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Microbial Fuel Cells: A Cutting-Edge Approach to Bioelectricity Generation

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Abstract

The present study describes a simple, membrane-less, single-chamber microbial fuel cell (MFC) that uses natural mud and surface water as sustainable bioelectricity substrates. The way the system mimicked sediment-water interfaces was dependent on native microbial communities effecting electrochemical reactions without proprietary membranes. Carbon rod anodes were buried in anaerobic mud to establish a microbial colony while stainless-steel mesh cathodes were introduced in aerobic water for oxygen reduction. Both voltage output and other parameters like pH, temperature, turbidity, and conductivity have been measured during the experiment. Monitoring revealed rising voltage levels and biofilm formation around the anode, indicating active microbial processes and effective electron transfer. It thus provides an indication of the role of cheap, green ecofriendly MFCs in decentralized energy and wastewater treatment, particularly in situations where resource possibilities are limited.

Keywords:

Microbial fuel cell, biosensor, Single-chamber MFC design, anaerobic anode, bio electrochemical conversion

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Introduction

Human competition with nature has always gone with natural disasters, wars, or economic crises. More recently, the urge has been growing in many places to find more sustainable energy sources with the least environmental burdens possible (Rabaey & Verstraete, 2005). Microbial fuel cells operate on a pretty simple principle: organisms oxidize organic compounds at the anode, and they give off electrons and protons, which are transferred through an external circuit to the cathode where they deliver the electrons as power, while the protons move through the electrolyte for charge balancing and finally closing the circuit. Thus, bioelectricity can also be obtained directly from any number of organic wastes such as sewage, industrial waste effluents, agricultural runoff, or polluted water bodies (Logan & Regan, 2006; Farhood, 2023). MFCs can also be operated remotely under conditions that are not so demanding in terms of either temperature or pressure and use natural microbial consortia, thus making them a cost-effective environmentally friendly system (Du et al., 2007). An additional advantage of MFCs is that they generate energy in synchrony with treating waste waters (Petrova & Kowalski, 2025). As organic pollutants break down during environmental remediation, a small amount of electricity can be produced as a byproduct of this process (Bala Krishna, 2021; Pant et al., 2010). Ideally, different microbial consortia from sediments and those from diverse polluted water environments would enhance electron transfer processes to maximize power output from the MFCs (Schröder, 2007; Bhattacharya & Kapoor, 2024). Attention has become predominant with regard to fungi for their efficiency in breaking down organic matter and their useless electron transfer capabilities, which would improve system performances (Tremblay & Zhang, 2015). Yet there are still outstanding challenges for MFC concerning low voltage output, scale-up problems, and varying activities of microorganisms; recent advancements made in electrode design and microbial enrichment, as well as system configuration, are solving a few of these problems (Li et al., 2010; Santoro et al., 2017). The objective of this research is to stimulate bioelectricity production through the MFCs built from naturally contaminated water and mud collected from different places in Iraq. It would also sustain enriching amounts of knowledge on self-maintained renewable energy systems by measuring time-dependent voltage output, environmental variables, and system-inherent microbial activity (Santoro et al., 2017; Patil & Das, 2024).

Materials and Methods

A Repeatable Format

The team set up a simple MFC based on membrane-less technology to allow microbial communities to produce bioelectricity. Minimizing costs and making the design less complex allowed the design to support the interaction between electroactive bacteria and the electrodes efficiently (Du et al., 2007; Logan & Regan 2006). The system forces hydrogen ions to transfer between the anolyte and cathode surface to allow direct microscopic oxygen reduction. Like previous studies, this concept challenges for a way to scale in practice that is affordable and straightforward. In quantum mechanics, we study how components of the atom interact with each other and how they are put together. Graphite rods were used as the anode since they possess excellent electrical capability, are chemically stable and compatible with microbial biofilms (Logan & Regan, 2006). The attachment points for electroactive bacteria found in graphite surfaces make this material suitable for carrying out steady electron transfers (Kim & Chang, 2004). The construction of the cathode as a stainless-steel mesh made it possible to perform oxygen reduction effectively and withstand the research environment (Rahimnejad et al., 2015). Most importantly, stainless steel does not corrode which is very crucial for safe, ongoing reactor use. We decided on a 500 mL cylindrical plastic vessel for the MFC reactor since it is both common and resistant to the chemicals and handling it is relatively simple. That way, the electrodes are matched and at least 2 cm apart to allow for good inside material movement and keep resistance minimal.

