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Reducing the burden of food processing washdown wastewaters using microbial fuel cells

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ABSTRACT

A tubular Microbial Fuel Cell (MFC) reactor consisting of four modules (total reactor volume of 1 l) was fed with food processing washdown water as a chemical oxygen demand (COD) removal process to decrease effluent pollution levels and discharge costs. Two different operational modes were tested: (A) Under static electrical loads with substrate circulated to and from different storage vessels and (B) employing maximum peak power point tracking (MPPT) whilst re-circulating substrate through a single storage vessel. After 7 cycles through the reactor, notionally equivalent to 28 concatenated tubular MFC modules, 84% of the soluble COD (960 mg l^{-1}) was removed from the effluent in Mode A and 70% (800 mg l^{-1}) in Mode B with MPPT. In the study, acetic acid was consumed first and propionic acid increased initially before depletion after 7 cycles, showing that higher carbohydrates were degraded during the effluent polishing process.

1. Introduction

Microbial Fuel Cells (MFCs) with chemical oxygen demand (COD) removal and simultaneous energy recovery present a promising technology for water effluent treatment. Organic matter can be oxidized by electrogenic bacteria, which can utilise the anode as the terminal electron acceptor in their respiratory and metabolic processes, to produce electrical current through an external circuit with an open air, passively aerated oxygen reducing cathode. Various studies have addressed the performance of such MFCs at laboratory scale, for feeding with simple synthetic substrates, such as volatile fatty acids (especially, non-fermentable acetate) [1], glucose [2] and sucrose [3]. However, MFCs can utilize a wide range of soluble or dissolved complex organic substrates present in wastewaters and renewable biomass. Several studies deal with real wastewater, such as domestic wastewater or wastewater from industrial processes, such as brewery wastewater [4,5], starch- [6], food- [7] and meat-processing wastewaters [7], swine wastewater [8], distillery wastewater [9], canteen-based food waste [10,11], food waste leachate [12,13] and effluents from dairies [14], as recently reviewed by El Mekawy et al. [15]. However, the power extracted from MFCs depends greatly on the composition of the wastewater. For example, in a study of bakery, brewery, paper and dairy wastewaters treated in the same reactor, high current output was only obtained with the paper wastewater [16]. Importantly, the power generated and the energy recovered by MFCs fed on real waste streams are commonly lower than the corresponding values for MFCs fed with simpler synthetic substrates.

In theory and without taking into account overpotential losses, MFCs exhibit a thermodynamic cell potential of $E^0 = 1.105$ V; for operating conditions of 16.9 mM acetate as substrate, pH = 7 and $pO_2 = 20265$ Pa; [17], when considering acetate oxidation oat the anode and oxygen reduction at the cathode. The real cell potential is significantly lower (approximately 0.5 V under R = 1000 Ω in a tubular MFC), due to the internal losses such as activation losses, ohmic losses and mass transfer losses. The ohmic resistance can be lowered by bringing the anode and cathode into close proximity. Mass transfer losses can be reduced by increasing the mixing, which will also avoid inhibitory local pH gradients near the anode biofilm and active cathode catalyst sites. In contrast, activation losses depend more on the electrode material and catalyst for oxygen reduction, than on the reactor design [18]. Apart from

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the design and material factors, there are several performance-determining parameters governed by the intrinsic characteristics of real wastewaters, such as their chemical complexity (single compound versus several compounds, types of sugars, carbon chain lengths, types of chemical bonding and elemental composition) and concentration, temperature, pH-value, the typical lack of buffering capacity and low conductivity [19]. The affinity of electrogens towards the provided substrate plays an important role [20]. The lower degradability of components in real wastewater adversely affects the COD removal efficiency. The addition of buffer might be needed to adjust the pH value and increase the conductivity, but also increases the cost of the treatment process. Apart from the most commonly used phosphate buffer saline (PBS), other buffer systems have been used to modify wastewater, such as bicarbonate [21] or borax [22]. However, a cheaper option may be to buffer the MFC using carbon dioxide/carbonate or bicarbonate [23,24]. A study by Nam [25] claimed that PBS and the zwitterionic buffer PIPES (piperazine-*N*, *N*′-bis[2-ethanesulfonate]) are the most suitable buffer systems for MFCs, however, any buffer (especially PIPES) represents an additional pollutant that needs to be removed/recovered. In our study, PBS buffer was used in a 4-module tubular MFC reactor.

