Universitat Autònoma de Barcelona
Facultat de Biociències

FINAL DEGREE PROJECT

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"Industrial project to convert Vic wastewater treatment plant into energetically self-sufficient using Microbial Fuel Cells"

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1. Description of the problem: Energy contained in wastewater is not well harnessed

"It is estimated that municipal wastewater contai
needed for its treatment in a modern municipal wastewater treatment plant (WWTP)" [5].

How to obtain more energy from wastewater is an unsolved issue that nowadays is being widely investigated by scientists from different approaches.

In the last decades, it has been an increasing need to use sustainable energy sources, to increase recycling and to reduce the human activity side products, such as wastewater. All, in order to reduce the environmental impact produced by human activity.

Microbial fuel cells (MFCs) are a technology that fulfills all these needs because it uses microorganisms that are not harmful or dangerous for the environment, it contributes to reducing the amount of residues dumped in watercourses, and produces sustainable and renewable energy.

2. Methodology for the elaboration of the project

Information from different scientific articles and books that talk about MFCs is used to explain the general and specific features of MFCs and how these could be applied in wastewater treatments. With this information, the best MFC approach is chosen to compare its characteristics and values with data of Vic wastewater treatment plant (WWTP) and to explore the feasibility of applying the MFC approach in Vic WWTP.

3. Objectives of the project

The aim of this project is to evaluate if electrogenic microorganisms, present in MFCs, are nowadays a feasible system to be used in Vic WWTP to cover all the energetical needs of the plant converting it into self-sufficient. Secondary objectives are to look over the economic costs and the effectivity of organic matter removal of MFCs if applied in Vic WWTP.

4. Materials and methods

As this project is completely theoretical, all the materials used are information, figures, tables and schemes obtained from different sources that are specified in the bibliography. This information is organized in three main sections: microbial fuel cells, Vic WWTP and equations to evaluate the data. Finally, the information from the different sections is integrated and treated in a way that permits us to evaluate the feasibility of the project, and to extract conclusions that meet with the objectives of the project.

Microbial Fuel Cells

Definition

A microbial fuel cell is a bio-electrochemical device that harnesses the power of microbial catabolic reactions to convert organic substrates directly into electrical energy (*Fig 1*) [6,7].

MFCs are a natural and sustainable technology with potential to be used in different applications such as bioremediation, energy production, or a mix of both.

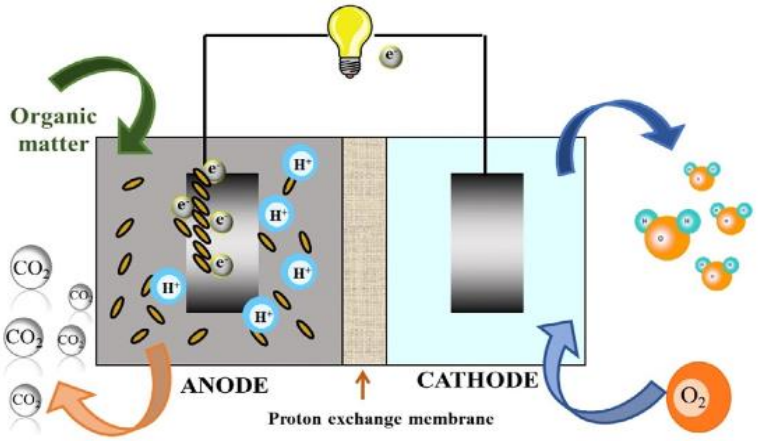


Figure 1. Microbial Fuel Cell scheme. *Image retrieved from Ref[7]*

Exoelectrogenic microorganisms

Exoelectrogenic bacteria are a group of microorganisms capable to transfer electrons to an extracellular electron acceptor (e.g. metal oxide, biofilm, cytochrome C). This kind of bacteria is used to power MFCs.
Bacteria produce electrons during the oxidative phosphorylation (to obtain ATP as a source of energy for the cell) and transfer them to a final electron acceptor element using an electron transport chain. The final electron acceptor is what differentiates the exo- and endoelectrogenic bacteria. Endoelectrogenic bacteria transfer electrons to an element inside the cell, while exoelectrogenic bacteria make it outside the cell. If a system with a cathode, an anode, and an external electric circuit is installed with these bacteria in a way that electrons can travel through it, it is possible to obtain energy creating the so-called MFC [6,7].

Exoelectrogenic species used in MFCs:

There are different species of bacteria, algae or even yeasts that are able to produce electricity. There exist a great variety of organisms that have shown to be electrogenic, and the taxonomic structure of these communities used in MFCs is highly variable. Nevertheless, trends nowadays usually include an enriched mix of electrogenic communities with a large proportion of Proteobacteria. Moreover, in MFC, the non-electrogenic microorganisms are also believed to assist in electricity generation through syntrophic cooperation with the electrogenic bacteria [6,7].

MFCs without mediators

The first MFCs models needed mediator components such as thionine, methyl blue or humic acid, that facilitate the transference of electrons from the bacteria to the anode [6]. Most of these components are toxic for the environment, for this reason, it made no sense to use mediator-dependent MFCs to treat wastewater. To this day, different systems with MFCs in which the transmission of electrons from the bacteria to the anode is done without mediators have been developed. Therefore, the technology can be used as a wastewater treatment because it does not generate toxic products. Geobacter biofilms are an e capture and transmit electrons to an external circuit [2].

