A critical view on microbial fuel cells: what's the next stage?

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Abstract

Background: MFCs has focussed the interest of the scientific community since the beginning of this century, which an outstanding increase in the scientific production over the last years. Thus, they approach the very remarkable number of 7000 scientific contributions only in 2017. However, the power generation has not increased considerably within this time frame. In fact, over the last years, it has practically stagnated due to the difficuties in the scale-up of the technology, revealing that their applications for powering high-energy demanding systems are not going to be fully developed, at least within a short temporal horizon, despite their potential benefits.

Results: Scale-up by increasing the size of the electrodes failed, because of the wrong assumption that a linear function described the relationship between the amount of power generated by MFCs and its size. It has been found a more efficient energy harvesting in smaller MFCs, mainly because of the reduction of the electrode spacing, the edge effect, the increase of the surface area-volume ratio and the decrease of the internal resistance. These features benefit the supply and diffusion rate of substrate and nutrients, the electron collection in the anode and the proton diffusion from the anode to the cathode. In turn, they lead to a new approach of scaling-up, based on minituarization and replication. MFCs can be connected connected electrically in series to increase the overall potential and in parallel to increase the overall current. However, cell voltage reversal and ionic short circuit issues must be solved in order to success in this approach.

Conclusions: Nowadays, and according to reported results, the applicability of the MFC technology in wastewater treatment does not make any sense at the light of the power levels reached, despite of the great variety of substrates that can be used and that it was seen as a paramount opportunity less than a decade ago. However, the electricity produced by MFCs can be used for powering other technologies such as biosensors, biologically inspired robots, remote devices, small electronic devices and even low energy demanding illumination.

Highlights

- Stagnation of MFC due to the difficuties in the scale-up.
- Success in number of publications constrasts the failure in getting high powering.
- Powering small technologies as the main application of MFCs
- WWTP cannot be powered efficiently with this technology in a short time period.
- Low selectivity for fuels: great variety of substrates can be used as fuel.
- Great variety of fields involved currently in MFC research.

Keywords

Microbial fuel cell; scale-up; wastewater; fuel; minituarization; stack

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Looking for new ways to manage energy: what is and why is important the microbial fuel cell concept?

An electrochemicall cell is a heterogeneous reactor in which redox reactions take place in the interfaces between electrons conductors (electrodes) and ion conductors (electrolyte). In fact, this type of reactor consists of two half-cells connected (namely anodic and cathodic compartments) and each half-cell contains an electrode (a metal or any other electron-conducting material) and an electrolyte (a liquid solution or a solid, with the capability of allowing the transport of ions through it). In many cases, the anodic and the cathodic compartments are integrated into a single electrolytic compartment. In others, the separation is obtained with the use of macroseparators, microseparators or ion exchange membranes.

The oxidation occurs on the anode surface, while the reduction takes place on the cathode. The electrolyte allows the transport of ions in each half-cell, from the anode to the cathode and vice versa. The electric current flows from the anode to the cathode through an external circuit, because of the potential difference produced between both electrodes (E). This cell voltage is related to the Gibbs' free energy on the Equation 1, where n is the number of exchanged electrons and F is the Faraday constant.

$$\Delta G = -nFE \qquad (1)$$

When G is lower than 0 ($\Delta G<0$), the process proceeds spontaneously and the cell transforms the energy produced by an spontaneous chemical reaction into electrical energy. Opposite, when this value is positive ($\Delta G>0$), the process is not spontaneous, although it can transform electric energy into a chemical energy by favouring oxidation-reduction reactions that does not occur spontaneously. There are many examples of electrochemical cells in which the free energy is negative. Many corrosion processes can be understood if they are interpreted in terms of this type of cells. However, the most important cells are those developed for transforming energy, where we can find batteries (discontinuous electrochemical cells), redox flow batteries and rechargable batteries (semicontinuous electrochemical cells) and fuel cells (continuous electrochemical cells).

Despite the great variety of applications of the batteries nowadays, the development of fuel cell can be more interesting from a researcher's perspective because there are many weaknesses that have yet to be solved, in particular those related with the catalysts used to transform the fuel into electricity. Thus, except for the case of platinum (alone or in combination with other metals) in the oxidation of hydrogen, methanol and other short-carbon chain alcohols or carboxylic acids at low temperature (PEMFC technology) and other cheaper metals, which allow the oxidation of simple hydrocarbons at very high temperatures (SOFC technology), there are not general catalysts which can face efficiently the oxidation of more complex organics.

Because of that, during the last decades, the use of bacteria as catalyst has gained special attention in this field, leading to the concept of Microbial Fuel Cell (MFC). The uniqueness of biocatalysts is that the catalytic efficiency depends on the microbial interactions in the community among them and with the electrodes of a fuel cell. These types of bacteria are called exoelectrogens. In its name, `exo-´ is referred to exocellular and `electrogens´ is related to its ability to transfer electrons to insoluble electron acceptors (1). The positive point is that this type of microorganisms (also called bioelectrogenic microorganisms) are not limited to the use of the same simple fuels than the inorganic catalysts, but they can also face the oxidation of more complex fuels (2). One of the cheapest fuel can be wastewater. For this reason, microbial fuel cells are frequently related to the treatment of wastewater, but this is not the only application. In fact, it can be one of the less interesting future applications, as it will be pointed out throughout this review.

