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Review

Biocatalysts in microbial fuel cells

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ABSTRACT

The advent behind microbial fuel cells (MFC) is to provide clean electricity from the waste organic material. The MFC produces electricity with the help of microorganisms. In the present review, the biocatalysts or microorganisms used in the MFCs are discussed. The most used microorganisms in the MFCs belong to *Shewanella*, *Proteobactor* and *Pseudomonas* families. In waste water based MFCs, mixed cultures are mostly used. This review covers the biocatalysts used in both anode and cathode. In the recent times, one of the most valuable development in the MFCs is the use of biocathodes, which eliminated various drawbacks of these cells and enhanced the power generation capabilities as well as the production of some useful gases like hydrogen. The present state of art of this technology still requires development in certain power output areas such as improvement of efficiency and cost reduction.

Contents

1. Introduction

Fuel cells need not be big to sit outside buildings or in rooms, nor need they be streamlined to fit in an automobile. They can be very small and can run on organic matter. There is presently a niche market for stationary fuel cells, about the size of a one-car garage with 300–200 kW fuel-cell power plants operating around the world. Biological waste materials may be anaerobically digested, subjected to pyrolysis, or otherwise pretreated to release hydrogen. Unfortunately, raw biobased materials cannot be thrown into a fuel cell, because they currently require preliminary processing.

1.1. Microbial fuel cells

The microbial fuel cell is a device that converts biochemical energy into electrical energy with the aid of the catalytic reaction of microorganisms [1]. Microbial fuel cells use bacteria or yeast cells as a catalyst, direct electron transport or in some cases mediators as electron shuttles and oxidizing agents as electron acceptors. The structure of the fuel cell is essentially an anode compartment with cells, with or without mediator, and an electrode separated from a cathode compartment. Membranes can be required if the anode chamber is anaerobic and the cathode uses oxygen. The cathode compartment comprises an electrode and an electron acceptor. The anode and cathode are connected via a circuit and electrons flow from the biological cells to the cathode electron acceptor because E° potentials of the active components are arranged in an ascend-

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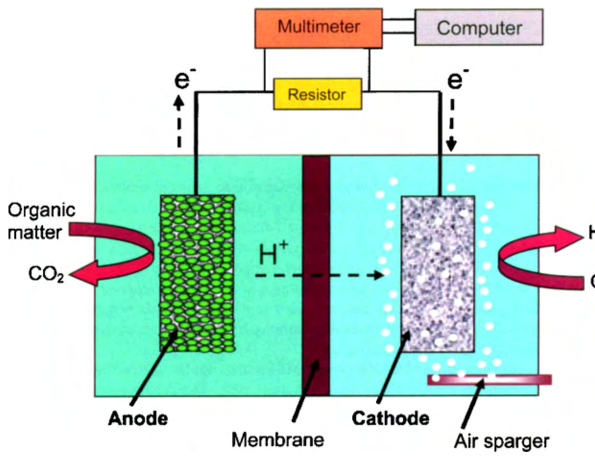

Fig. 1. Schematic of the basic components of a microbial fuel cell. The anode and cathode chambers are separated by a membrane. The bacteria grow on the anode, oxidizing organic matter and releasing electrons to the anode and protons to the solution. The cathode is sparged with air to provide dissolved oxygen for the reactions of electrons, protons and oxygen at the cathode, with a wire (and load) completing the circuit and producing power. The system is shown with a resistor used as the load for the power being generated, with the current determined based on measuring the voltage drop across the resistor using a multimeter hooked up to a data acquisition system.

Table 1
Species studied by the researchers in anode chamber.

S. no.	Species	References
1.	*E. coli*	Potter [14], Zhang et al. [15], Habermann and Pommer [22], Zou et al. [59], Park and Zeikus [60], Qiao et al. [61], Xi and Sun [62]
2.	*Shewanella oneidensis* DSP10	Ringeisen et al. [16], Biffinger et al. [18,19]
3.	*Shewanella oneidensis* MR-1	Manohar et al. [17], Biffinger et al. [18]
4.	*Shewanella putrefaciens*	Kim et al. [1], Park and Zeikus [21]
5.	*Pseudomonas aeruginosa*	Habermann and Pommer [22], Rabaey et al. [23–24]
6.	*Geobacter sulfurreducens*	Bond et al. [26], Reguera et al. [27,31], Trinh et al. [33]
7.	*Geobacteraceae*	Holmes et al. [29], Bond et al. [30]
8.	*Geobacter metallireducens*	Min et al. [32]
9.	*Dessulfobulbus propionicus*	Lovley et al. [53]
10.	*Geothrix fermentans*	Lovley et al. [54]
11.	*Paracoccus denitrificans* and *Paracoccus pantotrophus*	Rabaey et al. [55]
12.	*Rhodopseudomonas palustris* DX-1	Xing et al. [56]
13.	*Klebsiella pneumoniae*	Lewandowski et al. [57,58]