Superexchange

It is the basis of MFCs mediator-less electron transfer. In *Geobacter* MFCs, electrons resulting from intracellular acetate oxidation of a microbe are transported from the cytoplasm to cytochromes present in the outer membrane of the cell. Once in the extracellular environment, electrons are transferred between c-type cytochromes, that are either on cell outer membranes, aligned along pili or in the extracellular polymeric substances. Electrons move through cytochromes until they reach the biofilm/anode interface, where they are finally transferred to the anode and through the external circuit until reaching the cathode (*Fig. 2*) [2].

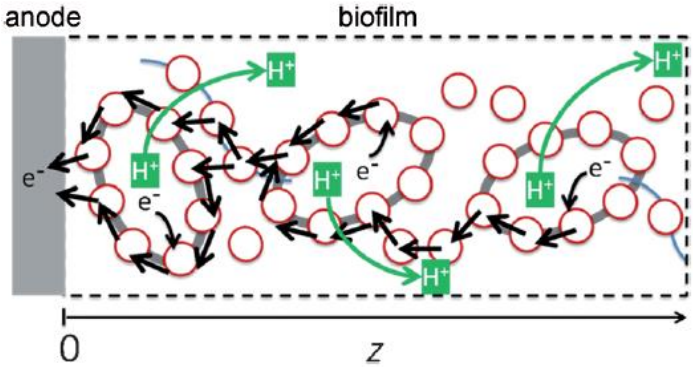


Figure 2. Electronic transference in a MFC biofilm. *Image retrieve from Ref.[2].*

To sum up, these electron transference circuits make electrons go from elements with more negative potential (the substrate of the media) to elements with more positive potential (the anode). This means that it is very important to have sufficient positive potential in the anode, which will depend on its material, and negative potential in the substrate to create circuit this "potential gradien

Architecture of MFCs

Basic components

All the following basic components and materials of MFCs [8] are represented in (*Fig.3*).

a) *Anode and cathode*

They are usually made of carbon because it is versatile, biocompatible, chemically stable, and conductive. It is available in various forms: graphite plates, granules, fibers, etc. In addition, these materials are quite cheap.

b) *Separator/membrane (PEM = Proton Exchange Membrane)*

It only permits cations to cross-over facilitating the H^+ exchange from the anolyte to the catholyte and avoids the passage of oxygen to the anolyte, which would reduce the oxidation reaction rate.

Nafion, a synthetic polymer based on tetrafluoroethylene has been the most used material in PEM for MFCs. However it is very expensive, and the membrane gets clogged easily, what makes it a non-optimal material to use in scale-up. Other low-cost materials such as natural rubber, glass wool or expanded polystyrene can be used with an efficiency that is competitive with Nafion.

Number of compartments

a) *Two-compartment MFC*

It contains an anodic and a cathodic chambers separated by a proton exchange membrane or a separator to allow proton transportation to the cathode while restricting the diffusion of oxygen into the anode (*Fig. 3*) [8].

b) *Single compartment MFC*

It is based on a simple anodic chamber without a defined cathode compartment. The cathode, usually in the presence of a catalyst is on the exterior side of the wall of the anodic chamber and utilizes atmospheric oxygen for the cathodic reaction. These designs are simpler, cheaper and, therefore, extensively utilized for research (*Fig. 4*) [8].

c) *Other designs*

Apart from the two classical designs explained before, there exist some other designs regarding the number of compartments such as membrane-less MFCs or multiple anode chamber MFCs [8].

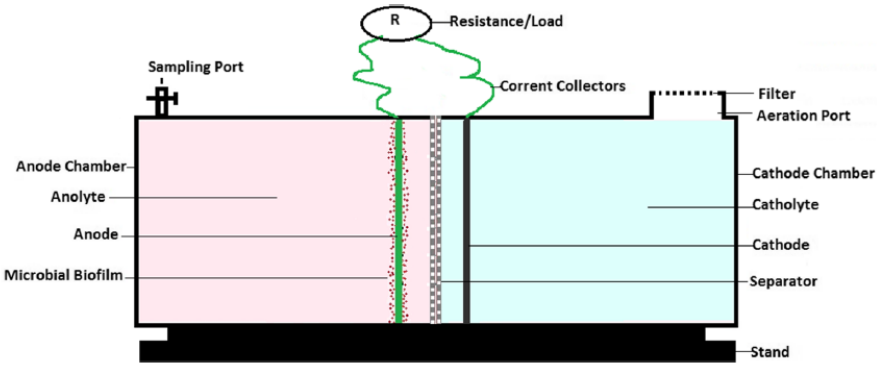


Figure 3. Schematic representation of a two-compartment MFC. *Image retrieved from Ref.[8]*

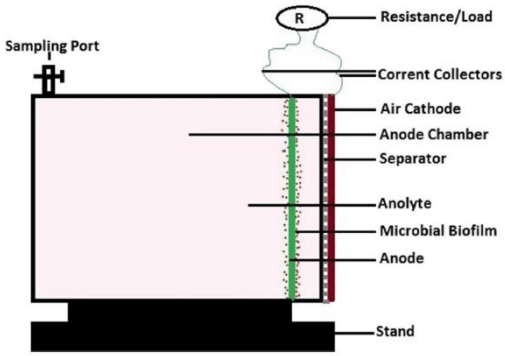


Figure 4. Schematic representation of a single-compartment MFC. *Image retrieved from Ref. [*

Shapes

The most common shapes used in scaled-up MFCs are tubular or plate reactors [7]:

a) *Tubular configuration*

A tubular anode is surrounded by a separator to isolate the anode from the cathode electrically. The cathode is wrapped around the separator.

b) Plateconfiguration

It consists of different rectangular plates with the separator sandwiched between the anode and the cathode (*Fig.8*).