In order to understand how a MFC works, a typical MFC scheme is shown in Figure 1. The MFC shown consists of two electrodic chambers (anodic and cathodic) and a semipermeable membrane between the electrodes. Bacteria oxidizes the substrate in the anodic chamber generating protons and other metabolic products, generally CO_2. The electrons are collected in the anode and travel to the cathode through an external electrical circuit, while protons pass from the anode to the cathode through the membrane. Once both electrons and protons reach the cathode, they are combined with oxygen molecules to carry out the reduction of oxygen into water.

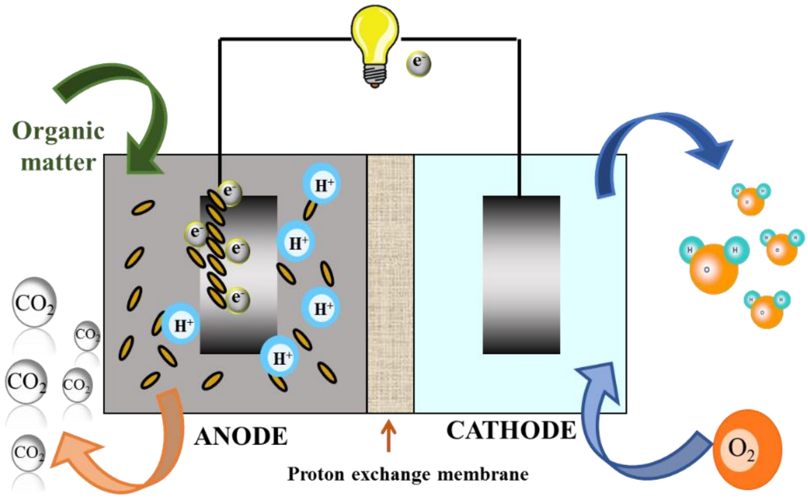

Figure 1. Typical scheme of a MFC.

Wastewater treatment with MFC: Are MFCs a feasible green alternative?

Despite of the interest of the National Aeronautics and Space Administration (NASA) to transform organic waste into electricity in long journeys during the 60s, and the good perspectives of this technology to reach this goal, the conception of MFC with two chambers (anodic and cathodic) separated by an ion exchange membrane was developed several decades later in the 70s and 80s (3) (with the exception of some pionering works, published since the very beginning of the 20th century, which pointed out the feasibility of the MFC concept and focused on the fundamentals). At that moment, the concept of bacteria catalysts in MFCs started to be fully explored not as a scientific curiosity but as a promising technology (4, 5). Thus, in 1991, the posibility to treat wastewater in MFCs was demonstrated (6). However, the power production was very low and the impact of the technology in reducing wastewater strength was not clear at all. It was not until 2004, when the feasibility of the link between the production of electricity and wastewater treatment was demonstrated by Liu et al (7, 8) by achieving practical treatment levels, while simultaneously it was generated significant amounts of electricity. This was an starting point in the massive evaluation of the technology.

However, the turning point was a theoretical and very optimistic study based on the extrapolation to full-scale of real data obtained at the lab-scale (9). It was pointed out that 2.3 MW could be produced simply by using the domestic wastewater of a town of 100000 inhabitants (assuming a load of 300 mg BOD L^{-1}). According to this study, with an optimized technology, this could result in a saving of $1 millions per year (assuming a cost of $0.05 kWh $^{-1}$) and in more than 1500 homes fully supplied with this power (assuming a consumption of 1.5 kW per home) (1).

This study attracted the interest of a large number of researchers because of the potentially feasible revolution in the wastewater treatment field. As it is well known, the conventional aerobic treatment requires an aeration process, which increases considerably the operation costs of a wastewater treatment plant (WWTP). The energy consumed by the aeration is over 0.5 kW h m^{-3}, which is followed by the large amount of surplus sludge generated and its treatment (10). In fact, reducing the energy consumption is a real challenge for environmental engineers, which is still very far to find an optimum solution. It was believed that MFCs could replace this conventional treatment in order to recover the energy contained in the biodegradable organic matter and create self-sufficient WWTP. This is summarized in the the energy balance for a municipal WWTP shown in Figure 2.2 (11), where it can be observed that the energy consumed by the MFC technology is much lower than the conventional treatment and how the energy generated by MFC technology can afford this energy consumption, at least from a theoretical point of view.