ing order. A schematic of an MFC system is shown in Fig. 1. Almost all reported microbial fuel cells employ bacteria as the catalyst and the trend is to use a consortium of organisms, often isolated from the waste stream, and then subjected to selection in the fuel-cell environment. Power produced is very low, but techniques exist to convert this to useful power levels. Very dilute organic wastes that cannot serve as substrates in other energy production systems can be used as energy source for microbial fuel cells. The microbial fuel cell not only recovers energy from dilute waste, but will also simultaneously bioremediate the waste, a process that currently requires energy input [2,3].

The MFC that utilizes mediator as electron shuttle is called mediator-based-MFC. The electron transfer from certain microbial cells to the electrode is facilitated by the help of mediators such as thionine, methylene blue, humic acid and so on [4]. Electrons are captured by the oxidized mediator and transferred to the anode. At the anode the mediator is oxidized, a process that releases electrons to the anode and returns the mediator to its reduced state. The ideal mediator has the following properties: (i) It should display reversible redox reaction to function as an electron shuttle; (ii) It should have appreciable solubility in an aqueous solution and stability; (iii) It should facilitate the electron transfer; and (iv) It should have low formal potential. The lower the formal potential, the larger the cell voltage since it is the difference between the cathode and anode potentials [5]. Up to now most study have focused on the generation of electricity by Fe(III)-reducing bacteria [1,6], glucose and starch fermenting bacteria [7], Sulfate-reducing bacteria [8] and others such as *E. coli*, *Enterobacter aerogens* and so on [4]. The detailed list of different microorganism at anode is given in Table 1.

However, there are MFCs in which mediator is excluded, known as mediatorless-MFC. In the mediatorless-MFC, electrochemically active bacteria are used to ensure high rates of fuel oxidation and electron transfer for the production of electrical energy.

2. Bacteria used in MFC

The development of processes that can use bacteria to produce electricity represents a plausible method for bioenergy production as the bacteria are self-replicating, and thus the catalysts for organic matter oxidation are self-sustaining. Bacterial reactions can be carried out over a wide range of temperatures depending on the tolerance of bacteria, ranging from moderate or room-level temperatures (15–35 °C) to both high temperatures (50–60 °C) tolerated by thermophiles [9] and low temperatures (<15 °C), where psychrophiles [10] can grow. Virtually, any biodegradable organic matter can be used in a MFC, including volatile acids, carbohydrates, proteins, alcohols, and even relatively recalcitrant materials like cellulose [11–13,2,3]. Chemical mediators or electron shuttles were routinely added to MFCs that resulted in electron transfer by bacteria and even yeast [14]. In the earliest studies by Potter [14] in 1911, the yeast *Saccharomyces cerevisae* and bacteria such as *Bacillus coli* (later classified as *Escherichia coli or E. coli*) were shown to produce a voltage, resulting in electricity generation. How that worked was not well known as there were no known mediators added to the cell suspensions, and *E. coli* [15] and yeast were not known to produce electricity at that time in the absence of mediators. Some of the bacterial species employed in MFCs are described as below.

2.1. *Shewanella species*

Shewanella putrefaciens is a Gram-negative marine bacterium. *S. putrefaciens* is also a facultative anaerobe with the ability to reduce iron and manganese metabolically; *i.e.*, it can use iron and manganese as the terminal electron acceptor in the electron transport chain (in contrast to obligate aerobes which must use oxygen for this purpose). It is also one of the organisms associated with the odor of rotting fish, as it is a marine organism which produces trimethylamines (hence, the species name *putrefaciens*, from *putrid*). In both solid and liquid media, *S. putrefaciens* is often recognizable by its bright pink color. On solid media, the colonies are round, fast-growing, and pink. The organism is also fast-growing in liquid media.

Ringeisen et al. [16] used *Shewanella oneidensis* DSP10 in growth medium with lactate and buffered ferricyanide solutions as anolyte and catholyte, respectively. Maximum power densities of 24 and 10 mW/m^2 were measured using the true surface areas of reticulated vitreous carbon (RVC) and graphite felt (GF) electrodes without the addition of exogenous mediators in the anolyte. Current densities at maximum power were measured as 44 and