It's not whether one design of MFC is better or more effective than others to apply in a WWTP, this will depend on the needs and characteristics of the system.

The internal resistance

The internal resistance involves ohmic, kinetic and transportation resistance, and these magnitudes should be reduced as much as possible to enhance the power output of the MFC [9].

Ohmic resistance is usually higher if we increase the ion transport distances and/or the reactor volume (*Fig. 5)* [4]. For this reason, to achieve a more efficient strategy in the scaling-up of MFCs, instead of having one big individual reactor, different MFC modules are stacked together with each module having their electron and cathode as close as possible [3,7].

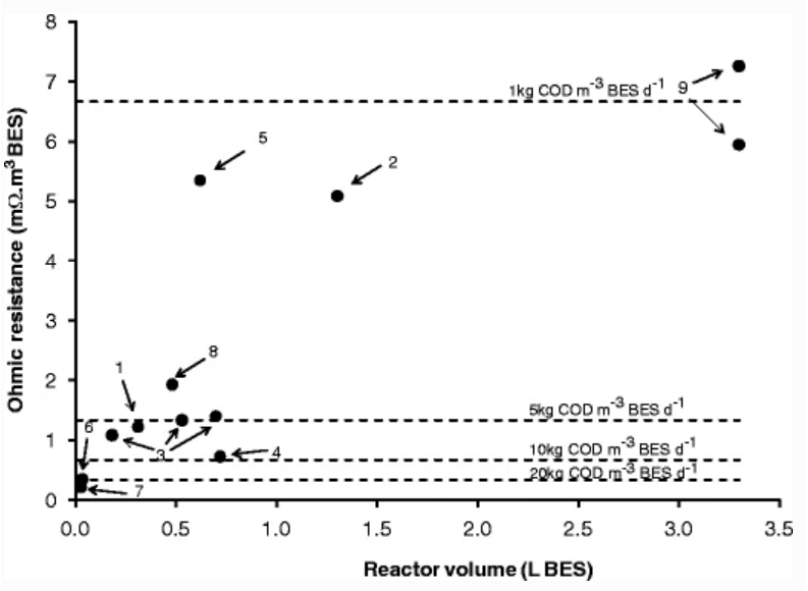


Figure 5. Ohmic resistance – Rector volume. *Image retrieved from [4*

The kinetics reaction rate per volume is related to the effective electrode surface area. This effectiveness usually decreases with the enlargement of the MFC reactor [4]. In scaling-up strategies, usually porous electrodes that occupy the whole electrolyte space are used to have the maximum rate: anode surface/volume. Transportation resistance is significant when MFCs treat a very diluted substrate, however, this can't be changed in a WWTP, because it will depend on the organic matter concentration of the wastewater that is arriving in every moment.

Electric circuit connection mode

Connecting multiple MFCs electric circuits in series increases potential and in parallel increases the current. In both cases power is increased [7].

Substrate

Regardless of the type of organic compounds contained in the fuel it is also very important that the fuel source has enough concentration of nutrients, adequate pH and conductivity to feed exoelectrogenic bacteria. Control of these values is necessary to be able to decide if the system has to be stopped until normal values are recovered to avoid greater problems such as the death of the microorganisms [7].

Studies in which a specific MFC design was analyzed used synthetic solutions to emulate wastewater composition [9] or simpler solutions such as pure glucose or acetate [3].

Vic Wastewater Treatment Plant

Processes and organic matter concentrations

DATA OF VIC WWTP (2019)											
	Flow rate (m^3/day)	COD									Electric energy consumption (Kwh)
		Water line initial and final values			Biologic reactor						
		Inital inflow (mg/L)	Final outflow (mg/L)	Removal efficency (%)	Water inflow (mg/L)			Water outflow (mg/L)	Removal efficiency (%)		
					From primary decanter	By-passed	Total				
January	23.910	656	36	94,5%	421	196,8	617,8	43,27	93,0%		405.309
Febrauary	21.701	794	43	94,6%	438	238,2	676,2	51,68	92,4%		351.608
March	20.172	860	41	95,2%	495	258	753	49,28	93,5%		381.827
April	21.314	776	32	95,9%	454	232,8	686,8	38,46	94,4%		367.703
May	23.235	816	32	96,1%	480	244,8	724,8	38,46	94,7%		393.995
June	19.995	872	41	95,3%	511	261,6	772,6	49,28	93,6%		372.519
July	19.149	818	45	94,5%	529	245,4	774,4	54,09	93,0%		406.283
August	17.778	706	40	94,3%	465	211,8	676,8	48,08	92,9%		356.852
September	20.646	779	37	95,3%	460	233,7	693,7	44,47	93,6%		362.443
October	20.370	1.064	38	96,4%	507	319,2	826,2	45,67	94,5%		411.520
November	20.762	1.054	41	96,1%	524	316,2	840,2	49,28	94,1%		402.887
December	21.074	790	41	94,8%	530	237	767	49,28	93,6%		388.236
Total year	250.106	9.985	467	-	5.814	2.996	8.810	561	-		4.601.182
Average	20842,17	832,08	38,92	95,3%	484,50	249,63	734,13	46,77	93,6%		383431,83
Designed for	25.000	1.616	-	-	-	-	-	-	-		-
CV	7,9%	14,6%	10,4%	0,8%	7,6%	14,6%	9,0%	10,4%	0,8%		5,5%

Table 1. Annual analytic report of Vic WWTP (2019).
"Designed for" refers to the maximum flow with which the plant was designed to operate. "CV" is the variation in % (standard deviation/average = [illegible]). "By-passed water" is 30% [illegible] been calculated assuming that the secondary decanter works the same way as the primary decanter. In this decanter 83,2% of the COD inflow goes out to the biologic reactor. With this and knowing that the final outflow is the same as the secondary decanter outflow we could calculate the incognita. "Removal efficiency average [illegible] (0,8%) [illegible]
All the data of the table has been obtained from Ref. [1] and through personal communication with Pere Parés i Cuadras, laborato [illegible]

Functional steps or processes with its water Chemical Oxygen Demand (COD) variations in Vic Wastewater treatment plant are explained here. We can use the 2019 average COD as constant reference because the CV is relatively low between months.

