Science of the Total Environment 648 (2019) 263–270

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Optimization of a single chamber microbial fuel cell using *Lactobacillus pentosus*: Influence of design and operating parameters

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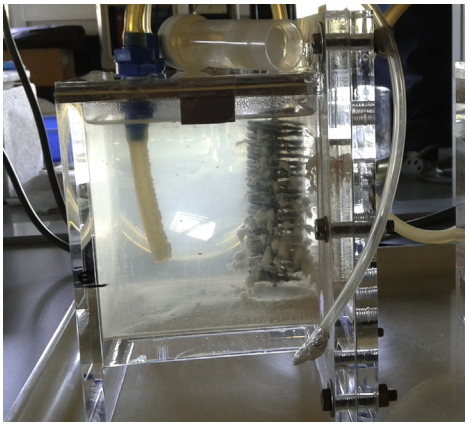
HIGHLIGHTS

- An experimental study of a feed-batch SCMFC with *L. pentosus* is described.
- The effect of different parameters on the SCMFC performance is presented.
- Different parameters were tested in order to achieve high power outputs.
- The biofilm formed on the anode electrode was characterized for each parameter studied.
- The maximum power density achieved was 5.04 mW/m^2 with a COD removal rate of 50%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 April 2018
Received in revised form 20 July 2018
Accepted 4 August 2018
Available online 05 August 2018

Keywords:
Microbial fuel cell
Wastewater treatment
Biofilm
Bioenergy production
Power output
Lactobacillus pentosus

ABSTRACT

Microbial fuel cells (MFCs) have been receiving an increased attention over the last years due to their potential to combat two global problems: waste pollution and energy demand. Additionally, when a wastewater is used, MFCs can perform its treatment while recovering energy, leading to the possibility of energy-producing wastewater treatment plants, offsetting their operational costs. However, to overcome their current limitations (lower power outputs and higher costs), a clear understanding of the effect of operation and design parameters on its overall performance is mandatory. Therefore, the goal of this work was to evaluate the effect of operating conditions - batch cycle and yeast extract concentration, and design parameters - anode electrode area, membrane thickness and active area, on the overall performance of a single chamber MFC. The MFC operated with a pure culture of *Lactobacillus pentosus* and a synthetic wastewater based on a real dairy industry effluent. The overall performance was evaluated through the power output and the COD removal rate. Additionally, the biofilm formed at the anode electrode was characterized in terms of biomass, proteins and polysaccharides content. For the conditions used in this work, a maximum power density of 5.04 ± 0.39 mW/m^2 was achieved with an anode electrode area of 61 cm^2, a batch cycle of 48 h, 50 mg/L of yeast extract and a Nafion 212 membrane with an active area of 25 cm^2. The different conditions tested had a clear effect on the MFC energy production and biofilm characteristics, but not on the ability of *L. pentosus* to treat the dairy wastewater. The COD removal rates were in the range between 42% and 58%, for all the conditions tested.

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https://doi.org/10.1016/j.scitotenv.2018.08.061
0048-9697/

1. Introduction

Dairy industries are responsible for producing a large amount of wastewater, since they generate up to 10 L of wastewater per litter of processed milk (Vourch et al., 2008; Kelly and He, 2014). Moreover, dairy wastewaters are characterized by their high organic load and high concentration of biodegradable organics, being for these reasons suitable for a biological treatment (Kolev Slavov, 2017; Venkata Mohan et al., 2010). Most of the wastewater treatment facilities spend energy using conventional technologies, such as anaerobic digestion and aerobic treatment, to perform the treatment (Logan, 2008). Anaerobic digestion can recover energy due to the ability of producing biogas and methane, but requires meso and thermophilic temperatures to operate, requiring an input of energy to achieve that. Additionally, in dairy wastewaters the methanogenic bacteria can be affected by the activity of acetogenic bacteria, responsible for the production of volatile fatty acids, decreasing the pH of the medium and, therefore, affecting the treatment efficiency (Carvalho et al., 2013; Kolev Slavov, 2017). The aerobic treatment provides high chemical oxygen demand (COD) removal efficiencies (Carvalho et al., 2013; Kelly and He, 2014), but requires huge amounts of energy for aeration, accounting for almost 60% of the total energy required in a wastewater treatment plant, and half of its operational costs (Kolev Slavov, 2017). Moreover, this treatment is known to produce large amounts of sludge, which requires further treatment, leading to an additional cost that can reach up to 500€/ton dry matter (Kolev Slavov, 2017; Mamais et al., 2015). Therefore, eliminating or reducing the drawbacks of conventional technologies by replacing them with more efficient ones is a research need. MFCs emerged as an alternative and cutting-edge technology by presenting several advantages over the conventional technologies: direct conversion of organic matter into electricity, allowing higher conversion rates/efficiencies; operate at ambient or low temperatures, reducing the heat requirements (costs and input of energy); do not require gas treatment since the only gas produced is carbon dioxide, which has no useful energy content; do not require an input of energy for aeration since the cathode can be passively aerated (SCMFC); can be used in remote areas, with a lack of electrical infrastructures/grid; can use a diversity of fuels, being considered for several different applications; can reduce solids/sludge production, reducing further handling and treatment costs (Mathuriya and Sharma, 2009; Velasquez-Orta et al., 2011; Venkata Mohan et al., 2010; Oliveira et al., 2013; Pandey et al., 2016). However, MFCs still have some performance limitations and costs above the desirable. To overcome that, the development of cost-efficient MFCs through the optimization of the system design and operating conditions is mandatory. In fact, it was found that these parameters have a remarkable effect on the cell power output, biofilm formation and stability on the anode, and COD removal efficiency (Oh and Logan, 2006; Hutchinson et al., 2011; Wang et al., 2012; Oliveira et al., 2013; Lanas et al., 2014; Vilas Boas et al., 2015). Despite the importance of the operating and design conditions on the MFC performance, until now, only few studies were performed with dairy effluents, leaving an open window for further research on this field (Faria et al., 2017).

