original research article

DENTISTRY WASTE TREATMENT THROUGH ENZYMATIC FUEL CELLS

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SUMMARY

Objective. Although waste is traditionally assessed as a polluting thing which need to be reduced or lessened, its management is a necessity wherever human beings live. Every year, global energy request increases. While oil products actually fulfil the great part of the energy demand, the growing difficulty in meeting it and, as a consequence, all the pollution and global warming problems are driving scientific research to an alternative and renewable energy. Waste contain a significant energy amount; if we could employ them and convert them into a reusable form, we might provide either to supply clean energy and to resolve the waste global problem. This issue is felt in a dental surgery too, because it concerns dangerous and infectious-risk waste disposal. The possibility of the employment of pieces of waste and consequently of their inside energy converting can represent a turning point in the clear energy field, gaining an enormous benefit for the environment and significantly lowering waste management costs. In recent years, Enzymatic Biofuel Cells (EFC), with substantial and green advantages have become a promising power source being distinguishable among the alternative energy conversion systems. Nowadays, since fossil fuel depletion and global climate change have started to threaten our existence and future, extensive research has been devoted on finding alternative energy resources and developing more efficient and environmentally friendly processes for energy storage and conversion.

Material and methods. Material employed (purchased by Sigma-Aldrich) were: Glucose oxidase (GOx), Nafion perfluorinated resin solution at 5% in a mixture of lower aliphatic alcohols and water, Polyethylene oxide. Stock solutions of D (+) glucose were prepared in a 0.1 M phosphate buffer solution and stored at 4 °C for at least 24 h before use. Carbon cloth electrode ELAT HT 140 E-W with a platinum loading of 5 gm^{-2} was purchased by E-Tek. Electrospun Nafion fibers were obtained as follows. Scanning electron microscopy was used to characterize the electrode morphologies.

Results. The current work focuses on enzymatic biological fuel cells (EFC), which are designed to convert the chemical energy of the fuel into electricity in a sustainable manner. The aim of our study is to develop enzymatic fuel cells using the infectious-risk special waste, such as blood and saliva, as fuels. Considering that blood contains glucose, the EFC devices development can be developed through the preparation of a glucose-oxidized (GOx) based bioanode, immobilized on an electrode surface.

Conclusion. During our research we developed an Enzimatic Fuel Cell prototype and we evaluated its ability to harvest energy from the blood and the saliva inside the risk-infectious medical waste and to employ it in order one day to help the energy requirements of a consulting room. This device is based on GOx as biocatalyst and either Nafion or low cost membranes based on polyaromatic polymers were used as polymer electrolytes. Moreover, we also have explored the performance of single chamber configuration, which directly eliminates the use of membranes, to assess the applicability of EFCs for dentistry waste management.

Key words: medical waste, enzyme fuel cells, material science, materials engineering.

Introduction

Dental surgery produces dangerous and infectious-risk waste requiring costly disposal processes. The use of such waste as fuel for a bioenergy production device would help reducing the cost of waste-management, thus leading to an overall significant environmental (1). Biological fuel cells are an innovative technological solution for a "sustainable" global economy. Such a technology allows indeed reaching at once both the goals of sustainable energy production and waste treatment, through the direct conversion of organic matter to electricity using biocatalysts (1, 2). Among biological fuel cells, enzymatic fuel cells (EFCs) have attracted increasing interest in the last years due to their applicability as power sources for portable electronics, and in particular implantable medical devices (3). EFCs are based on the conversion of chemical energy into electricity through the catalytic action of enzymes which require a fuel (i.e. a substrate) which can be readily oxidized. Medical waste are consisting on materials which cannot be easily employable for energy production with the exception of blood and saliva. These biological fluids contain glucose, which, on the contrary, can be exploit in producing energy amounts. Blood and saliva are, in fact, interesting candidates as possible fuel sources (1, 3).

