003; DiBucci and Boland; Strik et al, 2008).

Mediator-less microbial fuel cells, on the other hand, use special microbes which possess the ability to donate electrons to the anode provided oxygen (a stronger electrophilic agent) is absent (Scholz et al, 2003; Mohan et al, 2007). There are variants of the mediatorless microbial fuel cell which differ with respect to the sources of nutrient and type of inoculum used. They are the Plant-Microbial Fuel Cell, the Soil-Microbial Fuel Cell and the Metal Reducing-Microbial Fuel Cell and the Sediment Microbial Fuel Cell.

The plant microbial fuel cell operates on the principle that microbes are able to anaerobically break down and release electrons from the small molecular mass carbohydrates that are exuded from the roots of plants as a result of photosynthesis (Strik et al, 2007; Schamphelaire et al, 2008). During photosynthesis, the carbon dioxide fixed in the leaves is converted to small molecular weight carbohydrates and are sent to the plant roots where they are lost as root exudates (Schamphelaire et al, 2008). On microbial decomposition, protons, electrons and carbon dioxide are released. The carbon dioxide is released to the atmosphere, while the protons and electrons are used for the production of electricity as in the microbial fuel cell.

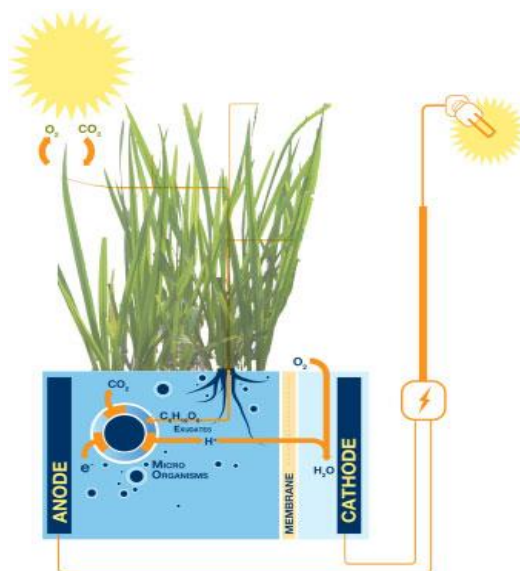


Fig. 2 A model of a Plant microbial Fuel Cell (Strik et al, 2008)

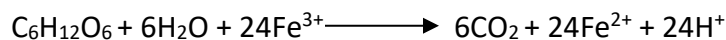
Soil-Microbial Fuel Cells use the soil as the source of nutrient rich anaerobic media, the inoculum, and the proton exchange membrane. The anode is placed in the soil, while the cathode is exposed to atmospheric oxygen. Since the soil is rich in complex sugars and nutrients due to plant and animal decay and harbours a large diversity of microbes including both aerobic and anaerobic microbes, the aerobic microbes serve as oxygen scavengers and filters, permitting the anaerobic microbes to transfer electrons to the anode (Logan and Logan, 2006).



Fig. 3 A model of a Soil-Microbial Fuel Cell (Source: Wikipedia, 2011)

Metal-Reducing Microbial Fuel Cells use certain microbes such as *Rhodospirillum rubrum*, *Clostridium botulinum*, *C. butyricum*, *Desulfotomaculum reducens*, *Rhodobacter capsulatus* and

Thiobacillus ferrooxidans. *R. ferrireducens* in particular possess the ability to reduce Fe(III) to Fe(II) during the oxidation of glucose to carbon dioxide by the reaction



In particular, *R. ferrireducens* can simultaneously transfer generated electrons to the surface of electrodes in anaerobic conditions. Microbial fuel cells using this organism are superior to previously described cells as *R. ferrireducens* is able to grow between 4°C to 30°C (with an optimum temperature of 25°C) and can be supported with a wide range of substrates [Scholz et al, 2003]. Also, its glucose oxidation operates at 80% electron efficiency (as opposed to *Clostridium spp*, which has only 0.04% efficiency). Also complete conversion from glucose to carbon dioxide can be achieved without the production of the gluconic acid intermediate (Lee et al, 2008; Scott and Murano, 2007). *R. ferrireducens* cells also possess long term stability, providing steady electron flow over extended periods of time. The cell can also be recharged very quickly and shows low capacity losses under open circuit conditions (Lee et al, 2008; Logan et al, 2006; Rozendal et al, 2008; Scholz et al, 2003).

