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Scale-Up and Performance of Microbial Fuel Cells

Project Summary



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Summary

This project focuses on scaling up, scaling down and enhancing a large microbial fuel cell (MFC) within the context of a wastewater treatment. Building upon earlier investigations that led to the creation and operation of a 1000-litre MFC, this reactor was restarted in 2025 following maintenance. Start-up and system control were required for this end. After satisfactory power generation was achieved, the system was tested for ongoing electrode maintenance, and the purified wastewater was recirculated into the cathodes to remove ammonia, producing purified water.

In addition, the newly constructed 300 L MFC reactor was started and controlled using polarization experiments and is now running automatically with online monitoring of currents and potentials. An MPPT and lithium batteries for charging were added. A second reactor with an improved design has been constructed and transported to a Wastewater Treatment Plant, where it is currently set up for cheese whey degradation.

1 Introduction

1.1 Overview

Wastewater treatment poses a significant challenge for our society, particularly as we look ahead to the future with a growing population and increasingly stringent environmental standards. The conventional method of wastewater treatment through biological oxidation is effective but demands a substantial amount of energy. Electricity consumption for this process can constitute up to 70% of the operating costs of wastewater treatment plants, consuming 0.3 to 2.1 kWh per cubic meter of treated water. The bulk of these expenses arise from the need to supply oxygen for the growth of microorganisms in the biological aeration basins, which break down organic matter. Consequently, there is active exploration of alternatives to this traditional yet costly approach.

One potential alternative is the utilization of Microbial Fuel Cells (MFCs) to treat wastewater, replacing the traditional biological lagoons. Microbial fuel cells reduce the energy consumption for wastewater treatment by about 75% and generate electricity in addition. The reduction is based on the intention to only supply the needed oxygen for microbial digestion and not as today to add it in highest excess. The second objective is current generation while purifying wastewater. Its efficiency is assessed without knowing exactly the absolute potential of the currents that can be produced. The calculations are empiric and based on an energy efficiency that is considered from the oxidation of digestible biomass, which amounts to 6 -12%. This is modest energy efficiency as far as this can be said today, but the savings by the two principles are substantial. Although there are approximations and assumptions, it reduces energy needs by 80% for a WWTP like the one the experiments are conducted (STEP Châteauneuf, Sion). If this technology is installed in the entire country, it may reduce the 1-2% of national electricity consumption.

It was observed that the reactors cleaned wastewater after prolonged operation of three years with about 80% of COD removal, by adjusting the flux the cleaning can be enhanced easily above 90%. This is the longest, so far executed MFC WWT process on that scale. It is important to restate that energy generation is only one of the advantages while energy savings are currently more important and the strength of the concept.

There are novel advantages of MFC use in wastewater treatment that are not possible with the existing treatment systems. The MFC reactor is closed and CO_2 that is inevitably produced by any wastewater treatment remains in the cleaned water and could be extracted. This potentially reduces the carbon food print of communities and industrial users. By the same token it reduces air pollution of volatile organic compounds and gases as they are not exhausted and remain in the system and become oxidized and therefore mostly removed by transforming them in the energy generation process into electricity.

This technology is in concurrence with other technologies to solve energy needs in particular. The question is if there are alternatives possible on WWTP directly as an integrated solution. One apparently feasible idea is the installation of solar panels that feed the air pumps what could be less expensive. Solar panels, however, have the systemic drawback that they cannot constantly satisfy the energy needs of a WWTP. The WWTP is in constant operation and needs power also during the night and in the winter months. In addition, during rain-fall the WWTP are usually in a heavy-duty situation and solar panels will not produce in this critical moment as long there is rainfall. The MFC system is in this respect less impacted and self-sufficient by its concept. With the large MFC it was observed that in the winter the MFC worked well at 11°C while the kinetics were about half as fast what means the system needs more volume but in summer there is more water but higher temperature, up to 21°C.

A 1000L reactor was installed first and tested at the Châteauneuf Wastewater Treatment Plant (Valais, Switzerland). This reactor operated continuously for three years, yielding promising results in wastewater treatment and green energy recovery. Energy recovery ranged from 0.006 to 0.060 kWh/m^3, with a Columbic efficiency of up to 14.9% and an Energy efficiency of 5.8%. In the best-case scenario, energy efficiency reached as high as 12%. With newly developed electronic regulation, steady

improvements are expected to eventually reach this latter value. The most significant advantage of the microbial fuel cell developed so far is that it can save up to 75% of the energy compared to the state-of-the-art wastewater treatment plant, as demonstrated in this project. Moreover, specific challenges such as voltage reversal, limitations in electron sink sources, elimination of micropollutants, and treatment of higher flow rates need further enhancement.

