

Microbial Fuel Cells: Methodology and Technology[†]

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Microbial fuel cell (MFC) research is a rapidly evolving field that lacks established terminology and methods for the analysis of system performance. This makes it difficult for researchers to compare devices on an equivalent basis. The construction and analysis of MFCs requires knowledge of different scientific and engineering fields, ranging from microbiology and electrochemistry to materials and environmental engineering. Describing MFC systems therefore involves an understanding of these different scientific and engineering principles. In this paper, we provide a review of the different materials and methods used to construct MFCs, techniques used to analyze system performance, and recommendations on what information to include in MFC studies and the most useful ways to present results.

Introduction

Microbial fuel cells (MFCs) are devices that use bacteria as the catalysts to oxidize organic and inorganic matter and generate current (1–5). Electrons produced by the bacteria from these substrates are transferred to the anode (negative terminal) and flow to the cathode (positive terminal) linked by a conductive material containing a resistor, or operated under a load (i.e., producing electricity that runs a device) (Figure 1). By convention, a positive current flows from the positive to the negative terminal, a direction opposite to that of electron flow. The device must be capable of having the substrate oxidized at the anode replenished, either continuously or intermittently; otherwise, the system is considered to be a biobattery. Electrons can be transferred to the anode by electron mediators or shuttles (6, 7), by direct membrane associated electron transfer (8), or by so-called nanowires (9–11) produced by the bacteria, or perhaps by other as yet undiscovered means. Chemical mediators, such as neutral

red or anthraquinone-2,6-disulfonate (AQDS), can be added to the system to allow electricity production by bacteria unable to otherwise use the electrode (12, 13). If no exogenous mediators are added to the system, the MFC is classified as a “mediator-less” MFC even though the mechanism of electron transfer may not be known (14).

In most MFCs the electrons that reach the cathode combine with protons that diffuse from the anode through a separator and oxygen provided from air; the resulting product is water (12, 15–17). Chemical oxidizers, such as ferricyanide or Mn (IV), can also be used although these must be replaced or regenerated (6, 18–20). In the case of metal ions, such as Mn that are reduced from Mn (IV) to Mn (II), bacteria can help to catalyze the reoxidation of the metal using dissolved oxygen (19, 20).

Microbially catalyzed electron liberation at the anode and subsequent electron consumption at the cathode, when both processes are sustainable, are the defining characteristics of an MFC. Using a sacrificial anode consisting of a slab of Mg alloy (20) does not, for example, qualify the system as an MFC as no bacteria are needed for catalyzing the oxidation of the fuel. Systems that use enzymes or catalysts not directly produced in situ by the bacteria in a sustainable manner are considered here as enzymatic biofuel cells and are well reviewed elsewhere (21).

MFCs operated using mixed cultures currently achieve substantially greater power densities than those with pure cultures (6, 7). In one recent test, however, an MFC showed high power generation using a pure culture, but the same device was not tested using acclimated mixed cultures and the cells were grown externally to the device (22). Community analysis of the microorganisms that exist in MFCs has so far revealed a great diversity in composition (6, 12, 23–25). We believe, based on existing data, and new data from our individual laboratories, that many new types of bacteria will be discovered that are capable of anodophilic electron transfer (electron transfer to an anode) or even interspecies electron transfer (electrons transferred between bacteria in any form).

MFCs are being constructed using a variety of materials, and in an ever increasing diversity of configurations. These systems are operated under a range of conditions that include differences in temperature, pH, electron acceptor, electrode surface areas, reactor size, and operation time. Potentials

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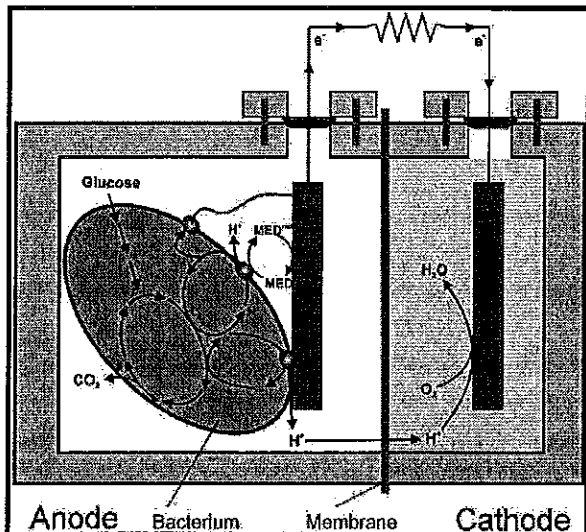


