Microbial fuel cells to produce electricity

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***Abstract*- Microbial fuel cell (MFC) provides a new opportunity for the sustainable production of energy in the form of direct electricity from biodegradable compounds present in the wastewater achieving the simultaneous water treatment. MFC is a device that converts chemical energy to electrical energy with the aid of the catalytic reaction of microorganism. This article provides a brief introduction to MFC along with its envisaged applications as one of the class of biological fuel cell.**

***Keywords:* Microbial Fuel cell, Electricity**

I. INTRODUCTION

The high energy intensive conventional wastewater treatment systems invites for the development of alternative treatment technology. There is a tremendous need to develop suitable and reliable technology for the treatment of wastewater. Such treatment technology should be cost effective, requiring less energy for its efficient operation and should generate less sludge. In addition, the treatment system should recover energy to make overall operation of wastewater treatment self sustainable.

Microbial fuel cell (MFC) provides new opportunity for the sustainable production of energy, in the form of direct electricity from biodegradable compounds present in the wastewater, achieving simultaneous wastewater treatment. MFC is a device that converts chemical energy to electrical energy with the aid of the catalytic reaction of microorganisms[1]. In a MFC, substrate (organic matter or biomass) is oxidized in the anode chamber producing carbon dioxide, protons and electrons[2]. Microorganisms here fulfill the role of catalysts in analogs to chemical fuel cells. The electrons and the protons produced in the anode chamber ends up at the cathode, via the external electrical circuit and through the proton exchange membrane (PEM), respectively. In the cathode, an oxidant (normally oxygen) is being reduced. Eqs. (1)–(3) illustrates the basic reactions occurring in MFCs, in the case of a sucrose fed wastewater in anode and oxygen as electron acceptor in cathode.

$$\text{Anode}: C_{12}H_{22}O_{11} + 13H_2O \rightarrow 12CO_2 + 48H^+ + 48e^- \quad (1)$$

$$\text{Cathode}: 48H^+ + 48e^- + 12O_2 \rightarrow 24H_2O \quad (2)$$

$$\text{Overall reaction}: C_{12}H_{22}O_{11} + 12O_2 \rightarrow 12CO_2 + 11H_2O$$

$$\Delta.G^\circ = -5792.2\text{kJ/mol} \quad (3)$$

Performance of a MFC is affected by the substrate conversion rate, over-potentials at the anode and at the cathode, the PEM performance, and internal resistance of the cell[2]. The optimization of MFCs requires extensive exploration of the operating parameters that affect the power output.

All the literature review supports performance of MFC under controlled conditions using different cultures. Enough attention has not been paid so far on evaluating performance of MFC exposed to changes in operating temperature and pH, which are among the important aspects for field application of the MFCs.

After a brief outline of the long and winding history of biological fuel cells, this article deals with the operating principles of Microbial fuel cells and their technological applications.

II. HISTORY OF BIOLOGICAL FUEL CELLS

For centuries, microorganisms, which transform food into an electron flow, were only a biological curiosity; but now scientists have made it possible to use them in watches and cameras as power sources[3]. Luigi Galvani, who noticed twitching of isolated frog leg when a brief electrical discharge was passed through it[4], was the first to observe the bioelectric phenomenon as early as in 1790 and the term bioelectricity was coined after that observation. In 1910, Michael Cresse Potter, a professor of botany at the University of Durham, UK,

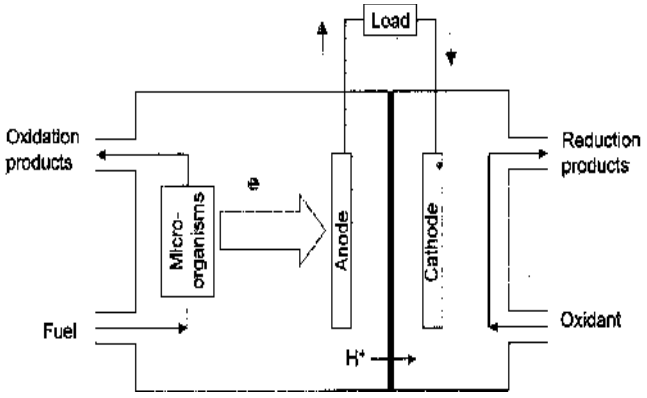


Figure1. A typical biological fuel cell representing current generation with the help of microorganisms. The fuel generated by microbial metabolism gets oxidized at the anode and usually oxygen is reduced at the cathode.