Natural sediments found in water bodies near the site with high organic matter content were used in order to create a diverse consortium of electroactive microorganisms. The biological medium served as a source for microbial inoculum and substrate provisions, providing biodegradable compounds needed for microbial metabolism and electron generation (Pant et al., 2010). The sediments were introduced in their direct form without sterilization to avoid disturbance of their indigenous microbial community structure and functional dynamics (Karimov & Bobur, 2024). External resistors were used to control current and stabilize the electrical output. This allowed for precise measurements of performance parameters for the system (Aelterman et al., 2006). The configurations had negligible interference with microbial activity while providing reliable electrical data.

Operational Monitoring

MFC units were maintained under controlled laboratory conditions of temperature within 22 and 25ºC approximating ambient environments conducive for microbial growth. The voltage and current outputs were recorded every 2 hours across a continuous period of 7 days to account for diurnal fluctuations and peak generation of bioelectricity. Periodically, other important physicochemical parameters of pH, temperature, and ionic strength were also measured using calibrated probes. These indicate environmental changes and thus can be analyzed for correlation with variations in electrical performance and other biological activities.

Laboratory Safety

All experiments were carried out in accordance with standard biosafety procedures for safety purposes in personnel and to avoid contamination. All surfaces and equipment were cleaned both before and after using them with the appropriate disinfectant before and after every experiment. When anyone was working with any biological material, the laboratory staff members put on their personal protective equipment, including gloves and gowns. Disposal of all wastes followed the institutional biosafety guidelines.

Results and Discussion

Madhavan et al. 2016 focused on optimizing a double-chamber microbial fuel cell (MFC) using wastewater as a substrate to generate bioelectricity. The MFC was constructed with aluminum and carbon as anodes and copper as a cathode, utilizing a 0.3% potassium permanganate solution in the cathodic chamber. The MFC demonstrated a COD removal efficiency of 77% over a week, with low internal resistances of 0.466 Ω for the aluminum anode and 0.673 Ω for the carbon anode. Polarization curves indicated an inverse relationship between voltage and current, while cyclic voltammetry revealed maximum current generation at -0.2V.

Rahimnejad et al. 2015 and Madhavan et al., 2016 surveyed microbial fuel cell (MFC) technology for bioelectricity generation, pointing towards their ability to utilize biodegradable substrates under mild operating conditions. The MFC unit consists of an anode and a cathode compartment separated by a proton exchange membrane. Western biologists traditionally tried to investigate life in order to comprehend its different aspects. generating electrons and protons. The review considers various factors influencing MFC performances, such as the choice of electrode materials, internal resistance, and efficiency of electron transfer. In spite of other challenges, such as low power output or lack of scalability, MFCs have important applications in wastewater treatment, biosensing, and biohydrogen production. The authors note that advancements in electrode design and membrane technology may increase MFC efficiency and broaden its practical applications.

Ali et al. 2015 came up with the optimization techniques for a double-chamber microbial fuel cell (MFC) for treating domestic wastewater while producing electricity. The results indicated that both anodic and cathodic reconstruction have a dramatic effect on electricity production, with optimal currents of 0.784 mA in summer and 0.645 mA in winter when validated by mediatorless MFCs. Peak power outputs were recorded as 209 mW/m2 and 117 mW/m2, respectively. Principally, for the biological and chemical oxygen demand (BOD and COD) during wastewater treatment, their significant reductions suggest high efficiency in pollutant removal. The findings corroborate the sustainability offered by the MFCs based on USPIOs in energy generation and landfill treatment and indicate that seasonality clearly affects microbial activity and, consequently, MFC performance.

Kausar et al. 2023 studied the use of green nanocomposites as enhancers in the performance of microbial fuel cells (MFCs) based on eco-friendly electrodes and solid electrolytes within this study. Traditionally, platinum-based materials have been replaced with green polymers and nanomaterials, such as bacterial cellulose, agricultural waste-derived graphene oxide, titanium dioxide, and zinc oxide, developed sustainably. All these materials possess high power densities, advanced proton conductivity, and improved biodegradability. High efficiency with less environmental impact can be achieved by using specific configurations such as carbon fiber-embedded bacterial cellulose/polyaniline composites and lignocellulosic-derived graphene oxide with metal oxides. The review also covers progress in developing green proton exchange membranes using sulfonated poly (vinyl alcohol), chitosan, and polyhydroxyalkanoate, which are promising alternative green materials to commercial Nafion membranes. Both theoretically and practically, green nanocomposites can replace metals or synthetic substances and help overcome environmental and cost-related challenges associated with improving a technology like microbial fuel cells.