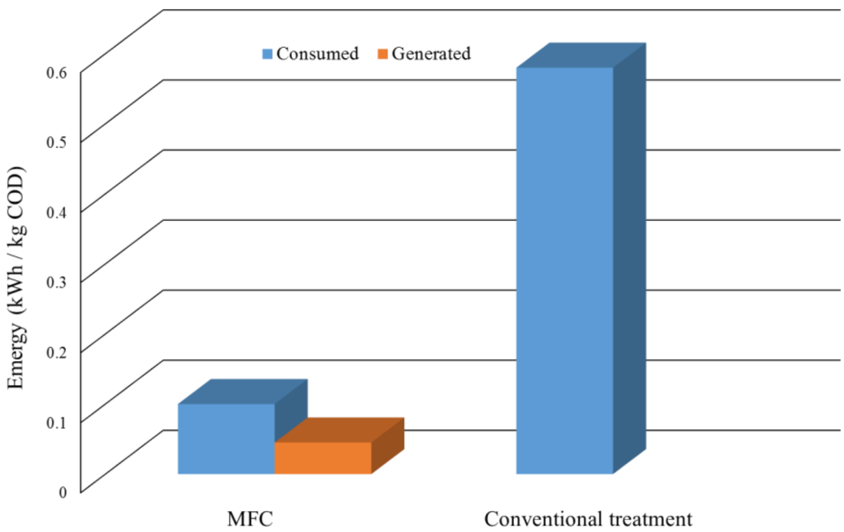

Figure 2. Energy balance of a municipal WWTP (11).

In addition, MFCs were expected to contribute to the multiple challengues that most concern the World population: resource depletion, energy shortage and environmental pollution. The benefits expected associated to the MFC technology are summarized graphically in Figure 2.3 (11).

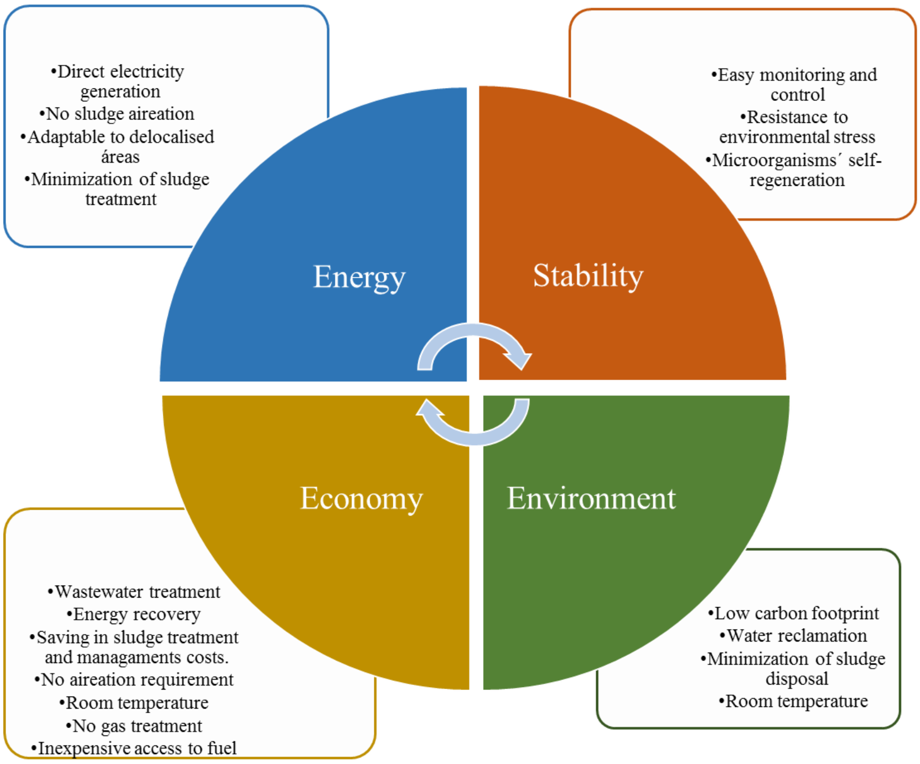

Figure 3. Potential benefits of MFCs (11).

All these calculations and expectations were based on the asumption of an ideal scale-up of the technology, which was a feasible asumption at the moment, when the study was made with data obtained at lab-scale. However, the initial expectatives rose by those initial papers decayed after several years without obtaining results that confirm their feasibility. Enlarge the size of the electrodes does not warrant to increase proportionally the production of electricity from wastewater and perspectives in this field nowadays are not as promising as a decade before. Anyway, there are many other potential alternatives raised by using MFCs, being the supply of low amounts of energy for electronic devices one of the most interesting currently. Although the wastewater application is not as attractive as it was believed, MFCs seems to have great advantages that still make them very interesting devices. The most important can be summarized in the following bullet points:

- Direct conversion of chemical energy of complex substrates into electricity (1).

- Operation at room temperature and even at low temperatures, distinguishing itself from the rest of bioenergetic processes (12).
- No aireation requirement. The cathode can be passively aerated (1).
- No gas treatment because the exhaust gases are enriched in CO_2 from non-fossil origin (13).
- No energy supply as MFCs have no moving parts (7).
- Easy and inexpensive access to the fuel as well as an easy fuel handling, because of the low selectivity of the microorganisms for the comsumption of substrates.
- Lower generation of sludge and therefore saving in sludge treatment and management costs (1).