demonstrated that organisms could generate a voltage and deliver current. Cohen at Cambridge revived Potter's idea in 1931. He described how a batch of biological fuel cells produced more than 35 V. But biological fuel cells became popular in the 1960s, when the National Aeronautics and Space Administration evinced interest in turning organic waste into electricity on its long-haul space flights. Algae and bacteria were among the first organisms used in biological fuel cells. During the mid 19th century, for the first time, Rohrback *et al*[5] designed a biological fuel cell in which *Clostridium butyricum* was used as a biological material to generate hydrogen by

glucose fermentation. In 1963, biological fuel cells were already commercially available for use as a power source in radios, signal lights and other appliances at sea. However, these fuel cells were not a commercial success and soon disappeared from the market. With the successful development of technical alternatives, e.g. solar photovoltaics for the energy supply on space flights, biological fuel cells suffered a short setback. Later, during the oil crisis of the 70s and 80s, the interest in the development of biological fuel cells was revived. In 1966, Williams[6] showed that biological fuel cells powered by rice husk produced 40 mA at 6 V. Rice husk is a potential source of lignocellulose, which on fermentation yields many useful enzymes and biofuels like ethanol that could be used in biological fuel cells. In 1969, Yao *et al.*[7] showed that glucose could be used as a fuel in the presence of platinum-black. Later, Karube *et al*[8] reported the generation of about 300 mA electric current from an *Anabaena* spp.-based biological fuel cell, in which phosphoric acid was used as the electrolyte. Bennetto and co-workers have made noteworthy contributions to biological fuel cells. They have developed and demonstrated improved biological fuel cells using various microorganisms and mediator systems. They showed that the mediators could enhance both the efficiency of electron-transfer and the reaction rate. Recently, Chaudhuri and Lovely[9] have reported that a microorganism *R. ferrireducens* can recover an electron from glucose oxidation in the presence of Fe^{3+} up to 83% without a mediator. Presently, efforts are being expended to improve the performance of mediator-less biological fuel cells as well as on finding an effective route to wire the microorganism to the electrode so as to promote the efficiency of electron-transfer.

III. *Microbial fuel cells*

The use of microorganisms in biological fuel cells eliminates the isolation of individual enzymes, thereby providing cheaper substrates for biological fuel cells. Microorganisms can be used in four ways for producing electrical energy:

(i) Microorganisms can produce electrochemically active substances through fermentation or metabolism. For the purpose of energy generation, fuels are produced in separate reactors and transported to the anode of a conventional fuel cell. Accordingly, in this configuration, the microbial bioreactor is kept separated from the fuel cell.

(ii) In the second configuration, the microbiological fermentation process proceeds directly in the anodic compartment of the fuel cell.

(iii) In the third configuration, electron-transfer mediators shuttle electrons between the microbial biocatalytic system and the electrode. The mediator molecules accept electrons from the biological electron transport chain of the microorganisms and transport them to the anode of the biological fuel cell.

(iv) In the fourth configuration, the metal-reducing bacterium having cytochromes in its outer membrane and the ability to communicate electrically with the electrode surface directly result in a mediator-less biological fuel cell.

A brief description of the aforesaid configurations is given below:

Microbial-systems producing hydrogen as fuel for conventional fuel cells: Various bacteria and algae, e.g. *Escherichia coli, Enterobacter* aero-genes, *C. butyricum, Clostridium acetobutylicum* and *Clostridium perfringens,* are known to be active for hydrogen production under anaerobic condition[10, 11]. The most effective hydrogen-producing microorganism is *C. butyricum*[12]. *E. coli* and *Enterobacter* aero-genes are facultative anaerobes and ferment both glucose and lactose as a carbon source to produce hydrogen.