Lastly, the MFC plant at the wastewater treatment plant is composed of materials such as RVC electrodes and VANADion™ membranes, which have become heavily soiled after years of exposure to wastewater. Reusing and reactivating the plant presently the most critical challenge for the continuity and future development of this type of facility, as outlined in this project.

1.2 Microbial Fuel Cell Technology

1.2.1 MFC elements and setup

Microbial fuel cells consist of two distinct compartments to generate electrical power: an anode chamber, where organic compounds are oxidatively broken down, and a cathode chamber, where oxygen serves as the final electron acceptor, ultimately forming water. These compartments remain separated by a membrane, such as the VANADion™ membrane as in the MFCs used at the Chateauneuf Wastewater Treatment Plant. In wastewater treatment applications, wastewater enters the anode compartment, nourishing various microorganisms that form biofilms on RVC electrodes. During this growth process, organic matter is transformed into H^+ (protons), e^- (electrons), CO_2, and smaller compounds. Electrons then travel through the biofilm to the anode, continuing their journey through an external circuit to reach the cathode, where they react with oxygen and condense water is released.

One can formulate these processes into three equations. *Eq. 1* illustrates the anodic reaction when acetate serves as the electron donor, while *Eq. 2* depicts the cathodic reaction when oxygen is the final electron acceptor. Combining these equations yields *Eq. 3*, representing the overall reaction within an MFC system involving acetate and oxygen.

$$Anode: \quad CH_3COOH + 2H_2O \rightarrow 2CO_2 + 8e^- + 8H^+ \qquad (1)$$

$$Cathode: \quad 2O_2 + 8e^- + 8H^+ \rightarrow 4H_2O \qquad (2)$$

$$Overall: \quad CH_3COOH + 2O_2 \rightarrow 2CO_2 + 4H_2O + Biomass + Electricity \qquad (3)$$

1.2.2 MFC electron transfer

Electron transfer is critical to the metabolism of components and the respiration of many life forms, including many microorganisms. Electrogenic microbes use a final electron acceptor using an higher electron transfer potential as donor. When electron acceptor compounds become limited in their environment, some microorganisms will switch to fermentation metabolism or synthesize their electron acceptors. As a way out there is in natural environments another pathway, microorganisms can use minerals or other organic compounds as electron acceptors.

MFC systems can be divided into two groups according to the electron transfer between the microorganisms and the anode. In the first group, called mediator MFCs, the microorganisms have no electrochemically-active-surface-proteins for electron transfer and require the help of an agent called electroactive mediator, such as sulfates, sulfites and others. In the second group, called mediator-less MFCs, microorganisms can generate electricity without the aid of a mediator. These microorganisms are, therefore, less costly to install in MFC systems. These are generally metal-reducing bacteria such as *Shewanella*, *Rhodoferax*, or *Geobacteraceae*. The two related mechanisms are described in the Figure 1 below.

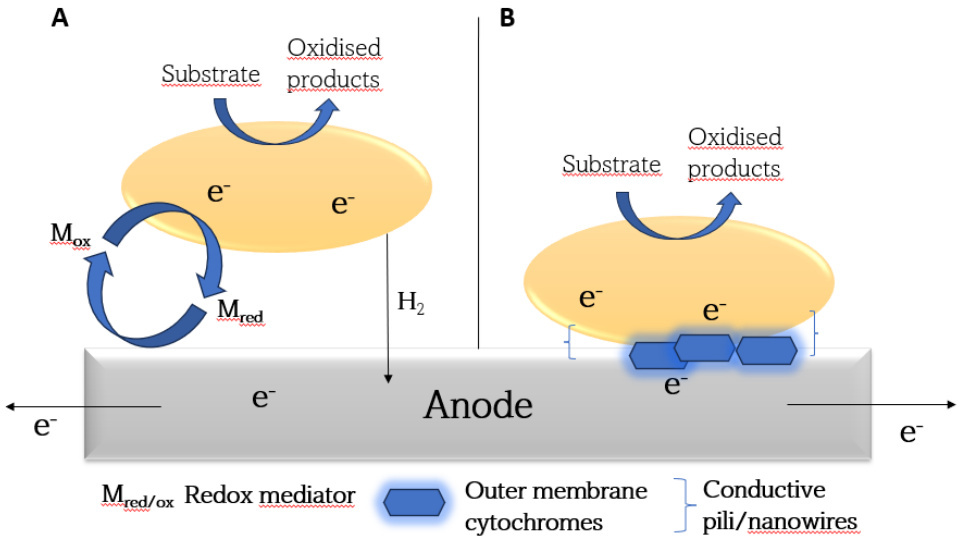


Figure 1: Electron transfer mechanisms from microorganisms to anode in the MFC system inspired by (Kalathil et al. 2018) with **(A)** MFC with mediators and **(B)** MFC without mediators

