

Technologies and potential behind microbial fuel cells

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Abstract. The development of Microbial Fuel Cell (MFC) technology has progressed greatly in the past few decades to the point where it can now be considered viable in certain industries. MFCs are cells that utilize microorganisms as catalysts to transform wastes into electrical energy, this new type of bioenergy can generate energy as well as decompose the wastes produced from industries and daily life. This article provides an overview of MFC's properties, factors influencing the performance of MFCs, recent applications and prospects of MFCs, and the advantages and weaknesses of MFCs. Biofouling and waste debris from reaction inside the cell as well as not suitable pH value will cause significant degrade in performance of MFCs, at the same time, magnetic field and environmental temperature can help improve MFCs' performance if utilized properly. Compared to other bioenergy technologies, MFCs do not need intensive heat and the cost of reaction materials is extremely low, nevertheless, the low energy output, relatively short life span, and high cost of materials building MFC itself are still barriers challenging MFCs to be widely adopted. Recently, MFCs are utilized in various areas, they are available for both electricity and hydrogen production, and they can deal with waste treatment or bioremediation at the same time. This paper aims at finding solutions to the existing problems of MFCs and exploring a wider range of areas that MFCs can be utilized.

Keywords: Microbial fuel cells, Waste treatment, water pollution, carbon nanotubes

1. Introduction

In recent decades, bioenergy has been noticed and utilized as an effective and renewable energy source, unlike other renewable energy like solar or wind energy, and one important part of bioenergy is using wastes to produce energy. This waste-to-energy process is highly concerned and quickly developed in the 21st century, especially in countries with heavy agriculture and industry. Microbial fuel cell (MFC) is one typical example of bioenergy that uses microorganisms as catalysts to convert materials in wastes to electrical energy and clean water. MFCs are not new technology since it has been raised and practiced in wastewater treatment since the 1970s. However, previous MFCs were facing the problem of low energy output, the extremely low energy output expectation made it even impossible to put MFCs into production. The most advanced technologies solved the problem of low output and allowed MFCs to become a new type of clean energy.

Environmental pollution from waste dumping has been a vital problem to most cities in developing countries, whether solid waste or wastewater are significant pollutants if not handled properly. Taking China as an example, although the pollution index of Chinese rivers is declining in recent years, it is still at a relatively high level (Industrial Added Value about 100 million China Yuan), which includes the fact that industrial areas are having 100 times more cadmium pollution than rural areas [1]. Considering this situation, if MFCs can be applied in most industrial factories in China, the water pollution problems caused by industrial wastewater will be solved much easier, and MFCs can generate energy at the same time to deal with high energy costs in factories.

Recently, MFC research attracts substantial attention from scientists, and a huge number of experiments were done about each part of MFCs, such as material, structure, and environmental influence. Consequently, articles about MFCs are mostly focusing on a certain part, performance, or materials of MFCs. Although MFCs are researched and developed extremely quickly in recent years, there are still some problems like energy output or lifespan that need to be solved. Despite these problems, MFCs have the potential to be utilized in a variety of industries, and even household waste treatment. Scientists found abundant factors that will influence MFCs' performance and new materials that can be used to construct MFC structures in order to improve efficiency. The last step needed to be researched will be how to combine these results in MFC, use materials and environmental factors to maximize the efficiency, and avoid or solve the weaknesses. Therefore, an overview of factors influencing MFCs and possible solutions to problems of MFCs is necessary.

This paper summarized the basic operating principles, functions, and material choices of each part of MFCs, factors that will influence the performance of MFC. Furthermore, this paper proposed available solutions to the existing problems of MFCs and discussed the areas that MFCs can be applied recently, as well as the future potential of MFC development.

2. Microbial fuel cells

2.1. Operating principles

The basic model of MFC is composed of a cathode, anode, microorganisms, resistance, and Proton Exchange Membrane (PEM). MFC utilizes microorganisms as bio-catalysts to catalyze reactions of wastes, microorganisms in the reaction accept the electrons released and transfer them into the anode of the cell, creating current, and generating electricity when this current flows through the resistance. This electricity production is based on Ohm's law, which is calculated as $V \text{ (voltage)} = I \text{ (current)} / R \text{ (resistance)}$, meaning when current flows through a resistance, this process creates electricity. And once electrons arrive at the cathode, they can be combined with protons from the PEM and oxygen to produce another final product, which is clean water (Fig.1).