The conversion of carbohydrate to hydrogen is achieved by a multienzyme system. In bacteria, it involves the conversion of glucose to 2 mol of NADH, a reduced form of coenzyme 1, namely -nicotinamide adenine dinucleotide of the vitamin niacin, and 2 mol of pyruvate formed by Embden–Meyerhof pathway. Pyruvate is then oxidized through a pyruvate–ferredoxin oxidoreductase producing acetyl-CoA, CO_2 and reduced ferredoxin. NADH–ferredoxin oxidoreductase oxidizes NADH and reduces ferredoxin. The reduced ferredoxin is reoxidized to form hydrogen by hydrogenase. As a result, 4 mol of H_2 are produced from 1 mol of glucose under ideal conditions as shown below. In practice, however, H_2 yield is only about 25% of the theoretical value[13]. Improvement in H_2 production is possible by genetic engineering techniques and screening of new hydrogen-producing baceria.

$$\text{Glucose} + 2\text{NAD}^+ \xrightarrow[\text{Embden–Meyerhof pathway}]{\text{Multienzyme}} 2\ \text{Pyruvate} + 2\text{NADH}. \quad (4)$$

$$\text{Pyruvate} + \text{Ferredoxin}_{ox} \xrightarrow[\text{Oxidoreductase}]{\text{Pyruvate–ferredoxin}} \text{Acetyl-CoA} + CO_2 + \text{Ferredoxin}_{red}. \quad (5)$$

$$\text{NADH} + \text{Ferredoxin}_{ox} \xrightarrow[\text{Oxidoreductase}]{\text{NADH–Ferredoxin}} \text{NAD}^+ + \text{Ferredoxin}_{red}. \quad (6)$$

$$\text{Ferredoxin}_{red} + 2H^+ + 2e^- \xrightarrow{\text{Hydrogenase}} \text{Ferredoxin}_{ox} + H_2. \quad (7)$$

$$H_2 \rightarrow 2H^+ + 2e^- \text{ (at anode)}. \quad (8)$$

A H_2/O_2 fuel cell comprising a platinum-black–nickel mesh anode and a palladium-black–nickel mesh cathode, and separated by a nylon filter operating at room temperature was connected to a bioreactor producing hydrogen[14,15]. The current and voltage output were dependent on the rate of hydrogen production in the fermenter. For example, an open-circuit voltage (V_{oc}) of 0.95 V and a short-circuit current density (i_{sc}) of 40 mA/cm^2 were obtained at a H_2 flow of 40 ml/min. The biological fuel cell operating under steady-state conditions for a week produced a continuous current between 500 and 550 mA.

The immobilization of the biocatalyst is primarily important in a bioreactor. In the biological fuel cell configuration described above, the immobilization of hydrogen-producing bacteria, *C. butyricum* is of great value as this stabilizes the relatively unstable hydrogenase system. The immobilization steps could be the trapping of microorganisms into polymeric matrices of polyacrylamide, agar gel or filter paper. The immobilized microbial cells continuously produced H_2 under anaerobic conditions for several weeks, whereas non-immobilized bacterial cells were fully deactivated in less than two days.

Microbial systems producing electrochemically active metabolites in the anodic compartment of biological fuel cells: In this configuration, the fermentation process is conducted directly at the electrode surface supplying the anode with H_2 fuel. Additional by-products of the fermentation process, namely formic acid, acetic acid and lactic acid are also utilized as fuels[16]. Besides, the base substrate glucose used for the fermentation process, byproducts could as well contribute to the anodic current. Hence, H_2 provided by the microorganisms can be a source of anodic current as indicated by the side reactions below.

$$\text{Pyruvate} \xrightarrow{\text{Pyruvate–formate lyase}} \text{Formate.} \quad (9)$$

$$HCOO^- \rightarrow CO_2 + H^+ + 2e^- \text{ (to anode).} \quad (10)$$

$$H_2 \rightarrow 2H^+ + 2e^- \text{ (at anode).} \quad (11)$$

In addition to fuels like H_2, formic acid, lactic acid and sulphur-containing electrochemically active metabolites like S^{2-} species, can be produced during the fermentation of lactate by *Desulfovibrio desulfuricans*, which are known to be sulphate-reducing bacteria, shown as follows.