One possible answer is the enzymatic fuel cell (EFC) technology, as reported in our feasibility study previously published (1).

These devices allow at the same time to degrade the organic matter present in the organic waste and produce electricity through the catalytic action of enzymes (2). Enzymes act as biocatalysts being capable of transforming bio-organic molecules through a cascade of redox reaction. Glucose oxidase (GOx) is the most common enzyme used in EFC device, owing to its ability to speed up the oxidation reaction of glucose, the most abundant carbohydrate found in nature. The main critical issue limiting the practical application of EFCs is the low enzyme stability and recent progress in nanobiocatalysis are opening up the possibility to improve power generation through EFC (3).

On the other hand, a fine design and optimization of cell architecture is also needed to assess the applicability of such a kind of devices for dentistry waste management. The optimization has to be focused on the enhancement cell performance in operating condition mimicking general dentistry waste, mainly constituted by blood and saliva, which contain glucose as a component.

The most common architecture used in the development of EFCs is the double chamber design built in a traditional "H" shape, consisting of two compartments connected by a tube containing a separator which usually is a Nafion membrane (4). The power density produced by these systems is typically limited by the use of membrane and large separation between anode and cathode which all increased total resistance of the cell (5, 6).

Because of this limitation, the development of different materials and cell configurations is needed to enhance power production through dentistry waste (1).

In this work, we develop innovative EFC configuration based on glucose oxidase as biocatalyst and replacing expensive Nafion with low cost membranes based on polyaromatic polymers (1, 4, 6).

Moreover, we also explored the performance of single chamber configuration, which directly eliminate the use of membranes, to assess the applicability of EFCs for dentistry waste management.

Materials and methods

N-fiber-GOx bioanodes were prepared as previously reported (1). Cathodes consisting in carbon clothes ELAT HT 140 E-W with a platinum loading of 5 gm^{-2} were purchased by E-Tek and labeled as CC. Stock solutions of D (+) glucose

(5 mM-1 M) were prepared in a 0.1 M phosphate buffer solution (PBS pH 7) and stored at 4°C for at least 24 h before use. PEEK was obtained by VICTREX and SPEEK was obtained in concentrated sulfuric acid H_2SO_4 96%, Aldrich (reaction temperature 30°C, reaction time: 145 hours). The SPEEK membrane was prepared as follows: about 400 mg of SPEEK was dissolved in 10 mL of DMA and the solution heated to 100°C under stirring. The solution was casted on a petri dish and kept at 80°C overnight. The membrane thickness was 165 ± 5 μm (1). Polarization and power density curves were acquired on EFCs assembled with N-fiber-GOx as anode, CC as cathode as SPEEK as electrolyte membrane. The EFC feed solution was PBS containing glucose in a concentration range of 5-100 mM. The cells were allowed to equilibrate at least for 6 hours to obtain stable open circuit voltage. By applying an external resistance and gradually reducing the load (in the 10 MΩ-0.5 kΩ range), a set of voltage (V) data as a function of resistance was obtained. To achieve polarization and power density curves, current values were obtained by Ohm's law.

Results and discussion

EFC assembly: materials and configurations

Once prepared bioanode, cathode and polymer membrane, these components were assembled into EFC devices with different configuration, as shown in Figure 1.