Vic WWTP steps (*Fig. 6, 7*):

- Water inlet ("Entrada de l'aigua")
- Roughing unit (1)
  There is a screening to remove large debris.
- Sand trap and degreaser (2 and 3):
  Sand and other relatively large solids fall by gravity and are removed from the media from the tank bottom. Fat goes to the surface by flotation due to density difference and is removed from the tank top. At Vic WWTP these steps are fused in one single step even that in (*Fig. 6*) appear as two different steps.
- Primary decantation (4)
  Before this step COD is 832 mg/l. Only 70% of the water goes into the process, meaning that the actual COD entering the decanter is 582,4 mg/L. The other 30% is bypassed directly to the biologic reactor. In this tank, water (with dissolved organic matter) is separated by decantation from solid particles (organic and inorganic matter) that are settlable. Here the process diverges in two treatment lines: sludge line (7 to 9) and water line (5 and 6). Sludge with water extracted from the bottom goes to the sludge line. Water extracted from the top goes to the waterline and has a COD of 484,5 mg/l.

¶ Biologic reactor (5)

In addition to water coming from the primary decanter (COD = 484,5 mg/L), we also have water coming from the by-pass made between steps 3 and 4 (COD = 249,6 mg/L). The bypass is made to have enough carbon concentration for bacteria to denitrify the water. All in all, water entering this step has a total COD of 734,13 mg/L.

In this process different microorganisms oxidize the organic matter, organic nitrogen and ammonia present in water and convert them into microbial mass. Air with oxygen is introduced so that the lack of O_2 is not a limitation for the reaction. Water then goes to the secondary decanter with a COD of 46,7 mg/L.

¶ Secondary decantation (6)

Water is separated from the microbial mass by decantation. All the microbial mass and the remains of inorganic matter (biologic sludge) precipitate to the tank bottom. Part of the microorganisms and sludge are redirected back to the biologic reactor to maintain the microorganisms population. The remaining are redirected to the sludge treatment. Purified water is sent back to the river with a COD of 38,9 mg/l.

¶ Sludge treatment (7)

Sludge is mixed, homogenized and partially dried by water evaporation. Once sludge is concentrated enough is sent to the anaerobic digester.

¶ Anaerobic digester (8)

Organic matter present in the sludge is converted into methane due to anaerobic digestion made by microorganisms. This methane is a source of energy that is sold later.

¶ Sludge dehydrator (9)

The remaining sludge that comes out from the anaerobic digester is dried and sent to a controlled deposit or is used as compost.