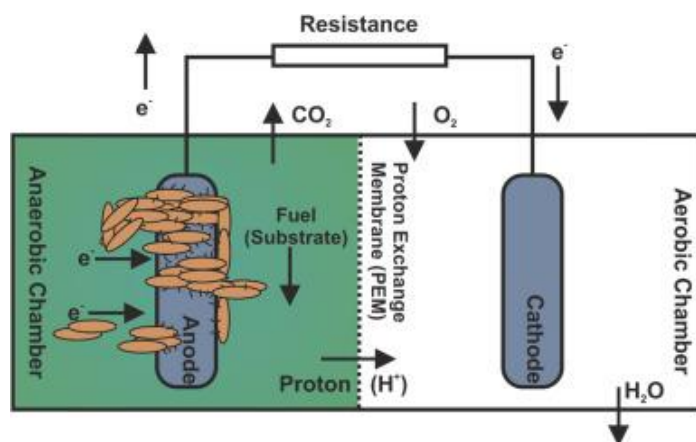


Fig 1. Operating principle of MFC [2].

2.2. Functions and common material choices of each part in MFCs

Fig. 2 shows some examples of MFCs [3]. Anodes in MFC works as an electron transporter, transporting electrons from microorganisms to the anode. Thus, the anode should be conductive, biocompatible, and chemically stable, also cannot be toxic to microorganisms. The most commonly used material is carbon and some metals that are not harmful to microorganisms [3]. And the interbody in the anaerobic chamber (anode side) solution, majorly some dye-stuff materials, is used for transporting electrons from the reaction between fuels and the microorganisms to the anode. Therefore, the interbody in MFC anodes should be able to effectively transport electrons from the reaction to the anode, they are supposed to be electrochemical active in the anode side, easy to obtain

electrons from the reaction, stable, and will not be consumed by microorganisms. Cathodes in MFCs are electrons acceptors. Oxygen is the most popular and suitable choice for aerobic chamber materials since it is cheap (free, you just need to pump it into the chamber) and sustainable (Fig.2 picture E). Hence the rate of reaction to produce water from oxygen depends on the overall effectiveness of MFCs, Pt catalysts are often used to increase the reaction rate of oxygen. PEMs serve as a barrier separating anode from the cathode, the most used PEM materials are Nafion PEMs. Nevertheless, Nafion PEMs are very sensitive to bio-pollution like ammonium, so the most suitable choice recently is Ultrex CMI-7000 PEMs.