The configuration shown in Figure 1a consists

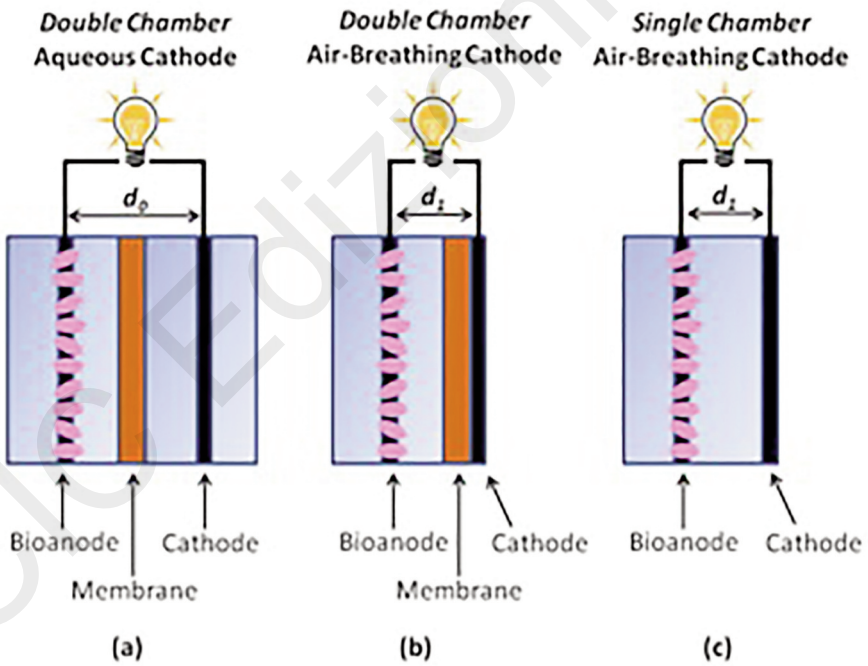

Figure 1
Schematics of the assembled EFC devices with different configuration: (a) Double Chamber Aqueous Cathode EFC, (b) Double Chamber Air-Breathing Cathode EFC, and (c) Single Chamber Air-Breathing Cathode EFC.

of two chambers (anode and cathode) separated by the SPEEK polymer membrane. In this configuration, the anode and cathode (at a distance d_0=4 cm) are immersed in two different environments: the semi-reaction of glucose oxidation takes place at the anode, producing of protons and electrons. Protons passing through the electrolyte membrane and electrons flowing through the external circuit are combined with oxygen at the cathode, generating electrical energy through the reaction reported in Figure 2.

The working principle and configuration of cell shown in Figure 1b is similar to that of cell in Figure 1a, with two important exceptions: *i)* the cathode is directly exposed to air instead of being immersed in the electrolytic solution, *ii*) the distance between anode and cathode (d_1=2 cm) is halved compared to the previous configuration.

The air-breathing cathode configuration allows to overcome mass transport limitations occurring at the aqueous cathode of Figure 1a, since the solubility of oxygen (mole fraction basis) in water is only 4.6 x 10^{-6} (25°C) compared to 0.21 in air (7-9). Moreover, by reducing the distance between anode and cathode, charge transfer is also enhanced, the travel distance of protons being significantly reduced. The cell configuration described in Figure 1c is a membrane-less EFC. In this case, anode and cathode experience the same environment without being separated by the polymer membrane and voltage loss otherwise could arise due to electrode depolarization. On the other hand, the point of greatest strength of this configuration is the drastic reduction of the total cell resistance. EFC performance of the different cell architectures was then analyzed.

EFC test: polarization and power density curves

The most effective method of evaluation of fuel cell performance is the polarization curve which plots the voltage generation as a function of current density produced by the fuel cell at varying electrical loads. Polarization curves can be used to generate power density curves by plotting the power produced by the cell *versus* the current density. This allows for the determination of the maximum power density generated by the EFC at the optimal potential, while the polarization curve provide deeper insights on the limitation of cell (ohmic drop, electrode kinetics, mass transport), hence providing suggestion for materials and configuration improvements (8, 9).

Figure 3 shows the polarization and power density (PD) curves of the Double Chamber Aqueous Cathode EFC.

This cell configuration allows achieving a open circuit voltage (OCV) values of 0.11 V, a maximum PD of 1.5 μWcm^{-2} (corresponding to a produced current density of 23 μAcm^{-2} and voltage of 60 mV), maximum current density being 43 μAcm^{-2} (10).