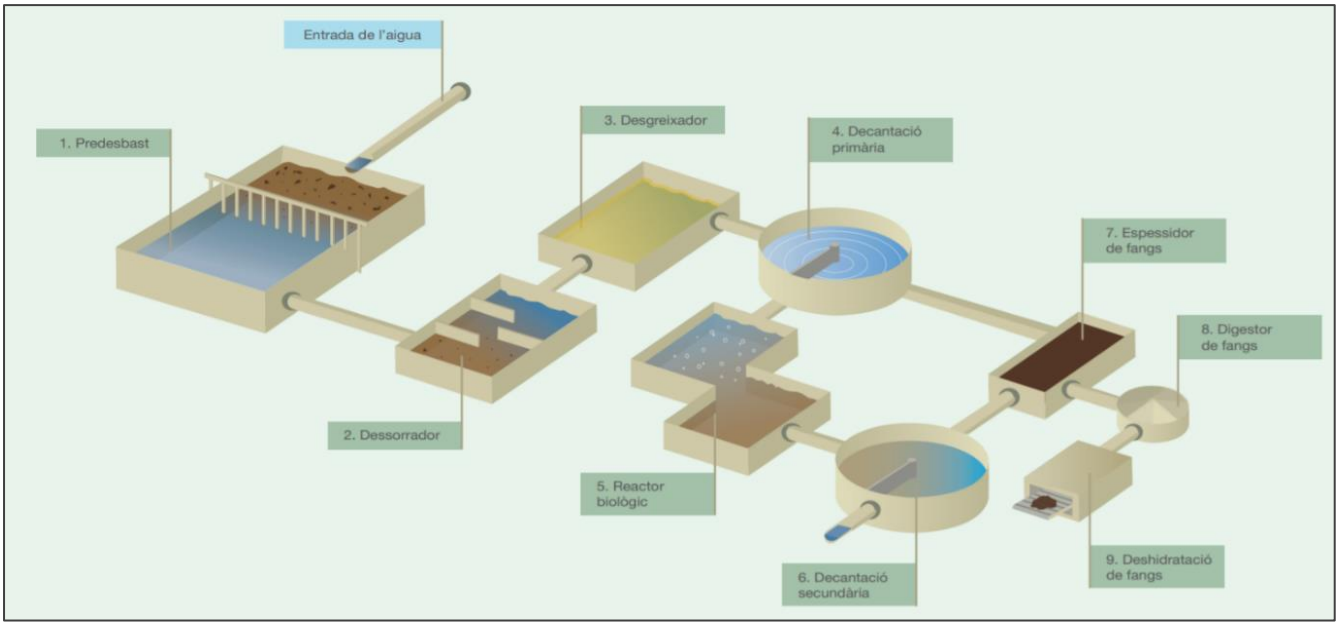


Figure 6. Water purification processes of a WWTP. *Image retrieved from [1]*

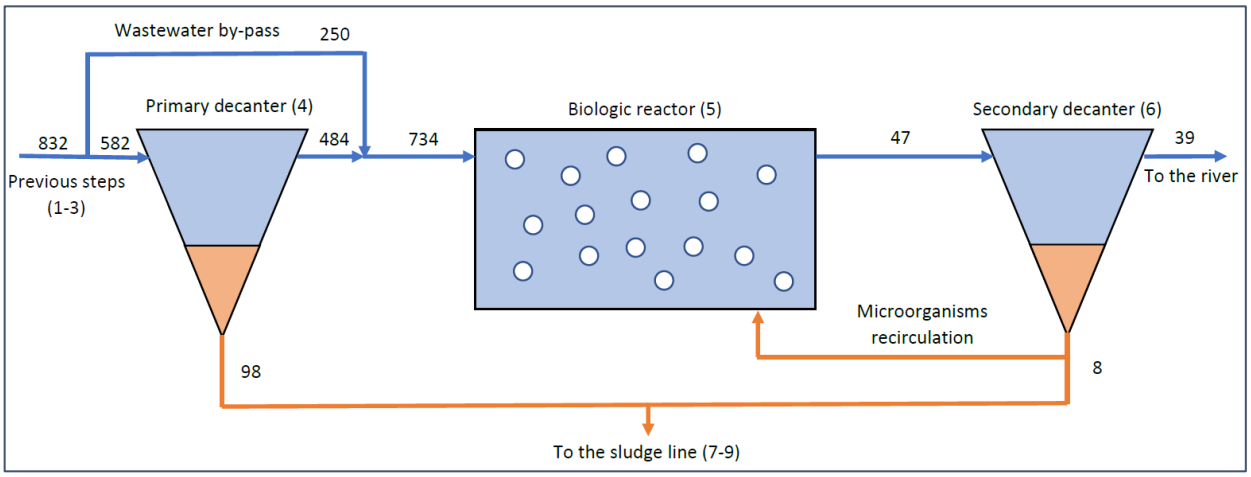


Figure 7. Water purification steps of Vic WWTP. Numbers above arrows are the COD values of the water in each step, expressed in mg/L. These COD values are rounded to the units. Numbers in parenthesis coincide with the process steps listed before and with numbers in *Fig.6. Informationobtainedfrom Table 1*

Equations to evaluate the MFC

All the equations of this section are obtained from Ref. [6].

Power generation

Power density

It permits the comparison of different MFC systems. It is a normalization of the power produced by a MFC depending on the volume of the reactor:

$$P_v = \frac{E_{MFC}^2}{v\,R_{ext}}$$

P_V = power density (W/m^3)
V = total reactor volume (m^3)
E_{MFC} = voltage (v)
R_{ext} = exterior resistance

This magnitude is the easiest to use when comparing the energy production of different MFCs. Usually, WWTP give us the water flow in terms of volume/time at which it operates, and MFCs for this application usually d o n ' t only have flat surface as anode, but they rather have porous anodes that occupy a specific volume so that the anode area of contact with the wastewater is very irregular and difficult to calculate. For all these reasons, it is better to have the power normalized for the reactor volume and not for the anode or cathode surface.

Coulombic efficiency (C_E)

Coulombic efficiency is the fraction of electrons recovered as current and the fraction of electrons present in the substrate. The closer to 1 (or 100%) the more efficient is the system.

$$C_E = \frac{\text{Coulombs recovered}}{\text{Total coulombs in substrate}}$$

COD removal efficiency

It is the amount of COD that a treatment can remove from the media, in other words, COD removal efficiency is the relation between the effluent COD (after the treatment) and the influent COD (before the treatment). In WWTP, this magnitude is very important to be as high as possible, otherwise, water cannot be liberated again into nature because high organic matter concentrations could damage the environment.

5. Description of the solution: Proposed MFC application design for Vic WWTP

Architectural and technical characteristics of the proposed MFC

Taking into account all the information referred to MFCs explained before, we can say that the optimal MFC to operate at a big scale in a wastewater treatment plant should have the following conditions:

- The whole MFC system should be composed of different small MFC units connected in parallel between them in a continuous operational mode water circuit (water flow is going through the system all the time).
- The design should permit to connect new units to amplify the capacity of the system through the years, if necessary.
- Each MFC unit should have its electrodes separated by a distance smaller than 10 cm and the anode surface-volume ratio of the MFC unit should be as high as possible. These conditions are essential to reduce the internal resistance of the system [9].
- Materials, especially the ones used in the anode, the cathode, and the proton exchange membrane should be cheaper and durable for a long time [7].
- Exoelectrogenic microorganisms should be an enriched mixture of species with a large proportion of proteobacteria [8].

After an exhaustive research into the literature to find the best MFC in terms of power production that also fulfills the conditions explained before, I decided to use the pilot-scale stacked MFC design created by Shijia Wu [9]. In this paper I also found enough data related to values of energy production, COD removal efficiency, flow rate and reactor volume among other magnitudes that will be needed to consider the feasibility of the project.