1.2.3 MFC working principle

To describe how a microbial fuel cell works, it's important to understand that the central element of this system is the bioanode, on which a biofilm of microorganisms is formed. This biofilm conditions the correct operation of the MFC, and it is, therefore, essential to have a robust biofilm that is electrochemically active. To optimize the process and performance of an MFC system, we need to consider the various factors that influence the interactions between the microorganisms contained in the wastewater and the anode, depending on the materials used for the anode.

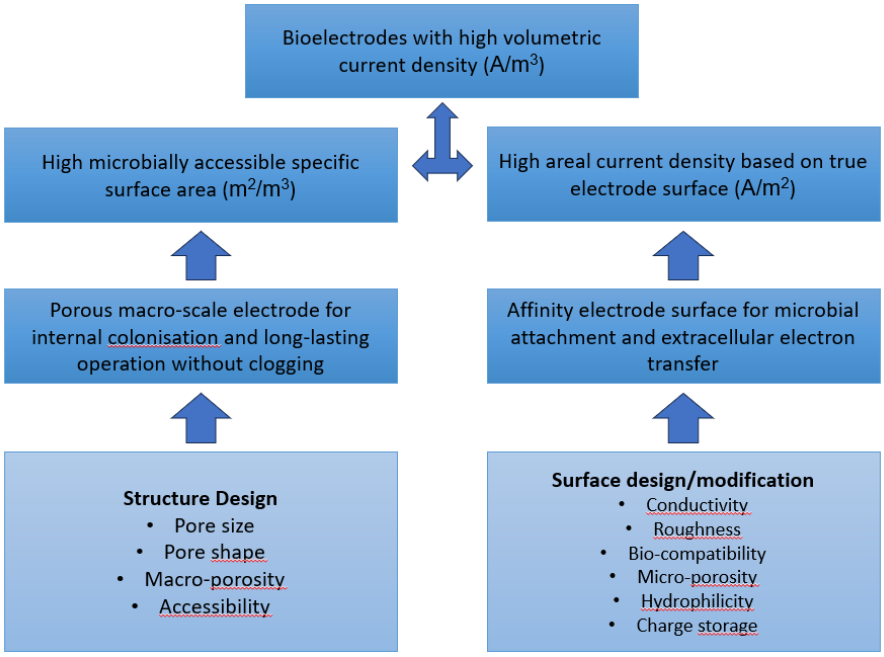


Figure 2: Various parameters influencing the anode-microorganism relationship, from electrode design to electrode surface.

The Figure 2 illustrates key factors in the design of efficient microbial fuel cell electrodes. In the first column, there is the "Structure Design," which includes considerations such as pore size, pore shape, macro-porosity, and accessibility. These factors are critical for creating a porous macro-scale electrode that allows internal colonization by microorganisms, ensuring long-lasting operation without clogging. Moreover, maximizing the microbially accessible specific surface area in square meters per cubic meter (m^2/m^3) is essential for enhanced MFC performance.

Moving to the second column, we focus on "Surface Design/Modification," which encompasses attributes like conductivity, roughness, bio-compatibility, micro-porosity, hydrophilicity, and charge storage. These features are crucial for achieving an affinity electrode surface that facilitates microbial attachment and extracellular electron transfer. Additionally, optimizing the true electrode surface area in square meters per square meter (A/m^2) leads to high areal current density, a key factor for MFC efficiency.

The convergence of these design elements results in bioelectrodes with a high volumetric current density, measured in amperes per cubic meter (A/m^3). This comprehensive approach ensures the development of MFC electrodes that efficiently harness microbial activity to generate electrical current, making them a valuable component of sustainable energy technologies.

1.2.4 Scale-up of MFCs

Designing a scaled-up microbial fuel cell system presents a multifaceted challenge dependent on several crucial parameters. Firstly, the need to attain reasonable energy production efficiencies relative to the reactor's liquid volume is paramount. Typically, scale-up is achieved through the modularization of smaller MFC units, but deploying too many units can become cost-prohibitive, necessitating innovative architectural solutions. Two other vital considerations in scaling up MFC systems are the efficient utilization of fuel. Anode and cathode potential, as well as ohmic losses, exert significant influence on these parameters. The accumulation of biofilm deposits on anodes can notably diminish MFC efficiency, increasing internal resistance and impeding electron flow between electrodes.

