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Operation of a bioelectrochemical system as a polishing stage for the effluent from a two-stage biohydrogen and biomethane production process

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ABSTRACT

Anaerobic bioenergy production processes including fermentative biohydrogen ($BioH_2$), anaerobic digestion (AD) and bioelectrochemical system have been investigated for converting municipal waste or various biomass feedstock to useful energy carriers. However, the performance of a microbial fuel cell (MFC) fed on the effluent from a two-stage biogas production process has not yet been investigated extensively in continuous reactor operation on complex substrates. In this study we have investigated the extent to which a microbial fuel cell (MFC) can reduce COD and recover further energy from the effluent of a two-stage biohydrogen and biomethane system. The performance of a four-module tubular MFC was determined at six different organic loadings (0.036–6.149 g sCOD L^{-1} d^{-1}) in terms of power generation, COD removal efficiency, coulombic efficiency (CE) and energy conversion efficiency (ECE). A power density of 3.1 W m^{-3} was observed at the OLR = 0.572 g sCOD L^{-1} d^{-1}, which resulted in the highest CE (60%) and ECE (0.8%), but the COD removal efficiency decreased at higher organic loading rates (35.1–4.4%). The energy recovery was 92.95 J L^{-1} and the energy conversion efficiency, based on total influent COD was found to be 0.48–0.81% at 0.572 g sCOD L^{-1} d^{-1}. However, the energy recovery by the MFC is only reported for a four-module reactor and improved performance can be expected with an extended module count, as chemical energy remained available for further electrogenesis.

1. Introduction

The environmental benefits of sustainable waste management with simultaneous energy recovery have been discussed widely in the literature and have motivated efforts to develop effective processes to recover bioenergy from waste. The polishing of effluents derived from wastewater treatment processes such as anaerobic bioprocesses, with the collateral intention of converting COD to useful power and maximizing the recovery of the chemical energy are essential environmental and economic considerations. The reduction of environmental impacts by removing pollution potential, reusing water and sustainably producing bioenergy from waste/wastewater treatment processes, has been rising in importance worldwide, with the adoption of more stringent regulations. For example, the EU has published a roadmap [1] on carbon abatement to 2015 and several directives including Renewable Energy (2009/28/EC), Landfill (1999/31/EC), Water Framework (2000/60/EC) and Urban Wastewater (91/271/EEC) have impinged on such process development.

Anaerobic systems such as anaerobic digestion (AD) or biomethane ($BioCH_4$) and biohydrogen ($BioH_2$) will generally discharge effluents which are still burdened with relatively high concentrations of organic contaminants. The soluble components of these contaminants include several volatile fatty acids (VFAs), which are odorous and increase biological oxygen demand (BOD) in the receiving environment. Post-processing to remove contaminates and/or realise this energy potential would be desirable; and would benefit from appropriate technologies [2]. The performance of two-stage anaerobic processes have been widely studied by several research groups and are known to provide potential to increase conversion efficiency over single stage processes [3–6].

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Biohythane (a mixture of $BioH_2$ and $BioCH_4$) production from two-stage fermentation is of rising interest for the valorisation of waste biomass by generating gaseous biofuel. Furthermore, the combined use of biohydrogen and biomethane is a promising approach to displacing fossil energy sources [7]. The context [2], and degree to which VFAs and other components in synthetic wastewater can be removed in multi-modular MFC system have been considered [8]. However, the performance of, and energy recovery from MFC systems using real effluent from two-stage AD and $BioH_2$ have not yet been investigated. Several studies have shown increased bioelectricity generation by using pre-fermented wastewaters in MFCs [9]. Microbial fuel cells were linked to a hydrogen fermenter fed on food processing wastewaters [10] or vegetable waste [11]. Recently Sharma and Li combined an anaerobic $BioH_2$ fermenter, continuously fed with synthetic glucose wastewater with a MFC [12]. In this context it is noteworthy that the removal of nutrients is a significant issue in dealing with AD effluent. However, this is less significant when considering wheatfeed as the substrate to the preceding $BioCH_4$/$BioH_2$ processes. Nutrient retention for recycling to land as fertiliser may be of greater interest with biomass energy crops. Studies have shown, that nitrification and denitrification [13–16] as well as sulfate [17] and sulfite [18] removal can be carried out in bioelectrochemical systems.