$$\text{Lactate} + SO_4^{2-} + 8H^+ \xrightarrow{\text{Bacteria}} S^{2-} + 4H_2O + \text{Pyruvate.} \quad (12)$$

$$S^{2-} + 4H_2O \rightarrow SO_4^{2-} + 8H^+ + 8e^- \text{ (to anode).} \quad (13)$$

$$2S^{2-} + 3H_2O \rightarrow S_2O_3^{2-} + 6H^+ + 8e^- \text{ (to anode).} \quad (14)$$

The presence of sulphides in the medium results in the inhibition of the metabolic bacterial processes because of their interaction with iron-containing proteins, e.g. cytochromes, causing the electron transport systems to be blocked. S_2^- species poison many metallic electrodes because of their strong and irreversible adsorption. In a typical experiment, porous graphite electrode impregnated with cobalt hydroxide as catalyst was used as the anode. Cobalt hydroxide undergoes transition into a highly catalytically active cobalt oxide/cobalt sulphide mixture. A biological fuel cell has been constructed with the above biocatalytic anode along with a graphite cathode activated with iron(II) phthalocyanins and vanadium(V) compounds. The anode and cathode are separated to maintain anaerobic conditions at the anode compartment. The poor performance of fuel cells arising due to the adsorption of by-products on the electrode surface is improved by an electrode modification process. The microorganisms processing glucose in a tank of the fermentation fluid are continuously pumped through a separate anode space. This is separated from the cathode space by a semi-permeable membrane. These bio-fuel cells have a new type of anode where a platinum electrode or a platinized graphite electrode is coated with a layer of the electrically conducting polyaniline, which is both biocompatible and electro-catalytically active. It absorbs electrons from the metabolism of the bacteria and transfers them to the anode. In this way, it plays a decisive role in current flow. During operation, the bacterial metabolic products along with the by-products of the electro-catalytic oxidation process settle on an uncoated anode and rapidly deactivate it. The polymer slows down this process considerably. Additional regular voltage pulses chemically convert the deposit and release them from the anode surface. This fuel cell continuously provides up to 1.5 mA/cm^2 of current[17]

Mediator-coupled microbial fuel cells: Reductive species generated by metabolic processes inside microbial cells are isolated by a microbial membrane. Thus, the contact of the microbial cells with an electrode usually results in only a diminutive electron-transfer across the membrane of the microbes[18], except in some special cases as described later. The electro-active groups responsible for the redox activity of enzymes present in the microbial cells are deeply buried inside their prosthetic groups, which leads to poor electrical communication between the cells and the electrode surface. The cells can, however, be wired to the electrode surface with the help of mediators. Low molecular weight redox species may assist the shuttling of electrons between the intracellular bacterial space and an electrode, and are referred to as mediators. The working principle of these mediators is shown schematically in Figure 2.

The mediator molecules should meet the following requirements[19]:

(i) The oxidized mediator should easily penetrate through the bacterial membrane to reach the reductive species inside the bacteria.

(ii) The redox potential of the mediator should match the

potential of the reductive metabolite.

(iii) None of the oxidation states of the mediator should interfere with other metabolic processes.

(iv) The reduced mediator should easily escape from the cell through the bacterial membrane.

(v) Both the oxidized and reduced states of the mediator should be chemically stable in the electrolyte solution, should be easily soluble, and should not adsorb on the bacterial cells or electrode surface.

(vi) The electrochemical kinetics of the oxidation process for the mediator-reduced state at the electrode should be fast.

A variety of organic compounds have been studied in combination with bacteria to test the electron-transfer efficiency of the mediator between the microorganism and anode surface.

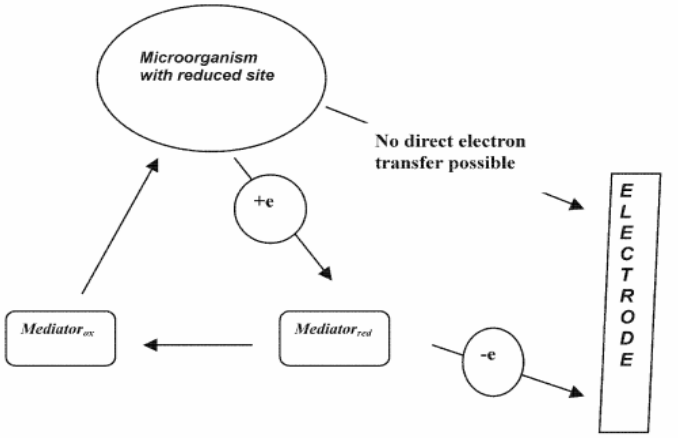


Figure 2. Working principle of redox mediators.

