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Is microbial fuel cell technology ready? An economic answer towards industrial commercialization

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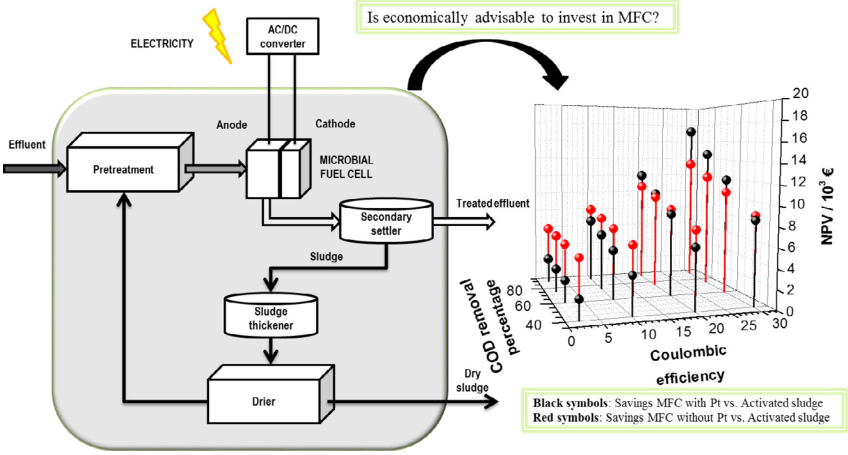
HIGHLIGHTS

- An economic assessment of an MFC implementation for wastewater treatment was performed.
- The Net Present Value and the Internal Rate Returns have been evaluated.
- Electrode area, use of Pt, price of electricity and inflation have been considered.
- Pt-free cathodes are economically more attractive for MFC wastewater treatment.
- This study can be a tool for future investors in this technology.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the last decade, Microbial Fuel Cells (MFCs) have experienced significant scientific and technological development, to the point of becoming close to commercialization. One key assessment that clearly establishes whether one technology can fully enter the market is the profitability demonstration. For this demonstration, classical evaluation criteria for investment decisions such as the *Net Present Value* and the *Internal Rate of Return* can be applied to a given proposal. This paper presents an economic assessment of a microbial fuel cell in a juice processing plant. Three different scenarios, optimistic, pessimistic and most likely scenarios based on the maximum power density of the cell on two basic MFC cases (cathodes with and without Pt, respectively), were studied and compared to the conventional activated sludge process. The results show that under most of the scenarios under consideration, including the pessimistic one, MFC is a more attractive option. Furthermore, a sensitivity analysis was performed with respect to the electrode area, and the annual growth rate of the electricity pricing has revealed that the electrode area parameter is the most influential, reducing the MFC profitability for larger electrode areas, whereas the higher the annual growth rates of the electricity price, the higher the MFC profits. In summary, the results of this study show that the implementation of MFC is a promising alternative to the use of classical aerated activated sludge, and it has potential economic benefits.

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1. Introduction

Fossil fuels have supported the industrialization and economic growth of all the economies in the world over the past century. However, because of the intrinsic characteristics of these fuels, depletion threatens their utilization as primary energy sources, as do growing environmental concerns (the emission of greenhouse gases and the consequent increase in the average global temperature). These concerns have catalyzed the development of alternative energy sources, such as fuel cells [1–5].

Conventional fuel cells that are based on the use of metallic catalysts to promote the oxidation of fuels such as hydrogen and low molecular weight alcohols are a mature technology. However, the costs associated with this technology are still unaffordable, which appears to be a bottleneck for their use, despite their solid scientific background. Microbial fuel cells (MFC) appeared as an alternative in the late 90s. Their history dates back even further, to 1912, with Potter [6]. This author emphasized the idea of producing electricity from the biological degradation of organic matter. Poor results discouraged further research until recent times, as a response to the demand for no net CO_2-emitting energy sources.

Microbial fuel cells are based on the use of microorganisms to degrade the organic matter contained in a substrate and, at the same time, to produce electricity. The electrons generated by metabolism are not donated to an acceptor molecule but to the surface of an electrode during an *incomplete respiration process* [7–12] as follows: (a) direct electron transfer, (b) intermediate metabolites acting as electron shuttles through a redox pair; and/or (c) micro-cilia (wires) that directly transport the electrons. These electrons flow through an external circuit and are consumed by the cathode during the reduction of the oxidant (e.g., oxygen). During this process, the protons that are generated by fuel oxidation are also consumed in the cathode, travelling from the anode to the cathode through a compartment separator. More instructive literature reviews about this system can be found elsewhere [13–21].