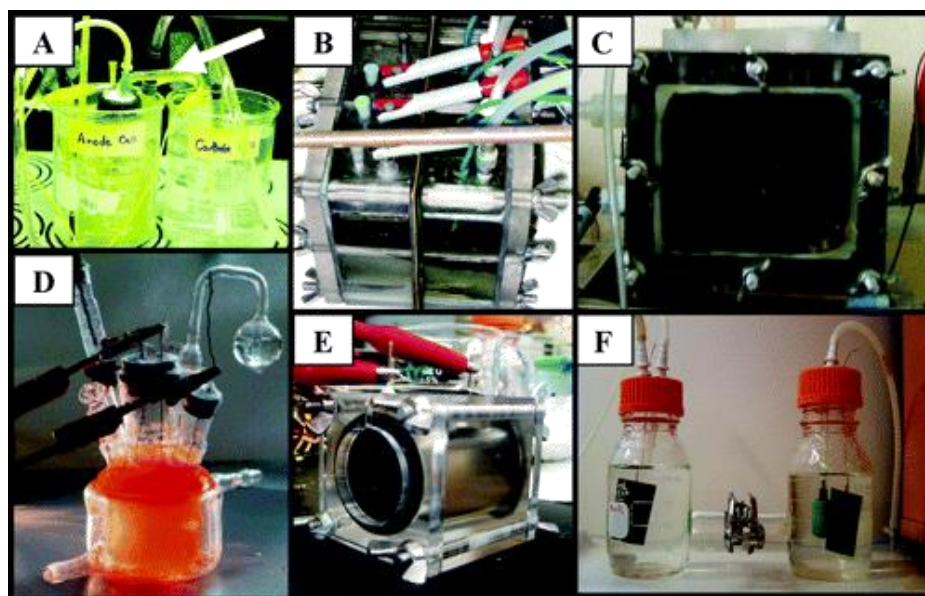


Fig 2. Some examples of MFCs [3].

3. Influence factors

There are also abundant factors limiting or promoting the performance of MFCs. Most of them are environmental factors considering the electrode and the catalysts. The major factors influencing MFCs' performance are waste debris and biofouling, magnetic field, environmental temperature, and pH.

3.1. Waste debris and biofouling

Since MFCs are mostly used in wastewater treatment, it will be easy to have some non-conductive, unreactive, and insoluble materials or debris stacking around the electrodes or microorganism community, therefore reducing the effectiveness of electron transporting or reacting activity. Biofouling is also a considerable issue since it will significantly influence the performance of PEMs, especially the Nafion membrane which is a popular choice for PEMs. Biofouling will make protons transporting much more difficult, thus increasing the electrical resistance; according to an experiment done by Choi et al., biofouled Nafion membrane shows about a 20% increase in resistance. Besides resistance, clean Nafion membrane is having a 20% better performance on both cell voltage and power density, and 8 times columbic efficiency (value that evaluates charge efficiency) than biofouled one [4].

3.2. Magnetic field

Recent studies revealed the fact that MFCs' performance is improved in magnetic fields less than 220 mT, this is because a suitable magnetic field enhances the bioelectrochemical activity. The 220 mT magnetic field with the most positive impact can improve voltage output up to about 3 times than MFCs without magnetic fields. However, MFC performance is not infinitely improving as the

magnetic field gets intenser, once the magnetic field around MFC becomes intenser than 360 mT, it will be detrimental to microorganisms' growth and performance, and thus decrease the energy output [5].

3.3. Environmental pH

MFCs operate with pH adjusted between 6.5 and 9.5, and the MFC operation shows the best performance and the maximum current generation in the environmental pH between 6.5 and 7.4 [6]. In higher pH environments the current generated will be lower and the internal resistance will be higher. Consequently, the voltage or electric energy generated will be lower in the high pH environment. And if the environmental pH is adjusted to a value lower than 6.5, the acidic solution will be harmful to the growth of most microorganisms, causing a disastrous decline of energy output and the longevity of MFCs. In these acidic environments, MFC will need acidophiles as anode microorganisms, *Acidiphilium cryptum* is a typical example of an acidophile adapted to the acidic environment [7].

3.4. Temperature

Unlike most bioenergy technologies that require high temperatures, MFCs are available even at room temperature or relatively low temperature. The Optimum temperature for an MFC operation environment will be 40-60°C, 15-35 °C, or <15°C, depending on the tolerance of microorganisms or bacteria used in the anode. Experiments done by Lobato et al. showed that changing anodic temperature within the tolerance range of bacteria will have a remarkable effect on the short-term behavior of MFCs; with higher operating temperature, the efficiency and output of MFCs are increased due to the increased microbial activity. Nonetheless, it should be noted that temperature modification can only affect the whole MFC system in the short-term, long-term behavior of MFCs will not be influenced by adjusting temperature [8].

4. Application

Current research and laboratory findings have shown that MFCs have relatively obvious advantages in real-world applications. Firstly, MFCS has higher energy transforming efficiency than other types of energy sources since MFCs directly transform substrates into electricity. Secondly, MFCs do not need an energy input to operate efficiently since only ventilation is required for providing the oxygen needed in the cathode. Apart from that, MFCs work well in normal and even low-temperature environments, making them stand out among other bio-energy technologies. With these advantages, MFCs can be widely used in a number of industries like wastewater treatment to reduce wastewater discharge and wastewater treatment costs and in cases where an energy source in a low-temperature environment is needed. When adjusted properly, MFCs can also be used for different purposes; especially in the environmental science field, MFCs have proven to be useful in bioremediation, hydrogen production, and renewable electricity production to some extent in this area.