Figure 4 shows the polarization and Power Density (PD) curves of the Double Chamber Air Breathing Cathode EFC.

$$C_6H_{12}O_6 + O_2 \xrightarrow{GOx} C_6H_{10}O_6 + H_2O_2$$

Figure 2
Harvesting energy by using EFCs: oxidation reaction of glucose into β-D-gluconolactone.

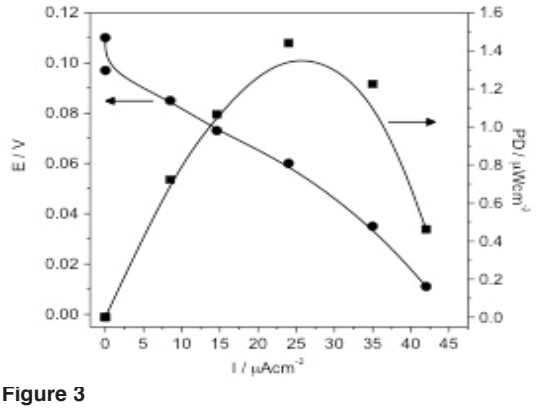

Figure 3
Polarization and Power Density curve of the Double Chamber Aqueous Cathode EFC.

This cell configuration allows achieving a open circuit voltage (OCV) values of 0.145 V, which is higher than that measured with the previous configuration. A maximum PD of 4.5 μWcm^{-2} (corresponding to a produced current density of 75 μAcm^{-2} and voltage of 60 mV) were achieved, and maximum current density produced was 150 μAcm^{-2}(10). The improved electrochemical performance of Double Chamber Air Breathing Cathode EFC with respect to Aqueous Cathode EFC can be ascribed to the reduced distance between anode and cathode and to the increased concentration of oxygen at the cathode side. Figure 5 shows the polarization and Power Density (PD) curves of the Single Chamber Air Breathing Cathode EFC (10) .

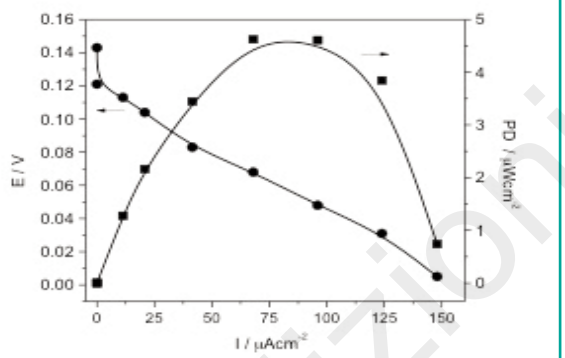

Figure 4
Polarization and Power Density curve of the Double Chamber Air-Breathing Cathode EFC.

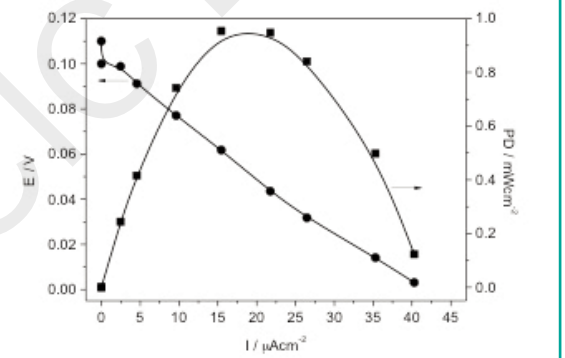

Figure 5
Polarization and Power Density curve of the Single Chamber Air-Breathing Cathode EFC.

This cell configuration allows achieving a open circuit voltage (OCV) values of 0.11 V, a maximum PD of 1.0 μWcm^{-2} (corresponding to a produced current density of 23 μAcm^{-2} and voltage of 50 mV) were achieved, and maximum current density of 40 μAcm^{-2} (9, 10). Table 1 summarizes the performance of the three proposed EFC configurations. In double chamber configuration, Air Breathing Cathode allowed 200% improvement in current and power density production compared to Aqueous Cathode. This is due to the increased content of oxygen at the electrode surface, which enhanced overall mass transport (10).

