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*Editorial*
# Advances in Microbial Fuel Cell Technologies

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Michael Potter pioneered microbial fuel cell (MFC) technology in 1911. Since then, for the last 20 years, the interest of scientists in MFCs has increased in the literature. Of particular interest is the fact that the devices can both treat sewage, generate electricity, serve as biosensors, e.g., in fermentation systems, or serve to recover nutrients. However, the effectiveness of the MFC is influenced by many factors, such as the concentration and type of substrate, electrode materials, external resistance, types of membranes, and the microbial composition of the anode biofilm. Over the past two decades, scientists have made great strides in developing MFC technology, so this editorial aims to collect and present the key components that affect the operation of cells. The main problem is the relatively low output power of the MFC, so below, different ways to increase the energy generated in the cells are presented.

One way to increase the efficiency of the MFC is to optimize the substrate concentration in the anode chamber since it directly affects the energy production and the substrate removal efficiency of the MFC. Sudden changes in substrate concentration can inhibit energy generation and reduce microbial diversity. Research indicates that selectively cultivated highly adaptive microorganisms can increase the stability and removal efficiency of MFCs. Ni et al. [1] showed that such microorganisms mainly belonged to Proteobacteria, Bacteroidetes, Firmicutes, Chloroflexi, and Spirochaetae. Zoogloea and Plasticicumulans were indicated as the most important genera of microorganisms, improving the efficiency of MFCs. Nosek and Cydzik-Kwiatkowska [2] investigated the impact of organic loading rate (OLR) on energy generation and changes in the anode bacterial consortium in MFC fed with municipal wastewater. The higher OLR favored the growth of exoelectrogens belonging to the genus Rhodopseudomonas, resulting in a stable electricity production over 37 times higher than at lower OLR. At a lower OLR, an abundance of microorganisms belonging to the genera Leucobacter, Frigoribacterium, and Phenylobacterium increased, which improved the COD removal efficiency to about 85% in the period of stable MFC operation.

Another operational parameter important in improving the performance of the MFC is the appropriately selected external resistance. Kloch and Toczyłowska-Mamińska [3] investigated the effect of changes in external resistance on COD removal and energy production in MFC fueled with wood hydrothermal wastewater. The highest COD removal efficiency did not always correlate with the peak power generated in the MFC. The highest wastewater treatment efficiency was obtained for the external resistance at which the power density was not maximized. The authors note that the optimization of energy production and the COD removal efficiency of the MFC should be performed separately, as different resistances are optimal for maximizing each of these two parameters. Potrykus et al. [4] conclude that external residence significantly influences the population distribution in the MFC. The population change from more electrogenic to more fermentative occurs with higher external resistances. Electricity production drops significantly as external resistance increases, while a change in resistance has a more negligible effect on COD removal. Therefore, the MFC exhibits lower electrical efficiency after operating with high external resistance.



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A selection of the electrode materials, the distance between the electrodes, or the type of oxidizing agents in the anode chamber can strongly affect the efficiency of the cells. In the extensive work by Al-Asheh et al. [5] on MFC performance optimization, researchers used different cathode and anode rod materials of similar size and thickness, including copper, aluminum, carbon cloth, steel, and brass, to determine the combination that led to the best results. They also investigated the influence of the oxidizing agents used (copper sulfate and potassium hexacyanoferrate), the shape, size, and distance between the electrodes on the current generated in the cell, and the voltage recorded. Their research showed that using a Cu-Al cathode resulted in better MFC performance in comparison with that of MFC with a carbon cloth electrode. The power of the MFC increased with increasing the surface area inhabited by microorganisms and due to air supply and mixing. The cell showed better performance if, for inoculation, microbial cultures previously used in MFC were used instead of the fresh ones. The authors recommended using small MFCs operated under aerobic conditions, with smooth membranes facing the chambers using Cu-Al probes and the high biomass concentration.