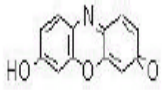
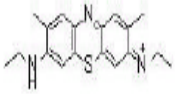
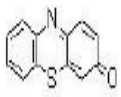
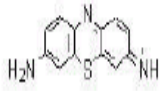
Thionine and organic dyes[20] have been frequently used as mediators in biological fuel cells. Redox potentials and structures of some of the electron relays (mediators) are summarized in Table 1. The overall efficiency of the electron-transfer mediators depends on many parameters, particularly on the electrochemical rate-constant of mediator re-oxidation, which depends on the electrode materials[21]. It is difficult to realize the perfect conditions for electron transport from a bacterial cell to an electrode. A mixture of two mediators can be useful in optimizing the efficiency. Two mediators, namely thionine and Fe(III) EDTA, are employed with the biocatalyst *E. coli* for the oxidation of glucose[22]. It was found that thionine is reduced over 100 times faster than Fe(III) EDTA. But the electrochemical oxidation of thionine is much slower than the oxidation of Fe(II) EDTA. Therefore, electrons obtained from the biocatalysed oxidation of glucose are transferred mainly to thionine. The reduced thionine is rapidly reoxidized by Fe(III) EDTA. The reduced Fe(II) EDTA transfers the electrons to the anode, and is kinetically fast.

Another example of a mixture of mediators promoting electron-transfer across the anode is demonstrated with the help of methyl viologen and 2-hydroxy-1,4-napthoquinone in the case of bioelectrocatalysed oxidation of glucose in the presence of *E. coli* immobilized on graphite particles. Table 2 summarizes the characteristics of biological fuel cells containing mediators.[23]

The electrodes should be designed so as to facilitate electrical contact between a biocatalytic system and an anode, and to improve the cell output. The mediators can be coupled to the microorganisms in three ways[1] (Figure 3): (i) as diffusional mediator shuttling between the microbial suspension and the anode surface, (ii) a diffusional mediator shuttling between the anode and microbial cells covalently linked to the electrode. The microbial cells can be covalently linked to the electrode surface having –COOH groups through amino groups of the microbial membrane resulting in the formation of amide bond. Standard organic reagents like carbodiimide and acetyl chloride are used to link the microbial cells to the surface, and (iii) mediator adsorbed on the microbial cells providing electron transport from the cells to the anode.

Mediator-less microbial fuel cells[23]*:* Fe(III)-reducing microorganisms are found to be electrochemically active as they have cytochromes in their outer membranes. It was first demonstrated with the Fe(III) reducers, *Shewanella putrefaciens*, that these can be used as a catalyst in a mediator-less microbial fuel cell. Recent studies have demonstrated that Fe(III) reducing microorganisms of the family Geobacteraceae can directly transfer electrons on to electrodes. However, the range of electron donors that these organisms can use is limited to simple organic acids such as acetate.

Table 1. Redox potential with structural formula of mediators used

Redox relay	Structural formula	Redox potential V (vs NHE)	Rate of reduction μmol (g dry wt)$^{-1}$s^{-1}*
Resorufin		–0.051	0.61
New methylene blue		0.021	0.20
Phenothiazinone		1.43	0.130
Thionine		0.064	7.10

*The dye reduction by *Proteus vulgaris* at 30°C, with 50 mM dye and 0.10–0.15 mg (dry wt) ml^{-1} microbial cells.