Once the polymer membrane was removed from the cell, SC Air Breathing Cathode EFC was still able to generate electricity. This finding pointed at the great selectivity of immobilized Gox towards glucose oxidation, allowing to produce power even without a physical separation between the anode and cathode compartment.

Waste management and disposal is likely to be one of the most topical and current subjects, due to their environment impact, in a more and more careful society toward the environment management (1). Unfortunately, in our contemporary society, even due to a wrong cultural education, waste is only considered like a problem and like something polluting, which must to be at any cost eliminated or reduced.

However, industrial progress modernity is changing these preconceptions, leading us to consider waste as a precious thing, an inexhaustible energy source, which has only to be

Table 1 - Electrochemical performance of Double Chamber (DC) Aqueous Cathode, DC Air-breathing Cathode, and Single Chamber (SC) Air-breathing Cathode EFCs.

Cell Configuration	E/mV	I/μ Acm^{-2}	PD/μ Wcm^{-2}
DC Aqueous Cathode	60	23	1.5
DC Air-breathing Cathode	60	75	4.5
SC Air-breathing Cathode	60	15	1.0

collected. Waste contains a significant energy amount, if we could employ it. If the significant waste energy amount could be employed and converted into a reusable form, we could provide both for the production and the distribution of pure source energy, solving former environmental problems like waste cumulation and pollution at the same time. This problem is felt in medical and dentist's surgery too, because of it makes worse the economic and environmental impact (1).

Dangerous and infective-risk waste management is one the key-problem consulting room feels, from either legal, economic and health point of view, considering the clinical-biological risk prevention of cross-infection propagation too (1, 10).

Biological waste energy employment and conversion could be a main turning point, earning great environment advantages and critically cutting down waste management costs.

Conclusions

Aimed by these targets, our research, allowed to develop a low environmental impact device, able to convert the organic part of infectious risk waste produced in a dental practice (mostly blood and saliva) into electric energy. To develop a low environmental impact device, able to convert the organic part of infectious risk waste produced in a dental practice (mostly blood and saliva) into electric energy. A deep analysis of the recent literature on this topic indicated EFC as an innovative method for the renewable energy recycling. This system allows the organic material direct conversion into electric energy employing enzymatic chains or bacteria. During this dissertation we widely explained how to produce electricity starting from blood and saliva employing their inside glucose. Exploiting the well-known biological and catabolic properties of glucose, we succeeded in observing potential difference and electron exchanges, able to be used as energy source. However, obtained results did not satisfy our expectations; although we gained by means of electron exchanges electric energy, this is not enough to guarantee, neither partly, a consulting room energetic needs, which is about 20/25 KWatt/die. In fact, the greatest energy amount gained by means of our double chamber air-breathing cathode (the most productive system) has been 60 mV, with 75 μAcm^{-2} intensity and 4.5 μWcm^{-2} power density. However, in our opinion, the direction to follow may be the right one; by means of our EFC prototype we succeeded in feeding a little fan, an Mp3 player and a pacemaker directly fed by the vascular circle blood that flows around it. In order to satisfy the bigger and more complex instruments energy needs, rather than only one enzyme (GOx), a complex enzymatic chain should be employed: it may gain, by means of redox reactions principle, during oxidative breathing process, a higher electron amount from the glucose molecule in order to produce more energy.

In the near future, research has even to focus on searching more productive enzymatic systems, which could gain more energy from other blood and saliva elements too, especially in their full-of-electrons protein part. Therefore, we may conclude that our three-years PhD experimental research did not give the expected results. However, it was neither a complete failure: we have applied to dentistry, with very-low efforts and with poor resources, chemical and physical sophisticated technologies, showing that it is possible to produce energy starting from biological toxic and infectious-risk special waste.

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