Due to the benefits described and to the initial expectatives in the wastewater treatment application, the number of publications related to MFC started to increase exponentially leading to an increased knowledge on a great variety of aspects that influences on the performance of a MFC and that must be considered in the search of applications. Thus, in the literature, it has been described the influence on the perfomance of this technology of the design and configuration of the MFC (14, 15), electrodic materials (16-28), use of membranes (8, 29-31), external resistance (32), inoculum source (33), substrate initial COD concentration (34-47), operational temperature (40, 48, 49), loading rate (32) and hydraulic retention time (50, 51), operation mode (52, 53), the pH (48, 54), the size (24, 55, 56), among many other inputs.

Figure 4 summarizes the number of the published papers related to MFCs according to WoS. As explained in the former paragraph, the topic has focussed the interest of the scientific community since the beginning of this century and approach a very important number of 7000 contributions in 2017 (last year with total data). In addition to this, the annual increase in the number of papers is also shown in this Figure. It reflects what it was stated regarding the expectatives: the maximum year increase (derivative of the number of paper published) was reached in 2013, just at this moment when the difficuties in the scale-up of the technology were revealed and scientific community started to realize that this application (at least to provide high energy powering) was not going to be fully developed in a short temporal horizon.

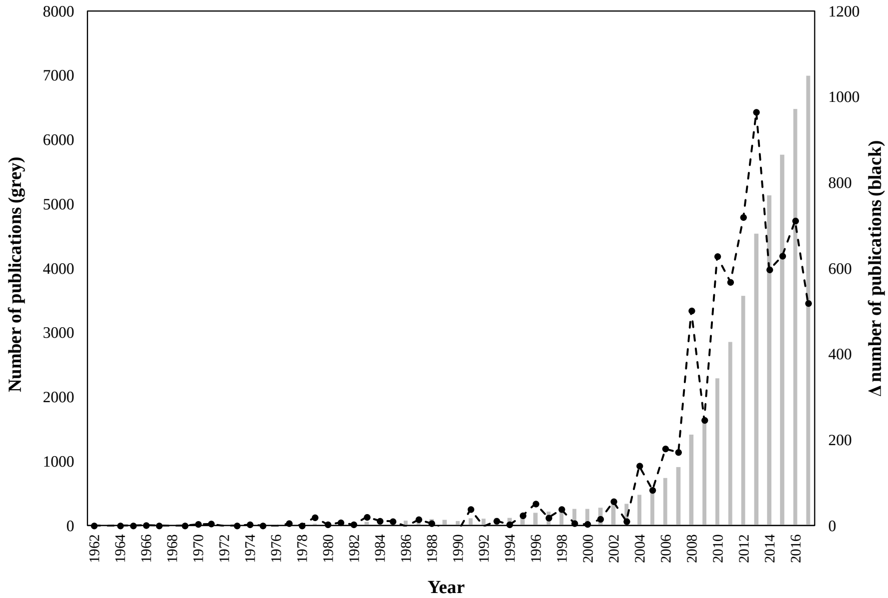

Figure 4. History of publications related with MFC (Database: Scopus). Symbols correspondece: (Grey columns) Number of publications; (Dashed black line) Increase in the number of publications compared to the previous year.

Thus, despite the rise of the number of publications and the scientific effort in optimizing MFCs since this technology was seen to be a promising way to generate clean energy, the power generation has not increased considerably within this time frame and this has become a very important and serious drawback.

Most recent studies are obtaining power densities in the range of 0.07-1 W m^{-2} (15, 27, 28, 57-65) and only in very optimized systems, these values increase up to 4-7 W m^{-2} (66, 67) (68). A microbial fuel cell capable of converting glucose to electricity at high rate and efficiency. Only few studies overcome these figures. It is important to point out that the higher the electrode area, the lower is the power density reached. This means that net production of energy is below the watt level. Thus, although less than a decade ago it was expected that MFCs could produce power densities up to the order of several decenes or hundreds of W m^{-2} and even it was expeculated with the production of megawatts in full-scale applications, to the best of our knowledge no MFC has reached these range of power density values and, in fact, no single MFC has reached even powers within the watt-level (69). In fact, the most interesting strategy to get significant amounts of charge, it is by harvesting the power and using intermittently as demonstrated by Donovan et al with a MFC, which produced on average 3.4 mW of continous power, powering intermittently a 2.5 W remote sensor. The power required was achieved by storing the energy in a capacitor, and then using it when the charge accumulated is enough for the application looked for (70).

In this reallistic context, the achievements reported are not enough for the implementation of this technology. Furthermore, despite the large number of papers published and patents filled, MFCs are yet to find their place in the commercial field (71). The reasons for the stagnation of the technology mainly lie in the scale-up but also in the power performance and financial aspects, although these two last important points do not make any sense until the first is completely solved (71). For this reason, during the recent years many studies have been focused in the scale-up process expecting the development of efficient and affordable devices that can produce considerable amounts of energy and can be accepted by market as well as by Society.