Among the two different designs commonly used for a MFC (dual chamber and single chamber), the single chamber is the most attractive one for scaling up this technology, toward its use in real applications. This mostly due to its design simplicity and elimination of the airflow, reducing the system energy requirements (Cheng and Logan, 2011; Oliveira et al., 2013).

Having in mind the current challenges in the MFC technology and toward the use of these systems in real applications, the aim of this work was to increase the overall performance of a SCMFC through the optimization of design parameters (anode electrode area, proton exchange membrane (PEM) thickness and active area) and operating conditions (batch cycle (hours) and yeast extract concentration). Since this work deals with the use of a MFC to treat a dairy wastewater a facultative anaerobic and heterofermentative lactic acid bacteria, *Lactobacillus pentosus*, that is presented in real dairy wastewaters and has the ability to degrade lactose (one of the main organic sources presented in this wastewater) was used (Pan et al., 2014; Zanoni et al., 1987). It should be here emphasised that for lab-scale studies, single cultures are preferred and commonly used over the multispecies one, since they allow studying the electron transfer mechanisms with some detail and in addition to an easier microbial characterization and cell optimization. In this work, the SCMFC performance was evaluated through its power output, COD removal rate. Additionally, the biofilm formed under each process condition was characterized in terms of biomass, proteins and polysaccharides content.

2. Materials and methods

2.1. SCMFC construction and operation

The SCMFC used in this work has an anodic Plexiglas chamber with a 1 L of working volume and an open-air cathode separated by a PEM, Nafion membrane (QuinTech, Germany) (Vilas Boas et al., 2015). In order to prevent leakage, two rubber gaskets were placed on each side of the PEM. All the experiments were performed under deaerated conditions on the anode side. A carbon fiber graphite brush (Mill-Rose company, USA) and a plain carbon cloth coated with 1 mg/cm^2 of platinum black (FuelCellsEtc, USA) were used as anode and cathode electrodes, respectively. The anodic chamber was sealed and filled with 70% of a synthetic dairy wastewater and the remaining volume (30%) with a culture of *L. pentosus*. The synthetic dairy wastewater consisted of 85 mg/L of glucose, 5 mg/L of yeast extract, 1300 mg/L of milk powder, 5 mg/L of starch, 50 mg/L of NH_4Cl, 22 mg/L of K_2HPO_4, 11 mg/L of KH_2PO_4, 78 mg/L of $MgSO_4 \cdot 7H_2O$ and 35 mg/L of $CaCO_3$ (Vilas Boas et al., 2015).

The experiments were performed at room temperature, and under three different batch cycles (hours): 24, 48 and 72, to evaluate the effect of the batch cycle on the system under study. Since this was the first parameter studied, the following experiments were performed with the batch cycle that provided the best overall performance (power output and COD removal rate). The effect of the membrane thickness was evaluated using two different membranes from the same material but with different thicknesses, Nafion 117 (0.183 mm) and Nafion 212 (0.051 mm) and the effect of the membrane active area was accessed using two membranes from the same material and thickness (Nafion 212) but with different active areas: 25 cm^2 and 42 cm^2. In order to analyse the effect of the anode electrode area (estimated through Eq. (1)) on the cell performance and particularly on the biofilm properties, two electrodes were used, BP1″ (6.5 cm of length and 2.5 cm of diameter) with an area of 61 cm^2, and BP3/4″ (2.5 cm of length and 2.5 cm of diameter), which area is 30 cm^2.

The specific surface area for each electrode (brush) was determined through the cylinder equivalent projected area as suggested by Lanas et al., 2014:

$$A_{electrode} = 2\pi r(h + r) \quad (1)$$

where r is the anode electrode radius (m) and h is the electrode length (m).

To evaluate the ability of the yeast extract concentration to act as a natural redox mediator, two different yeast extract concentrations were used, 5 mg/L (original concentration of the synthetic wastewater) and 50 mg/L (10 times higher the original concentration). This was evaluated through the overall cell performance, power output and COD removal rate.

2.2. Microorganism and culture conditions

L. pentosus (CECT 4023) was incubated for 2 days in MRS (Man, Rogosa and Sharpe) broth (Merck, VWR) at 37 °C. After that, the culture was centrifuged at 3777 g for 15 min. The cells were suspended in