Korsa et al. 2025 focused on the possible applications of MFC in sustainable biofuel production on the fact that they can act dualistically as energy producers and as environmental remediators. The authors highlight some of the major strides achieved in the advancement of MFC design, biomass conversion technology, and microbial enhancement. Cited as being capable of converting organic substrates such as wastewater, cellulose, and marine sediments into products such as bioethanol, biodiesel, and biogas, with a maximum power density of 3.02 W/m^2, are species such as Geobacter sulfurreducens, Shewanella oneidensis, and Saccharomyces cerevisiae. This improvement has been attributed to the use of nanomaterials in MFCs with the genetically engineered microbes to increase electron transfer and substrate use. The various configurations of MFC were compared-five-way flow, two-chamber, stacked, round and up-flow-on scale-up and energy efficiency. One could focus on the design type, the composition of the constituent materials, and the operating conditions. Obstructed by low voltage output and cost problems, the study, however, assures a brilliant future for MFCs in biofuel and waste treatment. The scenario is of having biofuel production and treatment goes under the circular bioeconomy models for sustainable energy and waste management.

Malik et al. 2023, MFCs serve as an eco-sustainable technology for treating the wastewater along with producing energy. It is interesting that microbe fuel cells MFCs deliver bioelectricity in wastewater treatment, which addresses the interlinked problems of energy and environment The authors mainly consider advancements in MFC design, materials, and microbial interactions with a focus on improving efficiency and cost for practical applications. MFCs, however, provide a future pathway toward renewable energy generation and wastewater management on an industrial scale although there are limitations such as low power density and high operational costs (Malik et al., 2023).

Mohyudin et al. 2022 described microbial fuel cells (MFCs) as novel paradigms for wastewater treatment and bioelectricity generation. They draw attention to the ability of MFC to convert organic substrates into electrical energy from microbial catalysis while emphasizing the influence of electrode materials and configurations on performance enhancement. Namakwa Chem has got quite a few reactors seized by OLX, their supplier. Mohyudin et al. 2022 also talked about the various designs of MFCs, such as dual-chamber and single-chamber configurations, which vary in efficiency for treating several types of wastewaters, especially those polluted with azo dyes. Many advantages, such as reduced sludge production and cheaper operational costs, make MFCs a promising alternative; however, the scaling up of the technology for applications today is still beset with challenges. Future works should aim to improve electrode stability and general power output.

Elshobary et al. 2021 reviewed algal-based microfuel cells (MA-MFCs) for sustainable bioelectricity generation. The potentials of microalgae of higher efficiency toward MFCs as the possible electron donors at the anode or oxygen generators at the cathode are discussed. The study discusses the different configurations of MA-MFCs and the important operating parameters affecting the performance and mechanisms of electron transfer. Due to several limitations, such as slow activity from autotrophic microalgae that require fairly optimized conditions, the use of MA-MFCs in practice is challenging, notwithstanding low operational costs and considerable potential for wastewater treatment. Indeed, further research will be necessary so as to improve energy production and linking MA-MFCs to other processes to advance environmental sustainability (Elshobary et al., 2021).

Ali et al. 2025 examined the prospects of microalgae-enhanced microbial fuel cells (MFCs) as a sustainable technology for energy production and wastewater treatment. It describes the twofold function of MFCs: converting organic waste into bioelectricity and, at the same time, treating water. The authors analyze the different anode materials, especially those having properties from nanotechnology to improve electron transfer and microbial adhesion, thereby optimizing MFC performance. Intense light, high pH, and pectin are the influencing factors determining the power output. While the future remains optimistic for MFCs, they present challenges to be faced for scaling up technology for commercialization, namely their cost and stability. Future research should focus on enhancing design configurations and material sustainability in order to promote the benefits of MFCs in alleviating global energy and environmental problems.

Mondal and Goswami 2024, have reported on the progress, barriers, and applications of microbial fuel cells (MFCs) as a green technology for bioelectricity generation and wastewater treatment. The new pruning deals with improving power density and system stability with better anode materials, especially with the applications of nanotechnology. Indeed, the MFC technology has setbacks; the least include inadequate power performance, huge material expenses, and the global up-scale challenges. In particular, the review addresses the way ongoing research in optimizing microbial communities, electrode design, and MFC integration with other technologies may improve feasibility in widespread adoption of this technology in renewable energy and for environmental remediation.