Scale-up of MFCs: what are the technology facts and limitations nowadays?

Scale-up of microbial fuel cells is an important challenge for the aplication of this technology, especially in the field of wastewater treatment, where extremely large amounts of electric charge are required to meet any relevant objective. This procedure requires an understanding of the effects of the reactor architecture, the materials used and the operational conditions on the MFC performance (72). At this point, it is important to highlight the relevance in the choice of a good cell configuration for the MFC and that, among all the very different types of cells existing, air-cathode MFC could be one of the most promising configuration for practical applications due to their relatively high power densities, simple configuration, compact structure, low space requirenent, easy coupling, sustainable operation and low cost (2, 8).

Years ago, it was believed that a linear function described the relationship between the amount of power generated by MFCs and its size (quantified in terms of anodic area). This was not a wrong asumption taking into account the state-of-the art at that moment, because this is the typical behaviour observed in conventional fuel cells. Increasing the size of each single fuel cell electrode (with a proper evaluation of ohmic loses and current distribution) and, then, stacking single MFCs, is a rather good solution to attain high electrode surface areas and maintain the good performance obtained at the lab-scale. Thus, for a given MFC potential, the current passing through the limiting electrode was expected to be directly proportional to the electrodic surface area, and hence, an increase in the surface area of the limiting electrode ought to result in a proportional increase in the power (73).

However, opposite to conventional fuel cells, this asumption is not valid in the case of MFCs. Thus, in literature it has been reported a very clear and dramatic power decrease with the increase of the electrode surface area (74-76). In practical terms, it means that, in extreme cases, it is necessary to increase the surface area almost 100-fold to double the power (75). In addition to this, deploying large electrodes can be very problematic because it can upset electrode spacing (72), that is linked with the increase of the internal resistance and limitations in the mass transport between anode and cathode. Figure 5 (75) illustrates this important drawback, by showing the evolution of the maximum power densities with the anodic surface area reported by various researchers (7, 8, 25, 37, 68, 77-89).

Results highlight the dramatic and important effect of the anodic surface on the power density generated. As an example, a reported study shows that a projected anodic surface area of 2 cm^2 resulted in an impressive power of 3000 mW m^{-2} (81, 82), but in another work with a projected anodic surface area much larger, 232 cm^2, the maximum power density reached only 26 mW m^{-2} (90). In addition, a sediment microbial fuel cell with an area of 1830 cm^2 generated a power density of 28 mW m^{-2} (77). This work shows that sediment MFCs also fit with the trend shown Fig. 5 (the decrease of the power density with an increase of the electrodic surface area), as well as many other published works within the topic. The trend of Fig. 5 reflects a steep climb in the power density when the surface area is smaller than 10 cm^2 and a drastic decrease in the power density when the surface area exceeds 50 cm^2.

The edge effect of the smaller electrodes may explain the relation between power decrease and the anodic surface area increase. Therefore, it was hypothesized that the power densities differences with small and large electrodes may be caused by the effect of the surface biofilm deposits on the electron transfer rate (75). In addition, mass transport of electroactive species to microelectrodes may also have an influence on this important weakness (91).

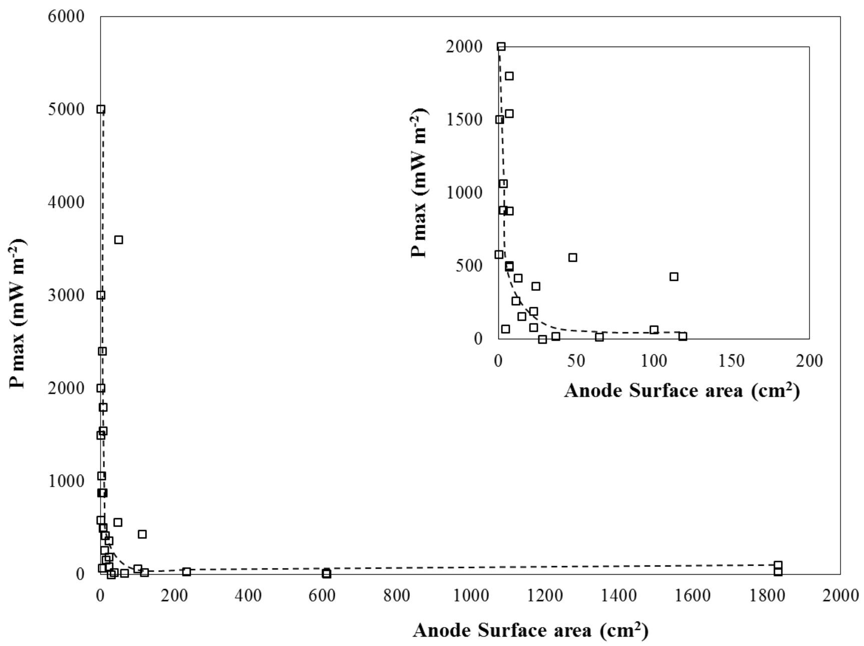

Figure 5. Power density vs electrode surface area. Figure extracted from literature from (75). Inset: data zoom for smaller anode surface areas.