The sediment fuel cell is a novel microbial fuel cell in which the anode is placed in nutrient-rich marine sediments and the cathode placed in seawater above the sediment. The resulting voltage gradient is sufficient to generate power. The anodic reactions include the oxidation of sulphides found in the sediments and the oxidation of organic matter by bacteria growing onto the anode. Potential for the use of this system in marine environments abound although accessibility to marine sediments may be difficult.

Advantages of the Microbial Fuel Cell

Green Power Generation: Microbial Fuel Cells are a very clean and efficient method of energy production (Strik et al, 2008). Plant-Microbial Fuel Cells, for example, produce energy from plants without the destruction of the plant or the reduction of yield (Schamphelaire et al, 2008). Carbon dioxide produced is essentially that which was fixed by recent photosynthesis and as such the process is carbon neutral. Root exudates from plants represent a source of greenhouse gases (Jones, 2008). Rice, for example, generates 20% of all worldwide methane emissions (Schamphelaire et al, 2008) (methane is more than 20 times more powerful than carbon dioxide as a green house gas). If Plant-Microbial Fuel Cells are globally implemented, the production of this dangerous green house will be reduced while generating electricity in the rural areas where rice is cultivated.

Low temperature power generation: Unlike conventional fuel cells such as molten carbonate and alkaline fuel cells which require high temperatures of about 500-750°C to operate, the microbial fuel cell and all its variants produce energy at low temperatures ranging from 18 – 35°C (Logan et al, 2006; He et al, 2005; Scholz et al, 2003). This is because the microbes involved are unable to tolerate high temperature and metabolize optimally in that temperature range (Rozendal et al, 2008; Scholz et al, 2003). This means that the microbial fuel cell can be operated indoors or within communities and can be used as a private source of power for homes.

Renewable and Sustainable Energy Source: Microbial Fuel Cells are renewable as they tap into already existing sources of feedstock including waste water which represents an environmental concern (Ogwuleka, 2009; Rozendal et al, 2008). Plant-Microbial Fuel Cells capture solar energy which is renewable and will be available for an estimated 5.5 billion years. Soil Microbial Fuel Cells are also renewable as the organic matter content of soil is very high and decomposition of plant and animal wastes will always occur.

It can solve industrial energy concerns: One of the major problems militating against industrialization in developing countries is the lack of steady power supply (Olise and Nria-Dappa, 2009). This forces industries to run batch processes rather than the more profitable continuous process. The production of energy from industrial waste water and effluents represents energy savings which can be invested into production (Ogwuleka, 2009). Thus industries may be able to generate at least a fraction of their own energy requirements thus reducing the demand on national grid systems.

Energy production is mostly in-situ. There is no need for expensive and time-consuming transportation and conversion procedures. Also, it could be profitable for rural areas as rural areas possess the highest density of plants and rich soil while having the lowest supply of electricity. This could boost rural development and curb rural-urban migration of youths.

Efficiency

Since the root exudates or carbohydrates in waste water are essentially low molecular mass, high conversion efficiency is possible (more than 60%). This is because no heat is produced and the process is not limited by Carnot's theorem (Lee et al, 2008).

Microbial Fuel Cells can be implemented in areas that do not compete with other primary functions such as agriculture and scenery. This includes rice fields, saline soils, wetlands and recreation areas. Marginal land can also be used. Schamplelaire et al (2008) showed that the integration of microbial fuel cells into rice fields had no significant difference on yield.

Microbial Fuel Cell technology may be a lifesaver for island communities without access to desalinated (fresh) water as the water produced at the cathode can be effectively collected pure. Microbial Fuel Cell technology can be used for desalination of water with attendant production of salt as a possible income source. It can also be used for the remediation of polluted water or effluents in order to ensure disposal of safe water thus improving environmental stability.

Applications

Apart from power generation, other possible applications of the microbial fuel cell and its variants include

Education

Small scale microbial fuel cells are easy to make and can be used to illustrate soil flora and fauna. They are also used as science projects.

Biosensor

Since the current generated from a microbial fuel cell is directly proportional to the energy content of the waste water used as fuel, microbial fuel cells can be used to measure the solute concentration of waste water. The Biological Oxygen Demand (BOD) is an indicator of the strength of a waste water sample and its evaluation involves long incubation periods which does not allow for real-time analysis. Microbial Fuel Cell-type biosensor can be used to measure real time BOD values.