MFC can easily be coupled to a wastewater treatment plant (WWTP). Conventional plants are divided into several sections, which are devoted to pollutants of different natures, namely particles, colloids, and dissolved matter, followed by the final refinement of the effluent [22]. Dissolved organic matter can be biologically degraded, whereas the other types are removed by physico-chemical processes. These processes require a large amount of energy, which may be reduced if part of the energy contained in the wastes was utilized. A more sustainable, affordable, robust and safer treatment is highly desirable for the current situation. Shizas and Bagley [23] gave a self-illustrative figure indicating that in the WWTP in Toronto (Canada), the waste contains 9.3 times the energy required for its own treatment. MFC can be an alternative to bridge this gap, due to the above-mentioned simultaneous capacity for treating waste and producing electricity. Furthermore, the anaerobic conditions of the MFC anode reduce and consequently facilitate sludge management (20% less sludge produced in [22]) compared to the conventional activated sludge process. Finally, aeration is only necessary for the cathode to guarantee a base dissolved oxygen concentration, even though biocathodes are under active, ongoing research [24–27].

The MFC state-of-the-art has experienced significant advances in recent years, allowing for maximum power densities of 2.08 $kW\ m^{-3}$ for lab-scale systems [28]. However, the actual power demand (even for simple systems) requires scaled-up systems. In this sense, experience has been gained over the years with different successful attempts [29–35]. This design can be considered a significant step in the future development of MFC. The obtained results feed back into the more basic systems, and they eventually modify the existing MFC architecture. MFC can also be used in remote locations with electrical infrastructure deficits or critical applications that should not rely on external power inputs. One important feature of the MFC is that, despite the apparent fragility of the system, it can operate robustly under a constant supply of wastewater (regarding not only its amount but also its characteristics). However, any system that is intended for commercialization must first pass through an economic assessment that verifies the profitability of the system to attract investors and allow commercialization.

Under these premises, this work focuses on an economic feasibility study of a Microbial Fuel Cell coupled with a wastewater treatment process in the fruit juice processing industry. Unlike other previous works, this research investigates the potential economic risks of this technology by including a sensitivity analysis of both the technical and economic variables that are subject to uncertainty and that represent a source of risk. Regarding technical variables, this research presents several power output scenarios that may occur, depending on the operating conditions (optimistic, most likely and pessimistic), with the presence or absence of platinum as the catalyst for oxygen reduction. Moreover, a design parameter used as the electrode area was assessed under those scenarios. In relation to economic variables, different electricity pricing and inflation scenarios were also investigated by developing a decision tree that is typically employed in decision-making to analyze their influence on the project's profitability. Finally, the alternative MFC viability is compared to that of the conventional activated sludge for different scenarios.

2. Case study

This work analyzes a case about effluent from the juice processing industry, and this industry is a healthy sector in the global economy. This effluent displays high organic matter loading, which is largely soluble in water (as dissolved organic matter) and is biodegradable. An aerobic biological treatment is very suitable for treating this type of effluent, and hence, it could alternatively be treated by an MFC [35].

Although different cell architectures have been proposed in the literature [36–39], one very simple, easily scalable with a large presence in the literature is the double compartment cell separated by a proton exchange membrane (PEM). A single MFC will be unable to produce a large output voltage, making it necessary to connect a sequence of MFCs in *series* [40–44]. Although the scaled-up systems may incentivize the development of more cost-effective membrane materials [30], it is important to note some of the issues that occur during the scale-up and stacking of the MFC as follows:

- An increase in the volume involves a decrease in the volume power density ($W\ m_{MFC}^{-3}$). However, a small MFC will be able to treat concomitant effluent volumes. As a consequence, there is an optimum MFC size.
- Connecting MFCs in series will theoretically lead to the summation of the individual cell voltage. However, the practical value is lower, due to the existing parasitic losses between the cells [45,46].

For the reasons mentioned above, this study involves a 10-cell system. Each cell is divided into two chambers: an anolyte, with a volume of 2.25 m^3, and a catholyte, with a volume of 1.125 m^3; the chambers are separated by a PEM. The wall of each compartment is made of methacrylate (20 mm thick), with a window adapted for placing the PEM. The electrodes are carbon cloth

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