Data that quantifies the edge effect in current densities in microelectrodes were obtained using electrodes with and without surface deposits. Thus, tests in the presence and absence of biofilm carried out by Dewan et al showed that the maximum current density at the potential of a biofilm-covered electrode changed with the electrode size, while the current density in the absence of biofilm and only for soluble chemicals was at the same potential, regardless of the size of the electrode (75). It suggested that the presence of the biofilm may affect both the electron-electrode transfer mechanism and rate, being the effect higher with smaller anodes. It was also pointed out that the potential ocurrence of redox-sensitive species discharging at various potentials because of the presence of the own biofilm, which obviously it does not occurr in the absence of biofilm. In addition, dissolved substances-electrode electron transfer, via biofilm, can be one of the keys of the electrodic surface area-power relation (75). Another important point to be considered is the considerable increase of the internal resistance (76) associated to high bacterial concentration, which slow down the movement of electrons and protons (92).

In order to efficiently recover the energy from the substrate by the biofilm on the anodic electrode, it is important to select a suitable hydraulic retention time (HRT). It is important to take into account that a larger compartment than the necessary can be counterproductive and detrimental to the system efficiency (93). Thus, it has been found a more efficient energy harvesting in smaller MFCs because of the reduction of the electrode spacing, the increase of the surface area-volume ratio and the decrease of the internal resitance. These features benefit the supply and diffusion rate of substrate and nutrients, the electron collection in the anode and the proton diffusion from the anode to the cathode.

This fact leads to a new approach to scale-up: stacking multiple small MFCs (93-95), in which multiple MFCs are connected electrically in series to increase the overall potential and in parallel to increase the overall current (96), leading to an increase of the electrodic surface area (89, 97) without promoting the drawbacks observed when the area is increased in a single cell. However, this setting has also two important challenges to be solved: cell voltage reversal and ionic short circuit can occur in MFCs with biocatalyzed electrode reactions. On one hand, voltage reversal arises due to unequal electrode potential between the unit cells cause in turn by a unbalanced substrate distribution (96, 98). On the other hand, ionic shorts circuit can take place in MFCs sharing the same anolyte and catholyte (14, 99) and points out weaknesses in the design of the device.

A great variety of MFC architectures has been used in the laboratory. The most frequent devices are single and dual chamber cube, dual chambered H-cell reactors (100), plate and tube shaped reactors (101-103) and cylidrical reactors (72, 100, 101, 104). However, the designs used in the scale-up stage are usually tubular or flat-plate reactors. On one hand, in tube configurations, a tubular anode is surrounded by a separator in order to electrically isolate anode and cathode. The cathode is wrapped around the separator. The cylindrical shape is given by the electrodic material used such as granular material or flat electrode (carbon clot, felt or veil) into a cylinder, cylindrical graphite or carbon fiber brush. Individual tubular MFC modules can be connected for further scale-up (94, 105). In addition to this, this design allows near optimal cross sectional dimensions that may be maintained during the scale-up resulting in minimal dead space (106, 107). On the other hand, flat-plate configurations consist of rectangular plates in which the separator is sandwiched between the anode and the cathode, which are mainly based on carbon materials. When scaling-up, this configuration favors the minimization of the electrode spacing, the increase of ionic diffusion rates and the reduction of internal resistance (15, 87). The length of the stack can be increased by connecting individual flat plate modules (76).

During the scale-up process, for practical applications, it is important to select the operation mode and the more suitable way for the circulation of the influent waste streams through the reactor, because can have an important effect on the wastewater treament efficiency (if this is the secondary goal of the MFC). MFCs fed in series can produce different substrate concentrations and different nutrient compositions available to bacteria, as compared with reactors connected hydraulically in parallel but also leads to a better utilisation of the substrate into electricity (14, 94, 108-110).

At this point, it is important to bear in mind that substrate has to be considered as the fuel of the MFC, and hence it is a key factor in the scale up process. It is important to take in mind that composition of many types of wastewater is particularly suitable for being used as fuel and for this reason the MFCs concept has been joined to the wastewater treatment technologies. Regarding to the different types of waste suitable for MFCs, there is huge variety of wastewater that can be used as substrate for bacteria. This fact allows MFCs to be used not only to treat domestic wastewater (41, 45, 111, 112) but also industrial wastewater such us brewery, food processing, paper recycling wastewater, sanitary and swine streams, yeast extract, refinery, starch, marine sediments, organic acids, alcohol, sulfide and algae (8, 37, 90, 113-123) (124). Efficiencies up to 80% in the COD removal have been reported (7).