4.1. Wastewater treatment

Wastewater from daily human activities has become an increasingly notable issue in the past century as the population has steadily increased as did average water consumption daily. This increase in wastewater production, if left untreated, can lead to environmental damages, especially in freshwater ecosystems. Currently, the most used method in wastewater treatment is the activated sludge system. This system is based on a reactor unit that uses highly concentrated microorganisms to degrade organics and remove unwanted nutrients from wastewater. However, this system has some major flaws. First, it requires a huge energy input that makes the entire treatment process very costly, both economically and environmentally. Second, it produces by-products such as carbon dioxide and nitrogen that, when released into the environment, cause further damage to ecosystems [3].

MFCs can be used as a more sustainable water recovery process in wastewater treatment. MFC technology is based on a biofilm that facilitates bioelectrochemical reactions through microbial oxidation. The oxidation process decomposes and absorbs organic matter. Meanwhile, oxidation has the chemical potential to produce electricity as well. The key benefit of using MFCs is their energy efficiency. The system requires no energy input. The only requirement is ventilation to facilitate the oxidation of bacteria. When compared to the traditional activated sludge system, MFCs can save explicit energy costs and have no impact on the environment, thus making it an appealing alternative method.

4.2. Electricity generation

MFCs also have the potential to be a renewable energy source because of their ability to convert chemical energy into electrical energy through the oxidation of complex organic carbon sources. The mechanism makes it possible for MFCs to be a clean and pollution-free power source. In a real-world study, MFCs were introduced to organic waste samples from a garbage dumping area from a wetland and showed the production of electricity [9]. In addition, the current increased as external glucose sources were added, and the bacterial colony grew in size. Towards the end of the experiment, researchers also found zero carbon dioxide emissions from the process, thus showing its sustainability.

4.3. Bioremediation

MFCs have potential in the field of bioremediation in the sense that the microbes powering the cell can break down contaminants in the environment. Bioremediation is the process in which microorganisms are used to break down pollutants in the environment. By introducing MFCs to contaminated sites, the microbes may have the potential to break down pollutants such as heavy metals, organic matter, waste, and excess materials in general. A specific real-life of MFC in bioremediation would be its use in remediating hydrocarbons in groundwater [10]. Researchers have shown MFCs are effective in remediating hydrocarbon petroleum contamination in groundwater sources. However, adjustments are needed to fit MFCs into the environment for them to function properly in a water source.

4.4. Hydrogen Production

Hydrogen is a useful fuel that can generate electricity and is used in many industries like petroleum refining and fertilizer production. By adjusting the MFC design to a MEC (Microbial electrolysis), where the device harnesses energy and protons in fermentation and combines it with an input of electricity, MFCs now have the potential to produce the hydrogen needed to power the sources mentioned above. In a case study conducted by Santoro et al, MFCs were proven useful in generating hydrogen and using iron catalysts. The experiment produced a quantifiable amount of H₂ power, showing MFCs' potential in the field [11].

5. Challenges and prospects

MFCs also have limitations, which could be the challenges that the MFCs technologies should face. Although MFCs do not need energy input, considering the usage of electrodes and PEMs materials, MFCs have a high associated cost. In addition, MFCs are having low energy output since the efficiency can be affected by a number of factors like excessive biofilm growth, catalyst inactivation, and biofouling; these factors also affect and could limit the lifespan of MFCs. Moreover, some lower-cost alternative technologies may be less difficult to promote and more easily selected in the market, which would have a certain impact on the development, testing, and promotion of MFCs as well. Apart from these challenges, it could also be seen that MFCs have relatively obvious and promising prospects, for it could be a source of clean energy, and by using the MFCs' characteristic for wastewater treatment, which could replace existing activated sludge processes to some certain extent.