Tubular designs can facilitate increases in the volumetric scale of the MFC by the addition of further modules. This reactor type has been successfully used at laboratory scale to treat synthetic sucrose wastewater [26], swine wastewater [27] and the effluent from a two stage anaerobic process [28]. Since power can be generated at very low organic loading rates, 0.04–0.42 g COD l^{-1} d^{-1} under R = 150 Ω with sucrose [26] and 0.036–0.572 g soluble COD (sCOD) l^{-1} d^{-1} under R = 1000 Ω with Anaerobic Digestion (AD) effluent [28], the tubular MFC design can also be used as an extra treatment stage before discharge to sewer, to lower COD to acceptable discharge limits. In these and other studies, the power output and the substrate concentration will decrease along the reactor length and will therefore possibly affect COD removal rate, Coulombic efficiency and also conductivity. Hence, the internal resistance varies from module to module and, consequently, each of the modules needs to be operated at a matched impedance at its particular internal resistance, in order to maximise power transference from the waste. This has been achieved by applying maximum power point tracking (MPPT) [29–31]. By dynamically controlling the load resistance, the MFC can be persistently operated at the maximum instantaneous power and is able to generate more power at higher efficiency compared to an un-controlled MFC with static electrical load [29]. MPPT can also be beneficial during start up [32,33]. To date, investigations into the effect of MPPT control on MFCs fed with real wastewater have been limited [34]. In this study, we present the COD reduction achieved in a four-module tubular MFC system operating on effluent from an aerobic washdown wastewater treatment process (WWWE), namely a Dissolved Air Flotation (DAF) unit, receiving wastewaters from a chilled food producing factory. The aim was to reduce the COD concentration, while simultaneously generating electricity to self-power the MFC process. The overall result should be a reduction in the costs incurred for discharging the effluent to sewer. An experimental methodology was developed to establish the likely effectiveness of the MFC process in removing COD. Concatenating the four available MFC modules, such that they were serially and hydraulically connected, made available a tubular array of moderate length. This array was used to emulate a significantly longer array of modules, by progressively recirculating the substrate through two different hydraulic arrangements, which below are referred to as modes of operation, A and B. Furthermore, the ability of an MPPT control strategy to enhance the COD removal was investigated to compare with operating the MFCs under static electrical loads. Industrial effluent with relatively low COD has been further reduced and it is estimated that significant cost benefits might accrue to the operator.

2. Materials and methods

The WWWE from a chilled ready-meal food-production company in the UK was fed to a longitudinal tubular MFC. Two different operating modes described below (A and B) were tested in the same four-module reactor. In both modes, the WWWE was re-circulated through the reactor. The modes differed in terms of buffer concentration (PBS; 35 mM versus 50 mM periodic doses), external electrical loading (100 Ω static load versus MPPT control) and operation (steady state versus continuous cycle) as described below.

2.1. Microbial Fuel Cell (MFC) construction

The MFC reactor used in this study consisted of four cells (or modules) linked hydraulically in series. Each of the modules (V_{module} = 250 ml) was made from polypropylene tube (230 mm long; 40 mm diameter) and was constructed using a membrane electrode assembly (MEA) cathode and a carbon veil anode (see Fig. 1), as previously reported [35]. The anode was fabricated by rolling carbon veil (230 × 450 mm; PRF Composite Materials; Dorset, UK) around a central perspex cylinder of 10 mm diameter. The cathode membrane assembly consisted of a cation exchange membrane (122 × 192 mm; CMI-7000, Membrane International Inc., NJ, USA) assembled with a carbon cloth cathode (163 × 82 mm) containing 0.5 mg cm^{-2} Pt as oxygen reduction catalyst. The reactor was inoculated with anaerobic digester sludge (1:10), 40 mM acetate in a 50 mM phosphate buffer, vitamins and minerals (χ = 9 mS cm^{-1}) and enriched under a 1 kΩ external load.

The four modules were separated by ballast and orifice plates to maintain a degree of compartmentalization of modules in the tubular MFC. After batch start-up, the MFC reactor was inclined (30°) and operated continuously with the WWWE, in two different Modes (A and B, see next section).

2.2. MFC operation

The reactor was connected and operated differently, both hydraulically and in terms of the applied external resistive electrical loading, in the Modes A and B illustrated in Fig. 1(b and c). Both modes adopted a recirculatory arrangement to simulate the concatenation of a larger number of MFC modules, as though several reactors were hydraulically linked in series. This arrangement was used in order to estimate the number of such modules that might be required to achieve a polished effluent and to determine the associated cost savings derived from the COD removal. However, Modes A and B differed in that the recirculation was effected through intermediate storage vessels of different volumes. In the case of operating Mode A, the WWWE was pumped through the reactor from a substrate supply bottle to an effluent storage bottle. This was done for three hydraulic retention times (HRTs) in order to achieve near steady state operation and this regime will be considered, henceforth, as one cycle for Mode A. The liquid volume in Mode A consisted of 2 l of the WWWE in storage bottles, while 1 l was in approximate plug flow treatment in the MFC reactor. In subsequent cycles, the effluent of the previous cycle was used as influent. Mode B was adopted to reduce non-electrogenic biological degradation of the organic matter while the substrate was in the storage bottles. In Mode B, the effluent from the 4th module was re-circulated to the first module through a buffering storage bottle (1.2 l). One cycle in Mode A required 3 days, whereas one cycle in Mode B required only 1 day, so allowing less scope for biological degradation of the substrate in the storage bottles. A static ohmic