Figure 6 shows the most relevant substrates used in published papers related to MFCs (125). It can be observed that nowadays, about the 60% of the studies related to MFCs used synthetic substrates. Glucose and acetate account for the 40% of the synthetic substrates but the variety of synthetic substrates is very remarkable, including fumarate, glutamate and propionate. Industrial wastewater was used in the 20% of the studies while ethanol in a 7%. The 40% of the total remaining used natural substrates, whose sources showed a great diversity: gross domestic wastewater (38%), lactate (17%), marine sediments (17%), sewage sludge (7%) and maltose (5%) (125). Synthetic wastewater is frequently employed in MFCs but its operation with real municipal and industrial wastewaters has also been tested satisfactory (121, 126). However, it is important to consider that, regardless of the type of organic compounds contained in the fuel, it must endowed with a suitable concentration of nutrients, adequate pH and conductivity in order to formulate the intended fuel for exoelectrogenic bacteria.

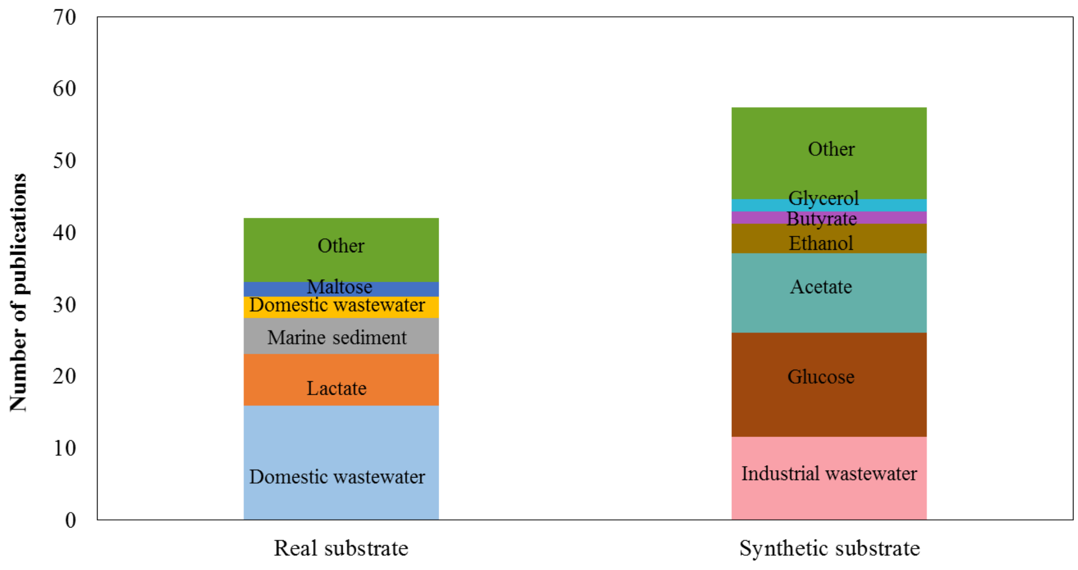

Figure 6. Types of substrates in aqueous solution used in MFCs. Figure extracted from literature (125).

Perspectives of the applicability of microbial fuel cells: what is the near future?

Last but not least in this introductory critical review, it seems clear the applicability of the MFC technology in wastewater treatment does not make sense at the light of the power levels reached by this technology nowadays. This does not mean that it is not worth to do research on it; it simply means that we are very far away from a real application. This applies for other environmental application with very good results at lab-scale such as the bioremediation of contaminated soils with MFCs, for which lab-scale studies point out that bacteria can remove around the 70% of uranium in a contaminated underground aquifer with the advantage of electricity generation (127). All those results for sure will be applied in the future, when the scale-up problems will be solved.

However, this does not mean that this technology could not be used nowadays for other applications, although it is important to take into account that the energy demand should fit to the energy exerted by those devices. One of the most interesting applications is to power up sensors for the analysis of pollutants (128, 129), where MFC can be used to quantify the organic load or also for the detection of toxic compounds. In addition, a change in the temperature, pH and conductivity can be also detected.

The electricity produced by MFCs can be also used for powering other technologies: biologically inspired robots, remote devices, small electronic devices (mobile phone

(130), laptop, TV, coffee maker and so on) (131) or even low energy-demanding illumination devices.