One of the most popular methods of increasing the power generated in the MFC recently is the modification of the anode. The surface structure and properties of the anodic carbon fabric can be improved by heat modification with acid. Ni et al. [6] studied thermo-acid anode modification that significantly influenced electricity generation and the structure of the MFC microbial community, whereby the power density increased by 350% compared to untreated carbon cloth. The anode performance can also be altered by anode modifications aiming at improving the deposition of microorganisms and the transport of electrons in the cell. Metal oxides with conductive polymers such as polypyrrole (PPy) are suitable materials for this purpose because they reduce the cell's internal resistance and improve the kinetic activity of the anode reaction. However, the conditions for the deposition on the electrode, such as the deposition time, are also critical. Fan and Xi [7] showed that for the Fe3O4/PPy-modified carbon felt electrode, the current density, and the COD removal rate were highest at the deposition time of 50 min. Under these conditions, in the MFC with Fe3O4/PPy-modified anode, the steady-state current density and the COD removal rate increased by 59.5% and 95.3%, respectively, compared to the MFC with the unmodified carbon felt anode. In addition, in the cell with the Fe3O4/PPy-modified anode, the lowest solution internal resistance (3.539 Ω) was observed.

An important factor influencing the efficiency of the MFC is the type of membrane used in the cell. The membrane separates the anode and cathode chambers and maintains anaerobic and anaerobic conditions in the chambers, respectively. The most commonly used membrane is Nafion 117, but the price of this material is relatively high; therefore, studies on other types of membranes are conducted. Banerjee et al. [8] analyzed literature data on the effect of membrane type on MFC operation. Membranes made of graphene oxide sulfonated polyether ether ketone and sulfonated silicon dioxide in sulfonated polystyrene ethylene butylene polystyrene ensured a 55% and 107% higher energy generation, respectively, in comparison with the Nafion membrane. In addition, the possibility of using clay or ceramic membranes as a separator in MFC was also described. The authors indicate that durability, porosity, and the potential for multiple uses of such membranes were worse than the Nafion membrane. On the other hand, Fan et al. [9] show that membranes can also be modified to improve the output power of the MFC. The experiment showed that modification of membranes with polyvinylidene difluoride (PVDF), sulfonated PVDF, and methyl methacrylate (MMA) improves the power generation capacity and the efficiency of wastewater treatment in MFC. The MFC demonstrated the best performance with a modified MMA membrane. In this MFC, the current density and the COD removal efficiency were 2224% and 72.9% higher, respectively, than in MFC with the conventional Nafion membrane.

The presented articles show that there are many operational factors influencing the energy production in MFCs, therefore further multi-dimensional studies are required to gain an in-depth knowledge of relations between the operational parameters and performance of MFCs.

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## References

1. Ni, H.; Wang, K.; Lv, S.; Wang, X.; Zhuo, L.; Zhang, J. Effects of Concentration Variations on the Performance and Microbial Community in Microbial Fuel Cell Using Swine Wastewater. *Energies* **2020**, *13*, 2231. [CrossRef]
2. Nosek, D.; Cydzik-Kwiatkowska, A. Microbial Structure and Energy Generation in Microbial Fuel Cells Powered with Waste Anaerobic Digestate. *Energies* **2020**, *13*, 4712. [CrossRef]
3. Kloch, M.; Toczyłowska-Mamińska, R. Toward Optimization of Wood Industry Wastewater Treatment in Microbial Fuel Cells—Mixed Wastewaters Approach. *Energies* **2020**, *13*, 263. [CrossRef]
4. Potrykus, S.; León-Fernández, L.F.; Nieznański, J.; Karkosiński, D.; Fernandez-Morales, F.J. The Influence of External Load on the Performance of Microbial Fuel Cells. *Energies* **2021**, *14*, 612. [CrossRef]
5. Al-Asheh, S.; Al-Assaf, Y.; Aidan, A. Single-Chamber Microbial Fuel Cells' Behavior at Different Operational Scenarios. *Energies* **2020**, *13*, 5458. [CrossRef]
6. Ni, H.; Wang, K.; Lv, S.; Wang, X.; Zhang, J.; Zhuo, L.; Li, F. Effects of Modified Anodes on the Performance and Microbial Community of Microbial Fuel Cells Using Swine Wastewater. *Energies* **2020**, *13*, 3980. [CrossRef]
7. Fan, L.; Xi, Y. Effect of Polypyrrole-$Fe_3O_4$ Composite Modified Anode and Its Electrodeposition Time on the Performance of Microbial Fuel Cells. *Energies* **2021**, *14*, 2461. [CrossRef]
8. Banerjee, A.; Calay, R.K.; Eregno, F.E. Role and Important Properties of a Membrane with Its Recent Advancement in a Microbial Fuel Cell. *Energies* **2022**, *15*, 444. [CrossRef]
9. Fan, L.; Shi, J.; Gao, T. Comparative Study on the Effects of Three Membrane Modification Methods on the Performance of Microbial Fuel Cell. *Energies* **2020**, *13*, 1383. [CrossRef]