Table 2. Examples of microbial-based biological fuel cells utilizing electron relays for coupling of intracellular electron-transfer processes with electrochemical reactions at the anode[76,a]

Microorganism	Nutritional substrate	Mediator	Cell voltage	Current or current density	Anode[c]
Pseudomonas methanica	CH_4	1-Naphthol-2-sulphonate indo-2,6-dichloro-phenol	05–06 V (oc)[d]	2.8 μA cm^{-2} (at 0.35 V)	Pt-black 12.6 cm^2
Escherichia coli	Glucose	Methylene blue	0.625 V (oc)	–	Pt, 390 cm^2
Proteus vulgaris *Bacillus subtilis* *E. coli*	Glucose	Thionine	0.64 V (oc)	0.8 mA (at 560 Ω)	Reticulated vitreous carbon 800 cm^2
P vulgaris	Glucose	Thionine	350 mV (at 100 Ω)[b]	3.5 mA (at 100 Ω)	Reticulated vitreous carbon 800 cm^2
P. vulgaris	Sucrose	Thionine	350 mV (at 100 Ω)[b]	350 mA (at 100 Ω)	Carbon
E. coli	Glucose	Thionine	390 mV (at 560 Ω)[b]	0.7 mA (at 560 Ω)	–
Lactobacillus plantarum *Streptococcus lactis*	Glucose	Fe(III) EDTA	0.2 V (oc)	90 μA (at 560 Ω)[b]	–
Erwinia dissolvens	Glucose	Fe(III) EDTA	0.5 V (oc)	0.7 mA (at 560 Ω)[b]	–
P. vulgaris	Glucose	2-Hydroxy-1,4-naphthoquinone	0.75 V (oc)	0.45 mA (at 1 kΩ)	Graphite felt 1 g (0.47 m^2 g^{-1})
E. coli	Acetate	Neutral red	0.25 V (oc)	1.4 μA cm^{-2} (sc)[e]	Graphite 100 cm^2
E. coli	Glucose	Neutral red	0.85 V (oc)	17.7 mA (sc)	Graphite felt 12 g (0.47 m^2 g^{-1})
E. coli	Glucose	2-Hydroxy-1,4-naphthoquinone	0.53 V (at 10 kΩ)	0.18 mA cm^{-2} (sc)	Glassy carbon 12.5 cm^2

[a]In most of the studies, the biological anode was conjugated with an O_2-cathode; [b]Value calculated from other data using Ohm's law; [c]Anode surface is given as a geometrical surface; [d]Open-circuit measurement; [e]Short-circuit measurement.

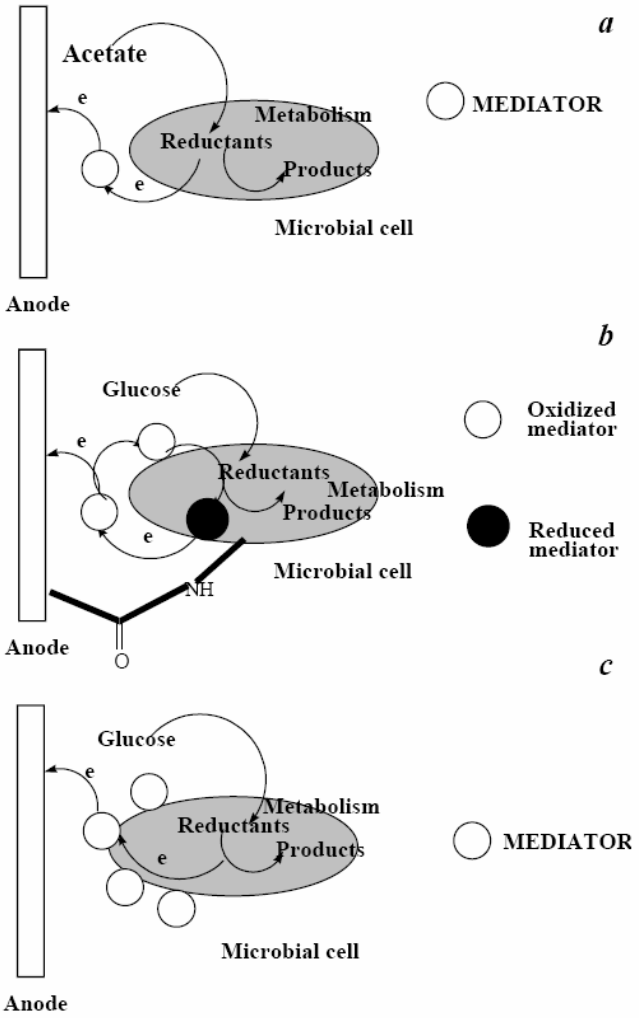


Figure 3. Various modes of attachment of mediators: ***a***, Mediator and microorganisms are present in the solution phase; ***b***, Microorganisms are covalently attached to the electrode surface; ***c***, mediators are covalently linked to the outer membrane of microorganisms.