Regarding to the biologically inspired robots, the first `real application´ of this technology could be a train toy, which works as a robot with stomach. It was named Gastrobot (132). In the artificial stomach, *E.Coli* metabolizes sugar and the products generated fed a stack of abiotic/chemical fuel MFCs. The energy generated by the stack allows to run the machine. Then, capacitors were added to the robot so the energy could be stored by itself (EcoBot-I) (133). Many improvements were carried out in EcoBo-I, such as the replacement of the ferricyanide cathode by air-cathodes and the glucose substrate by unrefined biomass (rotten fruits, dead flies and crustacean shells). It leads to EcoBot-II, which could perform sensing, information processing, communication and actuation phototaxis (134). EcoBot-III came into existence in 2010 and contained 48 miniaturized MFCs. It was the first self-sustainability robot by collecting their own feed and excreting the waste products (135). Following the patterns of EcoBot, it was demonstrated the possibility to partially charge mobile phones with small scale MFCs (71). 24 mini MFCs, which was fed with real urine, charged and power a Samsung GT-E2121B with a 3.7 V and 150 mA h battery. The energy stored in the battery after a charge to 3.7 V threshold led to an outgoing call of 4 minutes and 20 seconds. Another Samsung mobile phone with a larger battery of 1000 mA h was charged during 24 hours resulting in a powering of 25 minutes, an outgoing call of 6 minutes and 20 seconds and 6 text messages. The full charge of a Samsung Galaxy S I9000 smartphone battery (4.7 V and 1650 mA h) in 68 hours was demonstrated in 2017 (130). Illumination application has been recently demonstrated by lighting up a strip of 220 LEDs with 112 miniaturized MFCs continuously for several days (136).

Figure 7 shows the variety of fields involved in MFC research, from the engineering to Humanities.

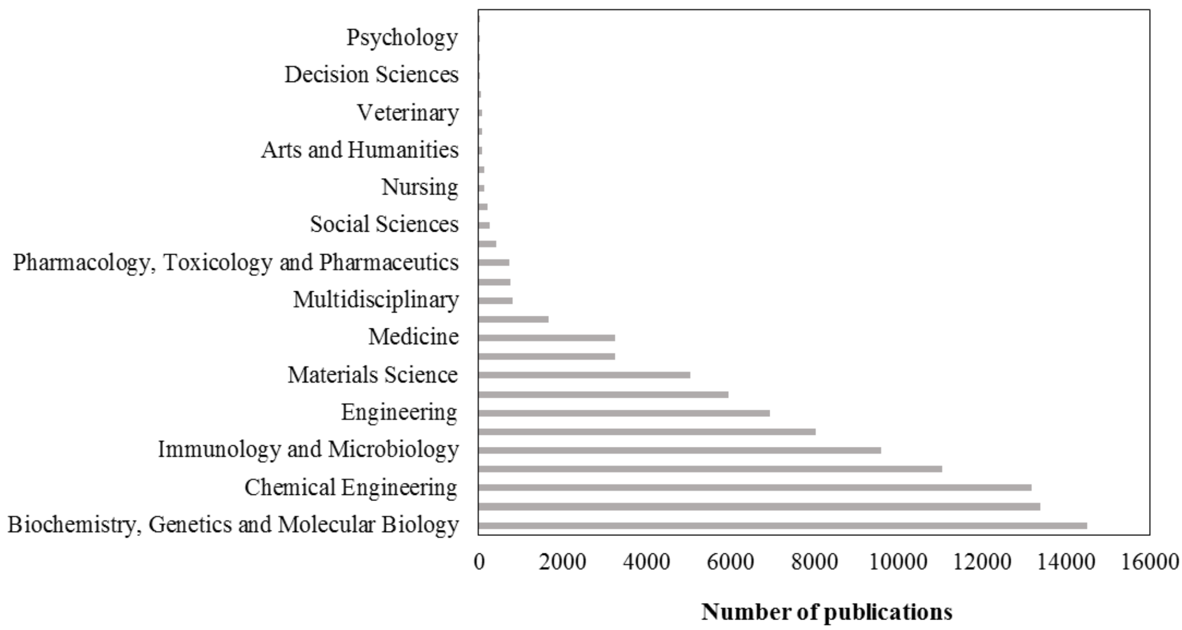

Figure 7. Number of publications per subject area (Database: Scopus).

It reflects the potential of the implementation of MFCs in our society, specially in the medicine area, in which MFC can be implanted in the human body. The MFC uses glucose or other metabolites extracted from the human body fluids as fuel. Thus, renewable and long-term power source for implantable biomedical devices such as pacemakers or mediators of blood glucose can be a reality. However, it is important to solve collateral risks related to health and safety that involves the use of microorganisms (137).

Hence, at the light of the existing literature, there is still a very important and bright future for this promising technology although objectives related to applicability has to be fixed to the real capacities of the MFCs: short temporal horizon for the development of applications involving the powering of small electronic devices, whereas very long temporal horizons for full implementation of large enviromental remediation applications. In the meantime, a very important effort has to be paid for the optimization of the heart of the technology: the electrochemical reactor.

Conclusions

Despite the high number of publications related to MFCs, this technology is stagnated because the power generation remains constant over the years and also due to limitations in the scale-up process. Initially, it was expected that the increase of the MFC size resulted in an increase of the power generated, but this assumption failed. During the most recent years, small devices has shown higher energy recovery efficiency than large reactors because of the reduction of the electrode spacing, the edge effect, the increase of the surface area-volume ratio and the decrease of the internal resitance. For this reason, the multiplication of small MFCs and its arrangement in a stack has become the new approach in the scale-up (minituarization and replication strategy), which has been reported as a succesful way to switch on small technologies.

Acknowledgements

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