The design created by Shijia Wu consists of a MFC unit with three anodic and three cathodic chambers stacked alternately between them and separated from the adjacents by a cation exchange membrane (CEM) (*Fig.8C*). All the chambers have the same size: 90 x 40 x 5 cm (0,108 m^3). The external casing of each chamber is made of polyvinyl chloride. The internal volume of each electrode chamber is 12L, amounting to a total internal volume of 72L for the whole MFC unit.

Both anode and cathode chambers are packed with small activated carbon granules creating a porous packed bed that works as base over which microorganisms produce its biofilm. Catholyte and the anolyte flow goes through the porous (*Fig.8B*). With this strategy, the electrode surface-volume ratio is very high.

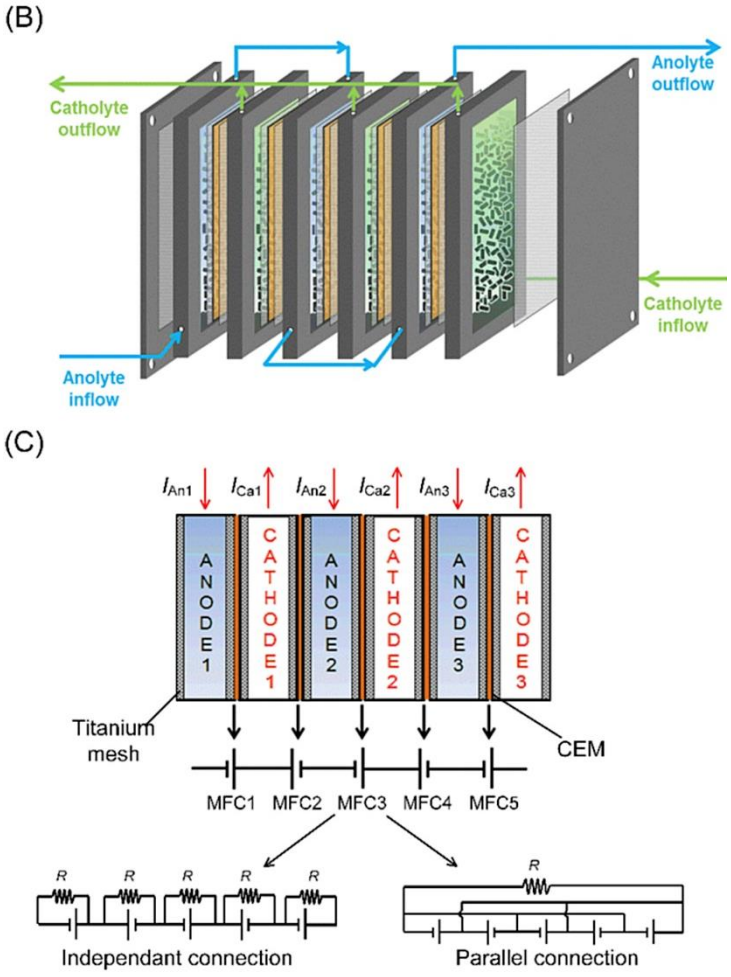


Figure 8. The MFC model architecture. *Image retrieved from Ref[9]*

The system works on continuous operation mode with both anolyte and catholyte flowing through independent circuits. On the one hand, the three anode chambers are connected in series by the anolyte flow (*Fig.8B*), which is a synthetic medium composed of CH_3COONa, H_2O, NH_4Cl and phosphate salts in proportions that emulate wastewater composition. On the other hand, the three cathode chambers are connected in parallel by a circular catholyte flow (*Fig.8B*), mainly composed of a sodium bicarbonate solution with other salts that is aerated on a external bucket to increase the amount of dissolved oxygen.

Both cathode and anode chambers have titanium meshes disposed on both sides of each cation exchange membrane and two more meshes are set on the blind side of the anodic and cathodic chamber ends. The whole MFC unit counts with a total of 10 titanium meshes (*Fig.8C*). These titanium meshes are used as inner current collectors and are connected between them in parallel (*Fig.8C*) to an external electric circuit through which the energy is obtained.

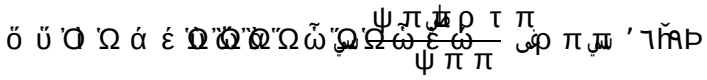
The anodes and the cathodes are inoculated at the beginning with anolyte and catholyte effluent obtained from a microbial desalination cell (similar to a MFC) of the authors' laboratory. In the article, the exact microbial population of the MFC is not analyzed or described, but it seems to be a heterogeneous community.

Power density production, anolyte flow, reactor volume, COD removal and coulombic efficiency of the proposed MFC

Working in continuous operation, a single MFC unit can produce a power density of 42,1 W/m^3 (*Fig.9A*) when the system has an influent COD of 800 mg/L [9].

The system works in an optimal anolyte flow rate of 12,6 mL/h or 3,024·10^{-4} m^3/day. The total volume of the unit is 72L or 0,072 m^3, meaning that the volume of each electrode is 12L, with only 5L of liquid volume [9].

The COD effluent is about 140 mg/L when the COD influent is 800 mg/L (*Fig 9B*). This means that the COD removal efficiency is 82,5%.



The coulombic efficiency (CE) is 14% [9].