Metal-reducing bacteria are the most used species in this type of fuel cells. Studies have been conducted to understand the mechanism of Fe(III) reduction by bacteria such as *Shewanella putrefaciens* and *Geobacter metallireduce*. Development of mediator-less microbial fuel cells using *Shewanella putrefaciens* IR-1 has been reported by Kim *et al.*[48]. In these fuel cells, the electrochemical activity of the microorganism has been confirmed by cyclic voltammetry when grown under anaerobic conditions, although no activity was found when they were grown under aerobic conditions. A gradual decrease in both coulombic yield and maximum current values was observed during the sequential batch operation of microbial fuel cells. Recently, there is a report on the bacteria, *Rhodoferax ferrireducens* that can be used in microbial fuel cells effectively without a mediator[22]. *R. ferrireducens* was isolated from anoxic sub-surface sediments of Oyster Bay, Virginia, USA as a dissimilatory Fe(III) reducing microorganism. *R. ferrireducens* grows on glucose in the presence of Fe(III). The stoichiometry of glucose utilization and Fe(III) reduction can be explained as below.

$$C_6H_{12}O_6 + 6H_2O + 24Fe(III) \rightarrow 6CO_2 + 24Fe(II) + 24H^+ + 24e^-. \quad (15)$$

The performance was tested in a system that comprised a reactor containing an anaerobically growing suspension of *E. coli* K12 in a standard glucose medium (55 mM glucose) and the fuel cell consisting of an anode compartment through which the bacterial medium was pumped. The cathode was woven graphite and the catholyte was a 50 mM ferricyanide solution in a phosphate buffer, akin to the buffer in a bacterial medium.

The recovery of electrons from glucose oxidation is 83% of the theoretical value available from glucose oxidation. Microbial growth is supported by energy derived from the electron-transfer process itself and results in a stable, long-term power production. This type of microbial fuel cell exhibits many of the desirable features of secondary batteries, including the ability to be recharged to the nearly original charged state subsequent to the discharge, the ability to accept fast recharge, reasonable cycle-life and low capacity-loss under open-circuit conditions as well as on prolonged storage under idle conditions. Thus, mediator-less fuel cells have an advantage over those with mediators in terms of cost as well as non-desirability of toxic mediators. In mediator-less fuel cells, there is also ample room to increase the efficiency of electron-transfer.

Comparision Between Chemical fuel cell and biological fuel cell.

	Chemical fuel cell	Biological fuel cell
Catalyst	Noble metals	Microorganism/enzyme
pH	Acidic solution (pH < 1)	Neutral solution (pH 7.0–9.0)
Temperature (°C)	Over 80	Room temperature, 22–25
Electrolyte	Phosphoric acid, sulphuric acid, etc.	Phosphate solution
Efficiency (%)	40–60	Around 40
Voltage (V)	≈ 1	≈ 1
Fuel type	Methanol, H_2, etc.	Any carbohydrate or hydrocarbon

III. Applications of biological fuel cells [23]

In about 200 years from now, vehicles will not have petrol tanks because our petroleum reserves will be depleted. An alternative, which is less wasteful and cleaner, is to power

vehicles directly with carbohydrates using biological fuel cells. The energy liberated during the complete oxidation of a monosaccharide like glucose or a disaccharide such as sucrose to carbon dioxide and water is about 16 x 10^6 J/kg, which is about 5 kWh of electrical energy and is just less than half the energy that can be obtained from equivalent amounts of fuels such as octane. But the efficiency of burning carbohydrate in biological fuel cells is potentially greater than burning gasoline. For example, a medium-sized car that needs about 200 Wh/km, could travel 25–30 km on one kilogram of a concentrated solution of a carbohydrate. Accordingly, 50 l of a strong sugar solution would give the car a range of more than 1000 km.