Desalination of Marine Water

Microbial fuel cell technology can be modified to desalinate marine water. This can be done by placing a third chamber between the anodic and cathodic chambers, separating the third chamber from the other two with ion-specific membranes that allow for the passage of either positive ions or negative ions but not the both of them in one direction. The salt water is poured into the middle chamber and as the MFC polarizes (and electrons gather on the cathodic side while protons accumulate at the anode), negative ions pass through the ion-specific membrane (which does not allow the passage of positive ions) to the anode region and vice versa. At the end of the reaction, the water left in the middle has lost both of the salt ions (Na^+ to the cathode and Cl^- to the anode) and is now salt free. Furthermore, the release of extra ions into the microbial fuel cell increases the efficiency of the MFC by countering concentration polarization (Rozendal et al, 2008). Hence, the process using salt water is more efficient than normal microbial fuel cells. This variant of the microbial fuel cell finds application in the marine industry, together with the sediment microbial fuel cell as possible low scale electricity generation techniques with the added advantage of clean and portable salt free water.

Factors Limiting Electricity Generation in Microbial Fuel Cells

Mass Transfer

The supply of sufficient substrate to the anodic bio-film and electron acceptor to the cathode surface at rates of at least the equivalent of the current generation is critical to sustain current generation (Rozendal et al, 2008). Also, the accumulation of waste products in the bio-film (oxidized intermediates or protons) needs to be prevented as the redox conditions may be altered and the metabolic activity of the bio-film hindered (Clauwert et al, 2007). A limited mass transfer of substrate or electron acceptors towards the anode or cathode can lead to concentration or mass transfer losses which are characterized by steep decrease in the voltage of the cell at near maximum current densities during polarization (Rozendal et al, 2008). For proper operation of the microbial fuel cell, both protons and electrons need to migrate freely from anode to cathode at the highest possible rates. Diffusion alone may not be sufficient to reach acceptable levels of current and cell potential. Drastic reduction in proton transport could reduce the anode pH below 5 making it uncondusive for bacterial proliferation. To solve this problem, turbulent conditions may be introduced at both electrodes by either shaking or recirculation of feedstock (Rozendal et al, 2008). However, energy is expended, reducing the overall efficiency of the system (Clauwert et al, 2008). This can reduce the performance of the microbial fuel cell. Concentration polarization can also result when compounds are being oxidized faster at the anode than they can be transported to the surface cathode and reduced.

This mostly occurs at high current densities when diffusion is seriously hampered by a thick and non-conductive biofilm.

Ohmic Losses

Ohmic losses are caused by the electrical resistance of the electrodes, the electrolyte and the proton exchange membrane. Ohmic voltage losses can be reduced by using high conductivity electrodes and membrane while reducing travel distance of the electrons within the electrode (Clauwert et al, 2008).

Activation Losses

In order to start the transfer of electrons from the electrochemical active microorganisms towards the electrode or to transfer electrodes towards a final electron acceptor, an energy barrier must be overcome, leading to voltage loss or activation overpotential characterized by initial steep decrease of cell voltage at the onset of electricity generation. Activation losses can be reduced by increasing electrode surface area, improving electrode catalysts, increasing operating temperature slightly (as microbes may die) and the establishment of enriched bio-film on the electrode.

Electron Quenching Reactions

Competing reactions such as fermentation, methanogenesis and respiration (if oxygen is present) result in a loss of electron and conversion of part of the substrate into anodophilic mass. Substrate leakages into the cathode results in electron loss as the load (and circuit) are by-passed (Mohan et al, 2007).

The use of novel catalysts (for improved oxygen reduction reaction) and electrodes is the subject of much research including that from Kim et al (2011), Scott et al (2007) and Saito et al (2011).

Conclusion

In spite of the above limitations, microbial fuel cell technology remains a viable option in the race towards global reduction of fossil fuel dependence and green energy. The challenges of obtaining improved and genetically modified strains of exo-electrogenous microbes to improve energy production and survival rates, novel fuel cell designs (to reduce activation and ohmic losses and research into novel catalysts which will improve the speed of the overall reaction are obstacles which are already being overcome via research.

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