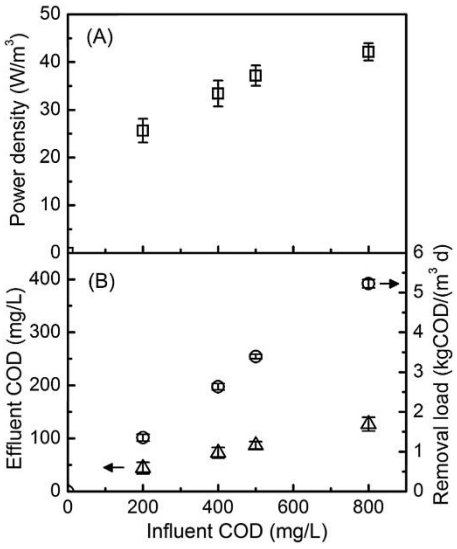


Figure 9. Power density (A) and COD removal (B) of the proposed MFC. Influent and effluent CODs are represented by triangles. Image retrieved from *Ref.[9].*

These values remained more or less constant during 6 months without changing any MFC component. Six months was the maximum amount of time during which the MFC was analyzed [9].

MFC applied in Vic WWTP

In the current Vic WWTP scheme the proposed MFC (*Fig. 8*) should substitute the biologic reactor unit (*Fig. 6, 7*). This substitution is the best possible to reduce the impact in terms of money spent and infrastructural changes but also to have the best energetical yield and COD removal efficiencies for the plant.

All the other processes of the plant should be maintained. The prior steps to the MFC (*1-4 in Fig6*) are needed to reduce the amount of organic and inorganic particles such as sand, sludge and fats that, otherwise, would plug the pores of the anode chamber. The by-pass of sludge from the primary decanter to the MFC could be maintained to achieve a higher amount of substrate oxidized by the microorganisms (approx. COD = 734,13 mg/L) that is translated in a higher energetical production. The following steps to the MFC (*6-9 in Fig6*) should

be maintained. In the case of the secondary decanter, to purify the water in a higher degree before returning it into the river; and in the case of the sludge line, to obtain energy through the anaerobic digestion and to dry the remnant sludge.

Vic WWTP is designed to treat a maximum flow rate of 25.000 m^3/day or $1{,}04 \cdot 10^6$ ml/h (*Tab. 1*). The optimal operation flow rate of a MFC unit is $3{,}024 \cdot 10^{-4}$ m^3/day. If the MFC has to be able to operate in moments of maximum flow rate, the plant has to count with a minimum of 82.671.958 MFC units connected in parallel. This amount of units occupy a volume of $8{,}93 \cdot 10^6$ m^3. This is an important drawback because the whole system should need an enormous space.

Nº of MFC units =

Whole MFC system volume =

The average Vic WWTP flow rate for the last year 2019 was 20.842 m^3/day (*Tab.1*). The average COD analyzed before the primary decantation in the same year was 832 mg/L (*Tab. 1*). However, part of this organic matter is lost in the sludge, so we will focus on the average COD value of the water before entering into the MFC, that is 734,13 mg/L (*Tab. 1*, *Fig7*). The relation between COD influent and energy density production is not linear (*Fig. 9A*), so we can easily interpolate which would be the corresponded energy production to 734,13 mg/L of COD. As this value is so close to 800 mg/L, we will assume that the COD entering at Vic WWTP is 800 mg/L. This organic matter concentration produces power densities of approximately 42,1 W/m^3. The daily power production of the MFC in this conditions would be 877,45 kW/day.

Vic WWTP total energy or power consumption in 2019 was 4.601.182 kWh (*Tab. 1*), translated to an average power consumption per day this is 12.605,98 kW/day. Then, taking on that no extra energy would be spent for the MFC catholyte aeration (it should be the same energy presently spent for the biologic reactor aeration) and assuming MFC inflow COD to be 800 mg/L, the energy or power produced by the system wouldn't be as high as the energy or power spent. In fact, it would only cover the 7% of the power produced in the plant or, in other words, the plant would have a power balance of -11.728,53 kW/day.

Apart from the energetical issue, it is also interesting to stress that the COD removal efficiency for the current biological reactor is 93,6% (*Tab. 1*) and for the MFC is 82,5% (*Fig. 9*) [9].

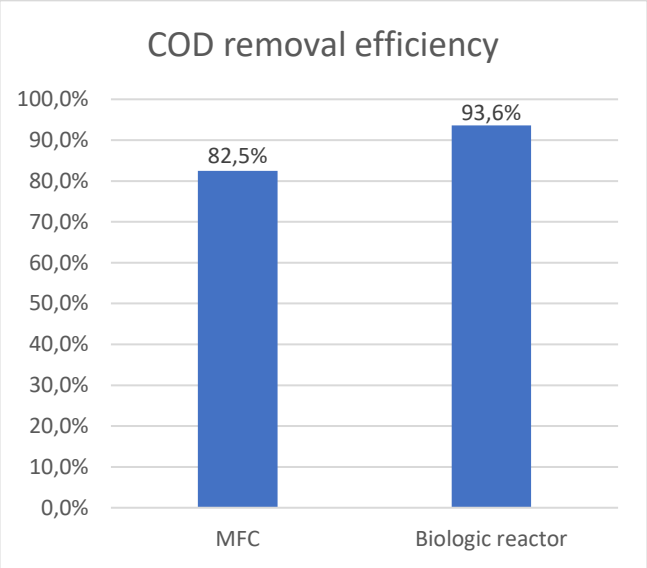


Figure 10. COD removal efficiency comparison between the current WWTP biologic reactor and the prosed MFC. *Information obtained from Table 1*