Since the energy output of MFCs is largely restricted by the surface area and the conductivity of electrodes, carbon nanotubes (CNTs) will be an available choice for electrodes considering their high specific area, chemical stability, and strong conductivity [12]. With the discovery and further research on the single-walled nanotubes (SWNT) and multi-walled nanotubes (MWNT), carbon nanotubes have been noticed and developed as semiconducting material (Fig. 3). Sharma et al. compared MWNTs with traditional plain graphite as electrodes material, the result shows MWNTs performed both larger total surface area and higher maximum energy output [13].

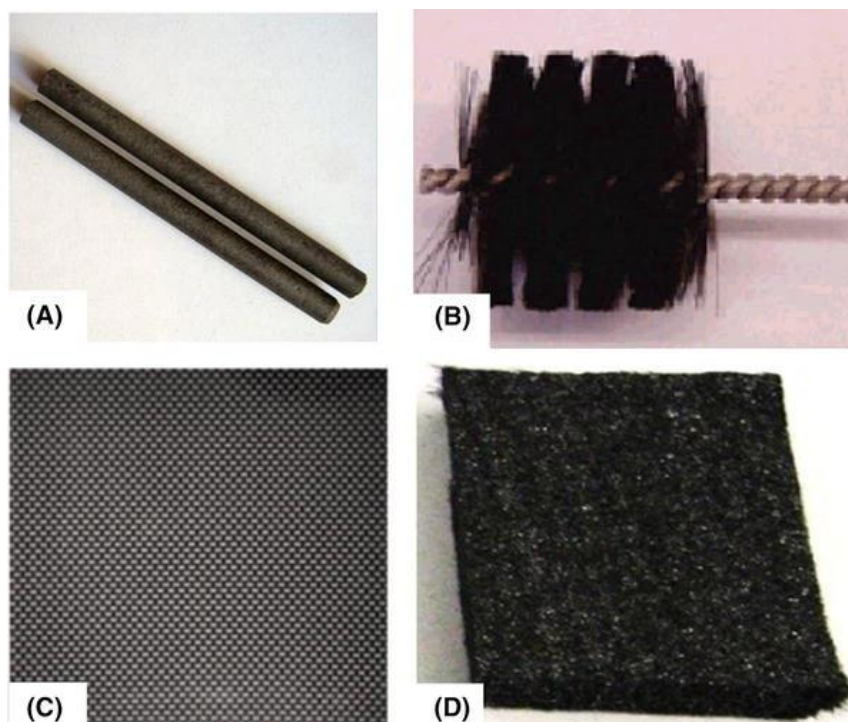


Fig 3. Carbon nanotubes examples [12].

6. Conclusion

In recent years, reducing pollution and recycling renewable resources can be regarded as the requirements of sustainable development, and gradually become one of the main measures and methods to achieve the SDGs. That is why MFCs and their related technologies receive more attention and further development. MFCs technology uses enzymes or microbial tissue as catalysts to convert the chemical energy of fuel into electricity using biomass energy. Based on the analysis of existing technology and research results, it does not emit pollution to the atmosphere and water and can decompose organic pollutants and sequester carbon, which could be considered environmentally friendly. Ulteriorly, the operation and conversion efficiency of the electrode and catalyst are fundamentally affected by chemical factors such as inert biofilm deposition, temperature, and environmental pH. In addition, considering that it is composed of biological components, the appropriate magnetic field intensity that can increase the biochemical activity is also included in the evaluation range as a catalytic factor. Moreover, MFCs in sewage treatment, new energy, biological power generation, and solid waste pollution treatment have the potential of the application. And at present, the biggest challenges it faces are scale, service life, and power generation efficiency, which would directly affect the chain economic benefits and environmental costs of its application. Hence, what we think the MFCs and their technologies need to be improved at this stage would be to reduce cost, increase production capacity, and prolong service life. Besides, the significance of this study is to systematically sort out and compare the status quo of MFCs, and as a suggestion for the wide application of MFCs and the further development trend of materials and technologies, this study is expected to elucidate and enlighten the frontier expansion of MFCs technology.

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