FIGURE 1. Operating principles of a MFC (not to scale). A bacterium in the anode compartment transfers electrons obtained from an electron donor (glucose) to the anode electrode. This occurs either through direct contact, nanowires, or mobile electron shuttles (small spheres represent the final membrane associated shuttle). During electron production protons are also produced in excess. These protons migrate through the cation exchange membrane (CEM) into the cathode chamber. The electrons flow from the anode through an external resistance (or load) to the cathode where they react with the final electron acceptor (oxygen) and protons (26).

are reported with different reference states, and sometimes only under a single load (resistor). The range of conditions, and in some cases a lack of important data like the internal resistance or power densities derived from polarization curves taken using different methods, has made it difficult to interpret and compare results among these systems (26). The variation in reported data has created a need to clarify methods of data collection and reporting. We have individually received many requests from researchers for details on construction of MFCs and for names of providers of materials

and equipment, indicating there is a need in the literature for a paper that provides a more comprehensive source of this information. In this paper, we therefore review existing types of MFCs, provide information on construction materials and give examples of manufacturers (although this should not be considered an endorsement of a particular company), and describe methods of data analysis and reporting in order to provide information to researchers interested in duplicating or advancing MFCs technologies. Additional information is available on the microbial fuel cell website (www.microbialfuelcell.org).

MFC Designs

Many different configurations are possible for MFCs (Figures 2 and 3). A widely used and inexpensive design is a two-chamber MFC built in a traditional "H" shape, consisting usually of two bottles connected by a tube containing a separator which is usually a cation exchange membrane (CEM) such as Nafion (12, 13, 23, 27) or Ultrex (18), or a plain salt bridge (27) (Figure 2a, f). The key to this design is to choose a membrane that allows protons to pass between the chambers (the CEM is also called a proton exchange membrane, PEM), but optimally not the substrate or electron acceptor in the cathode chamber (typically oxygen). In the H-configuration, the membrane is clamped in the middle of the tubes connecting the bottle (Figure 2f). However, the tube itself is not needed. As long as the two chambers are kept separated, they can be pressed up onto either side of the membrane and clamped together to form a large surface (Figure 2b). An inexpensive way to join the bottles is to use a glass tube that is heated and bent into a U-shape, filled with agar and salt (to serve the same function as a cation exchange membrane), and inserted through the lid of each bottle (Figure 2a). The salt bridge MFC, however, produces little power due to the high internal resistance observed.

H-shape systems are acceptable for basic parameter research, such as examining power production using new materials, or types of microbial communities that arise during the degradation of specific compounds, but they typically produce low power densities. The amount of power that is generated in these systems is affected by the surface area of

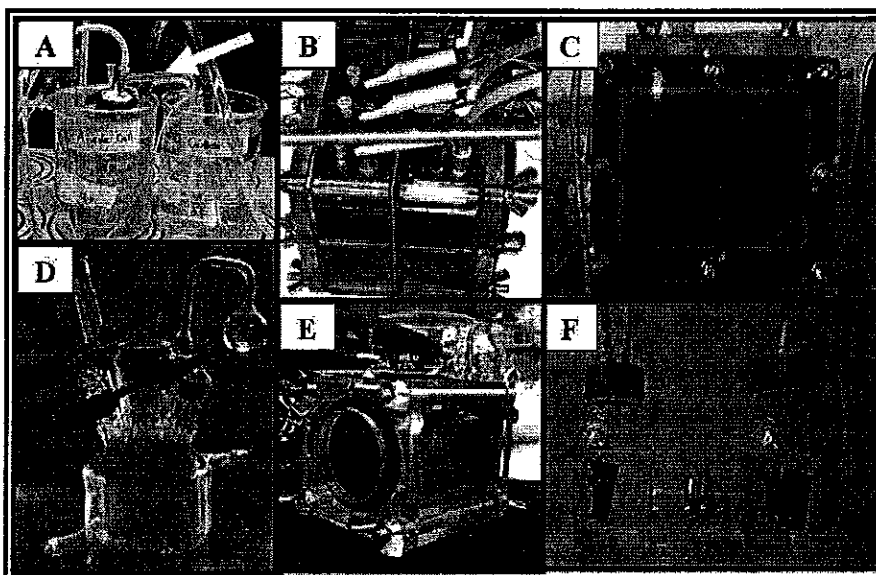


FIGURE 2. Types of MFCs used in studies: (A) easily constructed system containing a salt bridge (shown by arrow) (27); (B) four batch-type MFCs where the chambers are separated by the membrane (without a tube) and held together by bolts (7); (C) same as B but with a continuous flow-through anode (granular graphite matrix) and close anode-cathode placement (75); (D) photoheterotrophic type MFC (76); (E) single-chamber, air-cathode system in a simple "tube" arrangement (30); (F) two-chamber H-type system showing anode and cathode chambers equipped for gas sparging (23).