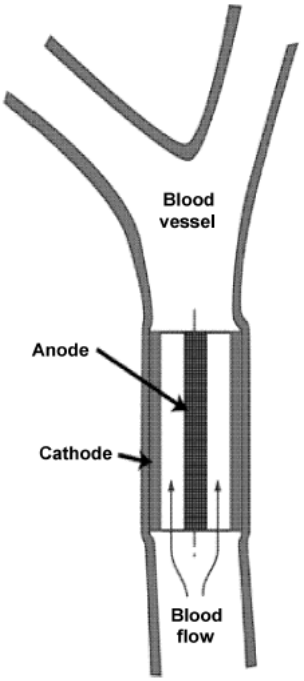


Figure 9. A biological fuel cell directly attached to the blood vessel (from Haselkorn[72]).

A biological fuel cell that is just 0.07 cm^2 in area, has been designed to generate as much as 300 tV for 2 h, an amount sufficient to operate tiny devices, including microscopic drug-delivery systems. Such a microbial fuel cell could power implantable medical devices as shown in Figure 9 and could help individuals who require regular doses of drugs, for example, AIDS patients. Apart from its small size, the system is unique because it utilizes glucose, a sugar present in the blood stream, as fuel. Such miniaturization has become possible due to the advent of BIOMEMS (Bio-micro electromechanical systems). Since biological fuel cells are known to supply low but stable power density, they are suitable for running devices constructed using MEMS technology. It has been shown by researchers at the University of California that a miniaturized microbial fuel cell could be integrated with MEMS based implantable medical devices. In comparison to lithium batteries as power sources for implantable devices, microbial fuel cells are smaller, less expensive and have a longer shelf-life.

A mobile robot platform has been built that derives its propulsive power from the digestion of real food in a bioreactor. This robot called 'Gastrobot' used harmless yeast and adopted a gas propulsion system without an electrical generation. When a carbohydrate-rich aqueous solution is mixed with yeast in a reaction chamber, fermentation takes place with liberation of carbon dioxide and it leads to substantial pressure build-up when constrained. Energy available in this pressurized CO_2 gas is used to propel the Gastrobot, which is achieved purely by mechanical means.

A Slugbot (from www.robotics.usc.edu).

'Slugbot' is a robot that utilizes the electrical power produced from biomass (Figure 10). Slugs are common pests found on agricultural land in the UK, where farmers spend about £20 million per annum on buying and spreading molluscicides. Slugbot ferments slug mass and converts it into electrical energy, which it uses to catch the slugs in the field. Stuart Wilkinson at the University of South Florida, who is currently interested in the development of hybrid biological fuel cells, has developed a meat-eating robot 'Chew Chew', which is powered by a microbial fuel cell and uses meat as a fuel. This has three wagons, each about a metre long. These robots could even kill human beings accidentally. One could construct molecular biological cells, which could deliver electrical energy to remove tumours and cancerous cells, and could act as drug-delivery systems.

Another important application of microbial fuel cells is in the field of waste water engineering. Microorganisms can discharge the dual duty of degrading effluent and generating power. When microorganisms oxidize organic compounds present in waste water, electrons are released yielding a steady source of electrical current. If power generation in these systems can be increased, microbial fuel cells may provide a new method to offset operating costs of waste water treatment plant, making advanced waste water treatment more affordable in both developing and industrialized nations. Different designs of fuel cell reactors based on chemical engineering principles like fluidized bed reactors, packed bed reactors, etc. are under trial. Tests have been conducted using single chamber microbial fuel cell (SCMFC) containing eight graphite electrodes as anodes and a single air cathode. The system was operated under

continuous-flow conditions with waste water. The prototype SCMFC reactor generated an electric power of 26 mW/m^2, while removing up to 80% of chemical oxygen demand of the waste water.[23]

Conclusions

The main challenge is in the electrical coupling of the biological component of the system with the electrodes of the fuel cells. By tapping the complete multi-enzyme metabolic pathways inside living cells, microbial fuel cells could last long and could utilize complex biofuels. A detailed characterization of the interfacial electron-transfer rates, biocatalytic rate constants and cell resistance is essential for the construction of microbial fuel cells. Although microbial fuel cells are in their infancy, the prospects of their applications look attractive.

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