Figure 1. shows experimental setup of a single-chamber microbial fuel cell (MFC) using mud as the anode medium and water as the cathode layer

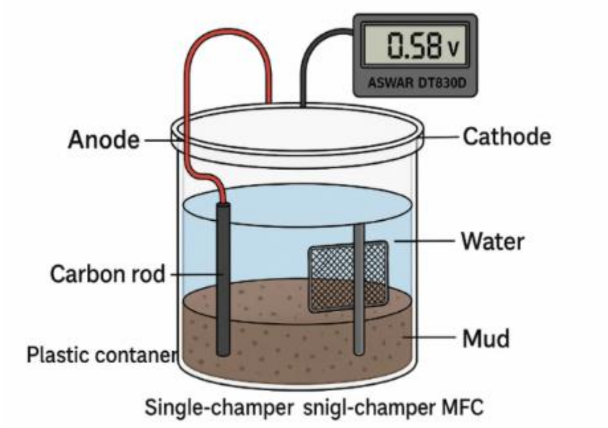

Figure 1. Schematic of a single-chamber microbial fuel cell (MFC) using mud and water

Figure 2. Represents a schematic diagram of a two-chamber human Microbial Fuel Cells (MFC) that produces electricity as well as biofuels including biogas, biodiesel, and bioethanol by breaking down organic materials, such as wastewater and agricultural residues. When an external circuit is connected, electrons move; protons cross a proton exchange membrane (PEM).

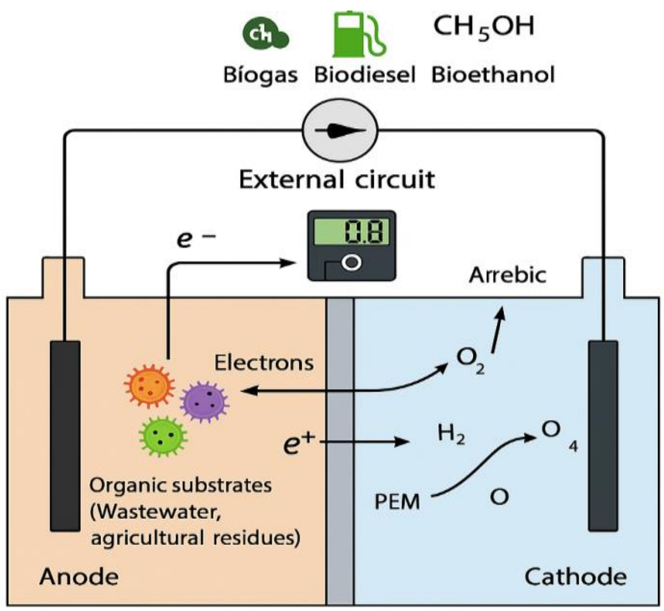

Figure 2. Bioelectricity generations and biofuel production in a microbial fuel cell

Figure 3. Shows a comparative analysis of power density (mW/m²) for diverse MFC enhancement strategies. The hybrids MFCs gave the maximum power output, whereas artificially modified microbes had almost similar performance as nanomaterial electrodes, which directly signifies the role of technology in MFC performance.