One notable application where the low energy efficiency is not a primary concern is the use of wastewater as a fuel for the microbial fuel cell to generate electricity. These MFCs function effectively with wastewater, both as a means to generate electricity and to conserve electricity. In the development of next-generation microbial fuel cells that can be scaled up to larger entities, electricity savings emerge as a pivotal consideration. Paradoxically, the architecture of these future microbial fuel cell stacks are developed as scaled-down version. This scaling down enhances the efficiency of their use.

When constructing scaled-up microbial fuel cells, the containment of volatile compounds within the MFC stack becomes essential feature. These volatile compounds are converted into electricity, while CO_2 predominantly dissolves in the purified wastewater. The setup should facilitate the recovery of CO_2, potentially aligning with future wastewater treatment regulations that may mandate CO_2 removal.

Operational simplicity is another crucial aspect of scaled-up microbial fuel cells. Nevertheless, electricity harvesting from microbes remains a challenging endeavor. Some scale-up projects overlook electronic harvesting technology in favor of short-circuiting units to facilitate wastewater treatment. Conversely, other approaches utilize maximum power point trackers to ensure effective wastewater purification, albeit with occasional voltage reversals and stack imbalance. To mitigate this issue, units with voltage reversals can be deactivated, achievable through the use of individual maximum power point trackers. Simplifying the electronic setup, a single MPPT controller can potentially manage multiple MFC units simultaneously in serial, parallel and mixed stacks, streamlining the operation of scaled-up systems.

Another critical consideration when constructing scaled-up microbial fuel cell (MFC) systems is the associated cost. As documented by (Liang et al. 2018; A.-J. Wang et al. 2020), the cost of establishing such a system can range significantly, from 735 USD/m^3 to 36,000 USD/m^3. Notably, the primary expenditure arises from the acquisition of membranes and electrodes. The future viability of large-scale MFC systems hinges on three key factors: enhancing the cost-effectiveness of system production,

extending system longevity, and establishing efficient methods for the reuse and recovery of various materials, particularly electrodes and membranes.

Efforts to reduce manufacturing costs, increase the durability of MFC systems, and implement sustainable practices for materials reuse and recovery are critical in shaping the feasibility and widespread adoption of the large-scale MFC technology. These considerations align with the broader goal of making MFC systems more economic and environmentally sustainable for a variety of applications, including wastewater treatment and energy generation.

1.3 Research Purpose and Scope

1.4.1 Project progress and objectives for Key Performance

The initial phase of the Odin III project focused on establishing a method for cleaning and restarting the scale-up reactor (MFC 1000L) at the wastewater treatment plant in Châteauneuf (WWTP of Sion). The critical aspect of this reactor refurbishment involves determining which materials can be reclaimed and which require replacement. This entails a comprehensive examination of the Reticulated Vitreous Carbon (RVC) technology employed in electrode manufacturing, with a focus on a cleaning method that maximizes both quality and quantity. Additionally, cleaning of PETG units is undertaken in preparation for the final reconstruction of the reactor.

Several pertinent questions remain unanswered for scale up systems in a real environment, and the Odin III project aims to address these obstacles and uncertainties along two kinds of Key Performance Indicators (KPIs):

Key Performance Indicators for scale up WWTP-MFCs

a) Energy savings:

   The MFC system reduces energy consumption in a WWTP.

   Target values:
   The objective is an electricity consumption reduction of 75-85%. 75% is the minimal value to achieve (in general it is impossible to assess it directly today due to scaling issues).

b) COD Conversion Efficiency:

   The MFC converts organic substrates (e.g., wastewater COD) into electricity what can be assessed.

$$\text{Coulombic Efficiency (CE)} = \frac{\text{electrons recovered as current}}{\text{total electrons available in substrate}} \times 100\%$$

   Target Values:
   Pilot/full scale: Should achieve 4.7–14.9% CE. This value can be adjusted to top end values >90%, however CE is only useful as a KPI if there is a certain effluent flux because CE values alone are not meaningful in the current scale up MFCs.

c) Organic load Removal:

This is the fraction of chemical oxygen demand (COD) removed from the feedstock by the MFC.

Target Values:
Full scale: 80-95% COD removal, sufficient to meet wastewater discharge standards for small plants consistently and achieve sufficient progress to reach data for large systems.

d) Microbial electron transfer based energy efficiency

This KIP is measured in a formal manner based on empiric data. Scientifically it is of an uncertain nature as our research shows that energy losses for electron transfer are substantial even in model experiments with *Shewanella*, it is therefore unclear for the moment if the assessment methods needs to be redefined and that electricity generation has reached the possible upper potential for plant operation and is therefore already larger than currently discussed and assessed.