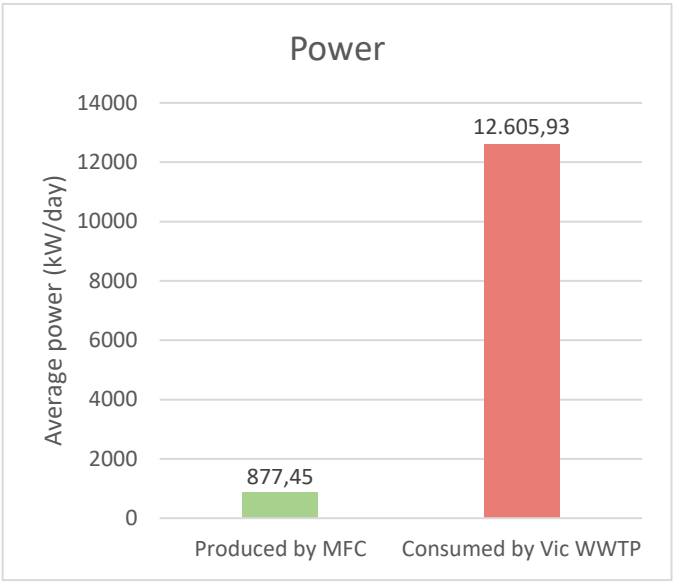


Figure 11. Comparison of power produced by the proposed MFC and power consumed by Vic WWTP. *Information obtained from Table 1*

(*Fig. 12*) presents a general view of the energetical and economical costs of MFCs compared to activated sludge systems, the most used nowadays in WWTP. In this data from 2013 we can see that the initial capital cost is considerable, mainly due to expensive materials used in MFCs [5], and the energy produced is not high enough to neutralize the energetical costs needed for the MFC operation. Though, these energetical costs are considerably less than for the activated sludge system.

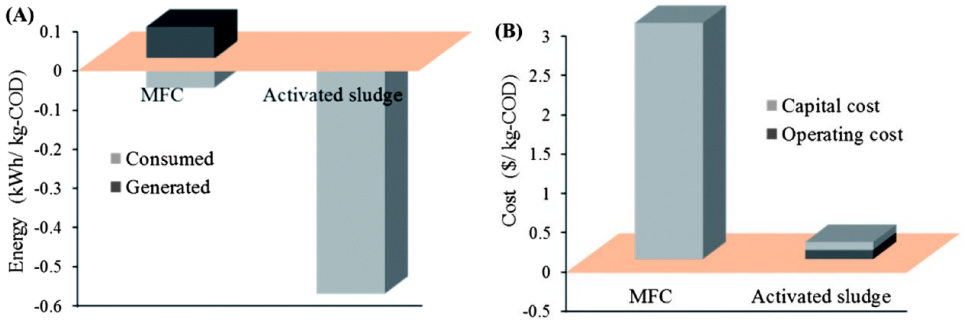


Figure 12. Energy generated and consumed comparison (A) and estimated costs compoarison (B) for MFCs and Activated sludge systems. *Image retrieved from Ref[5].*

6. Conclusions

Before drawing any conclusion, I would like highlight that all the data and calculations are made in a theoretical basis. This means that there have been a lot of assumptions to approximate values as much as possible to the reality of Vic WWTP plant and the proposed MFC. Even if I consider them good enough to evaluate the feasibility of the project, the best way to assess this would be scaling-up the MFC and testing it in similar conditions to those of Vic WWTP.

After gathering all the data, we can conclude that microbial fuel cells are not capable to produce enough energy applied in Vic wastewater treatment plant to cover all its energetical costs, in other words, this system is still not good enough to make Vic WWTP energetically self-sufficient (*Fig. 11*).

Even that from an energetical point of view the main objective of the project is not feasible, the proposed MFC has a COD removal efficiency quite similar to the biologic reactor of Vic WWTP (*Fig. 10*), meaning that it could substitute its function in terms of organic matter elimination without producing significative changes in the final COD. Apart from the organic matter removal, MFCs are also really appreciated to achieve a much higher volume of sludge removal compared to conventional aerobic oxidation treatments [7], this gives an extra worth for MFC to be applied in WWTPs.

Furthermore, we should also evaluate another key aspect before consider applying MFCs into WWTP: the economic cost. In this project we have not provided much data related to this field as it was a secondary objective. Though, the current materials used in MFCs are broadly expensive [5,7], causing the initial and maintenance costs to be too high to scale-up the system into an industrial application such as a WWTP. Especially if we compare it to the cost of t o d a systems used in WWTPs, the activated sludge, that is much cheaper. Nevertheless, if the energetical production of MFC was high enough, the cost of the energy for the operation of the plant would be reduced. At this point, we could try to assess a long-term economic yield comparison between the total costs of the system with MFC and with activated sludge to see which is cheaper. It may seem to be unimportant, but in all these calculations we should also consider all the amount of sludge that MFC would save us to treat afterwards in comparison to conventional aerobic oxidation treatments. Reducing the amount of sludge to treat would be a significant saving of time and money. Finally, we also have to say that with this MFC design, we would need a very large space in which the proposed MFC system would be built, and this supposes to spend extra capital for the construction of the building and the equipment.

Albeit the application of a MFC into WWTP is not workable nowadays, at least as it is done in this project, I believe that further investigation in the optimization of the energy production density; as the current C_E is only 14%; and the reduction of the economic costs could allow the scale-up of MFCs to make this application possible. Apart from the WWTP application, MFCs are very useful technologies and they have great potential in other environmental applications such as bioremediation of contaminated soils, powering-up small sensors for the analysis of pollutants, detecting toxic compounds or quantifying organic loads among others [7].

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