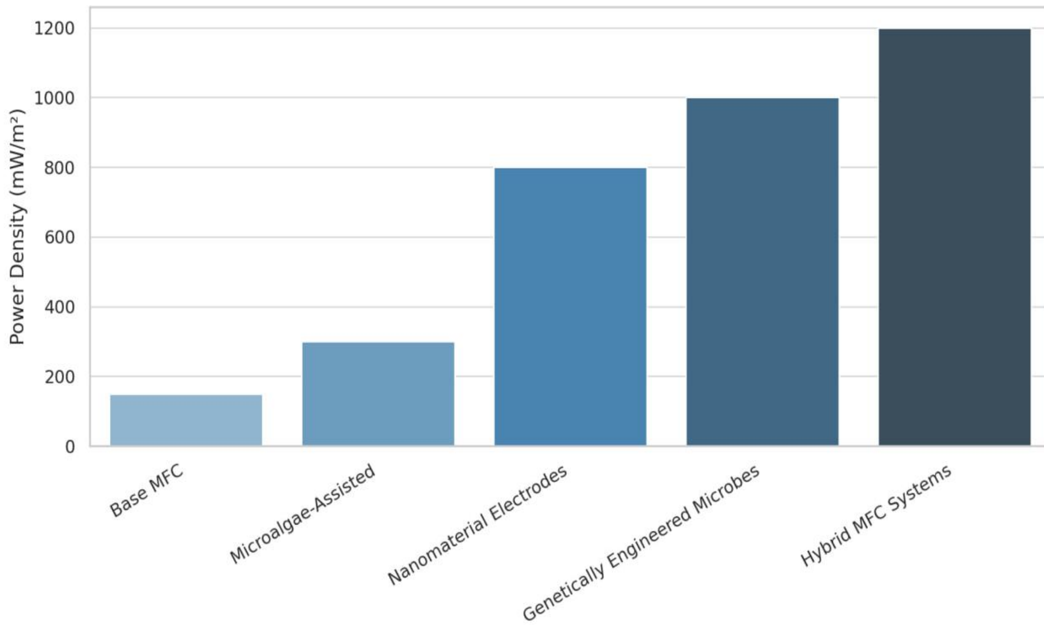

Figure 3. Effects of enhancement strategies on power output in microbial fuel cells

Figure 4. Shows carbon rod anode embedded in anaerobic mud and stainless-steel mesh cathode in surface water enabling electricity generation by native microorganisms

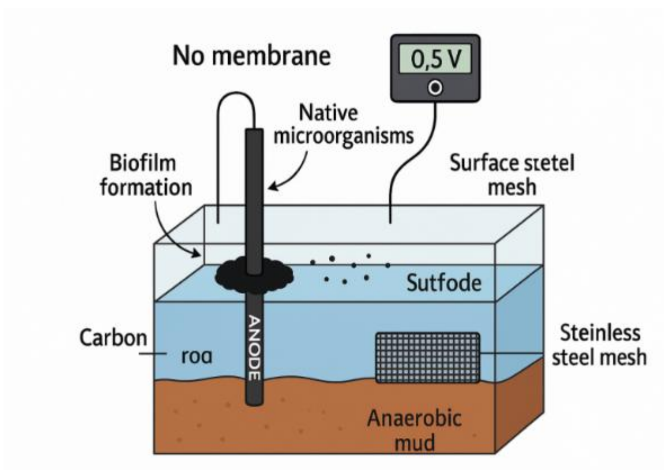

Figure 4. Diagram of a single-chamber microbial fuel cell (MFC) without a membrane

Figure 5. Shows evaluating the performance metrics of different mfc configurations and their impact on energy output efficiency

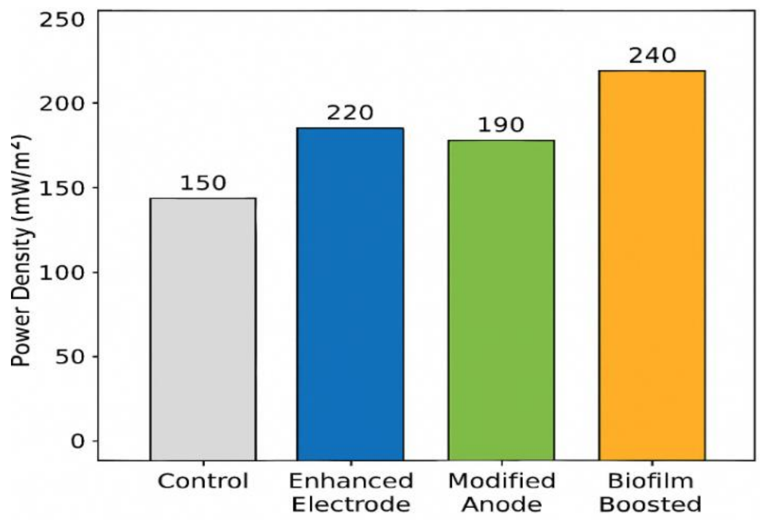

Figure 5. Power density comparisons in various microbial fuel cell systems

Conclusion

This probe shows that locally sourced mud and water can be harnessed within microbial fuel cells (MFCs) for the generation of bioelectricity. An innovative single-chamber MFC design with no membranes or external fuel input was successfully used to harness indigenous microbial populations within the experimental period. This thus continuously improved voltage output indicating strong microbial activity and also a good biofilm formed on the anode. A range of environmental parameters such as pH and temperature were monitored, thus supporting a better understanding of their effect on microbial efficiency. Deriving energy sustainably thus becomes a possibility, and the complementary objective of MFCs in treating organic waste may argue MFCs an attractive option for communities restricted by a lower resource base. Amanira are likely to continue to upscale and improve the efficiency of this technology for maximum benefit in the renewable energy industry and environmental sustainability.

Conflict of Interest

The authors declare that they have no competing interests.

Author Contributions

All authors' contributions are equal for the preparation of research in the manuscript.

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