Target Values:
6-12% of energy efficiency based on COD removal, while a value of 6% with current calculations should be achieved regularly.

e) Remaining Emissions Water/Air:

Assessment of pollutants (COD, nitrogen, phosphorus, greenhouse gases) remaining in the effluent or emitted into the air.

Target Values:
No gaseous emissions (<1%) are possible since the MFC is a closed system. Therefore a low greenhouse gas footprint compared to conventional wastewater treatment. CO_2 remains as HCO_3^- in purified wastewater (could be recovered). COD, NH_4^+, PO_4^{3-} and toxic trace elements levels shall comply with environmental regulations either for less than 10'000 Inhabitant installations or for larger WWTP systems.

f) Economic Factors / Commercial Viability:
Metrics relating to cost-effectiveness of MFC systems need to be defined, the development on the upscale design and operation are not resolved. And known KPI need to be fulfilled if it concerns large installations, for remote applications economies may need detailed assessments in a case-by-case approach.

Target Values:
Payback period is 10 years for public WWTP installations.
Affordability needs to be below 30 years of constant WWTP operation.

Technical KPIs

a) Restart or new start timelines: How long will it take to complete the start or restart of a new or otherwise idle MFC process into full operation? This should not last longer than two weeks (currently four weeks with a fresh start) for WWTPs in general and to some extent in remote location operations, such as alpine cheese making factories. The latter is every year start in Spring on high altitudes at relatively low temperatures, it has to work there as fast as possible.

b) Electrode cleaning:
Electrodes need to be cleaned or renewed from time to time, cleaning is seen as more sustainable but has to be cost-effective, financially and ecologically. Performance should be restored to >99%.

c) Cleaning and replacement of membranes: it should be feasible to clean membranes. The replacement requires a mechanical intervention and should be a simple process by an adapted reactor design. The challenge to open and close the reactor should be short, robotics is seen as a possible future tool to automate larger installations.

1.4.2 Planning and construction of a scale up microbial fuel cell unit made from concrete

The objective is to pioneer the development of a large-scale Microbial Fuel Cell (MFC) unit constructed from concrete. This MFC is abbreviated as “MFC300L”. This innovative unit houses multiple microbial fuel cells interconnected within it, similar to the previously utilized multi-unit MFC stack configuration. The system's operation will be powered by wastewater and cheese whey as the fuel source in separated processes.

This pioneering effort is a significant step forward in the application of MFC technology, as it explores the potential of concrete as a construction material for scale up MFCs. The interconnected setup of multiple MFCs within the unit holds promise for enhanced energy production and wastewater treatment efficiency. Moreover, the utilization of a unique combination of wastewater and cheese whey as fuel sources underscores the versatility of MFCs for handling diverse organic substrates for sustainable energy generation and purification of diverse wastewaters.

The MFC300L has a totally different spatial structure as the MFC1000L: in the MFC300L, water circulates vertically (from bottom to top), whereas the MFC1000L has a horizontal configuration and flux.

Moreover, the MFC300L is intended to be simpler to scale up in view of its architecture and operation, bringing it closer to a model that could perhaps one day be commercially viable.

This innovative project not only aims to advance the field of MFC technology but also has the potential to contribute to sustainable waste management and energy production in an environmentally friendly manner. Further research and development in this area may pave the way for new opportunities and applications for MFCs in diverse industrial and environmental contexts.

1.4.3 Second phase of the project

During the second phase of the project the objectives were to restart the MFC1000L that was initially cleaned and restarted to compare the new process phase with the previous one to determine the effectiveness of the revision. And after the acclimatation, i.e. after the biofilm has reached maturity, the goal is to recirculate the outlet wastewater into the cathodic compartment in order to reduce the ammonium concentration because previous studies showed that the ammonium reduction was insufficient to reach the legal level for release into the environment which correspond to 2 mg/l (“The Swiss Confederation, Water Protection Ordinance"). One of the goals for the MFC1000L is also to test electrode cleaning during the process according to the protocols previously established.

2 Conclusions

Both reactors were started in 2025 with wastewater as the inoculum. The start up with the 300 L reactor was realized with the protocol performed in the model analysis of 200 ohm and polarization showed that biofilms grew as expected. With the 1000 L reactor the voltage controller was activated and data recorded.

The performance of the two systems was in the expected range. The 300 L MFC did run stable and not structural abnormalities were observed. The design was in this way good enough to start the construction of a second 300 L reactor.

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