To the author's knowledge the combination of a realistically scalable MFC reactor with a two-stage biogas producing system has been recently proposed [19], but has not yet been investigated. In this work the effluent from a sequentially connected hydrogen fermenter ($BioH_2$) and methanogenic reactor ($BioCH_4$) system was introduced to a MFC to determine its ability to polish the effluent at low organic loading. Massanet-Nicolau et al. [20] have shown that the two-stage process increased the methane yield by 37% compared to the single stage fermentation. To further reduce effluent COD and increase the energy recovery from wheatfeed pellets fed to the system, a tubular four-module MFC reactor was fed with the two-stage effluent at different OLRs in the study reported here. The effects of changing OLRs on the performance of the tubular four-module MFC were investigated and power production was determined. Coulombic efficiency, COD removal efficiency and energy conversion efficiency were determined on the basis of the MFC's influent COD concentration and COD removal.

2. Materials and methods

A tubular axial flow MFC was operated on the effluent of a two-stage biogas process in order to investigate the suitability of the two-stage effluent as a substrate for BES and to investigate the effectiveness of the oxidation reactions in the anode chamber, albeit in the context of an MFC.

2.1. Microbial fuel cell (MFC) construction and operation

The two-stage $BioH_2$ and $BioCH_4$ reactors were operated in series hydraulically, as described in the previous report [20]. The $BioH_2$/$BioCH_4$ effluent was fed to a longitudinal tubular reactor with four MFC modules (each module of 0.25 L) as previously reported [8,21]. The complete three stage system is illustrated in Fig. 1. The carbon veil anodes (230 × 450 mm per module; PRF Carbon, UK) were spirally rolled around a perspex cylinder of diameter 1 cm. The membrane electrode assembly was made from a cation exchange membrane (CMI-7000, Membrane International Inc.; 122 × 192 mm) assembled with a carbon cloth (163 × 82 mm) cathode containing 0.5 mg cm^{-2} Pt. The modules were separated by ballast and orifice plates, to maintain a degree of compartmentalisation in the tubular MFC. The reactor was inoculated with anaerobic digester sludge (1:10); 40 mM acetate in 50 mM

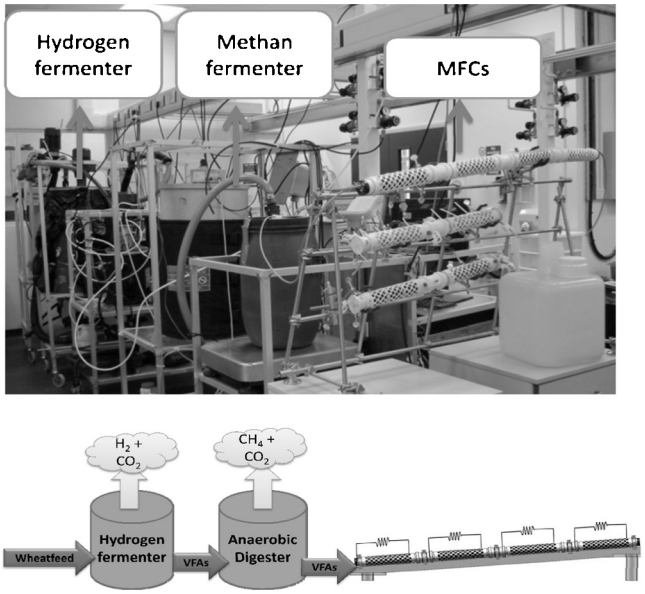

Fig. 1. 10 L hydrogen fermenter, anaerobic digester (V = 25 L) and tubular MFCs.

phosphate buffer, vitamins and minerals. After batch start-up, the MFC reactor was inclined (30°) and operated continuously at five different organic loading rates (OLRs). The effluent from the anaerobic digester was filtered through a stainless steel sieve to exclude particles larger than 0.21 mm. The composition of the filtered effluent determined on a daily basis varied and contained on average 3.300 g COD L^{-1}, 2.500 g sCOD L^{-1}, 0.080 g L^{-1} acetic acid, 0.030 g L^{-1} butyric acid; a pH of 7.7 and a conductivity of 12.9 mS cm^{-1}. Different OLRs (0.036; 0.053; 0.086; 0.337; 0.572 g sCOD L^{-1} d^{-1} designated OLR1 to OLR5, respectively) were maintained by dilution of the filtered $BioH_2$/$BioCH_4$ reactor effluent. The undiluted filtered effluent from the $BioCH_4$ reactor at the end of the experiment was higher in sCOD (6.149 g sCOD L^{-1}) and resulted in an organic loading rate of 4.427 g sCOD L^{-1} d^{-1} which was also supplied to the MFC reactor (see Fig. 3b and Fig. 4). The MFC influent was kept refrigerated and was introduced to the tubular reactor at a rate of 0.5 mL min^{-1} through an external peristaltic pump (Watson and Marlow, Falmouth, UK). The constant flow rate lead to a hydraulic retention time (HRT) of 33.3 h for the whole reactor or 8.3 h for each module, respectively. All reactors were

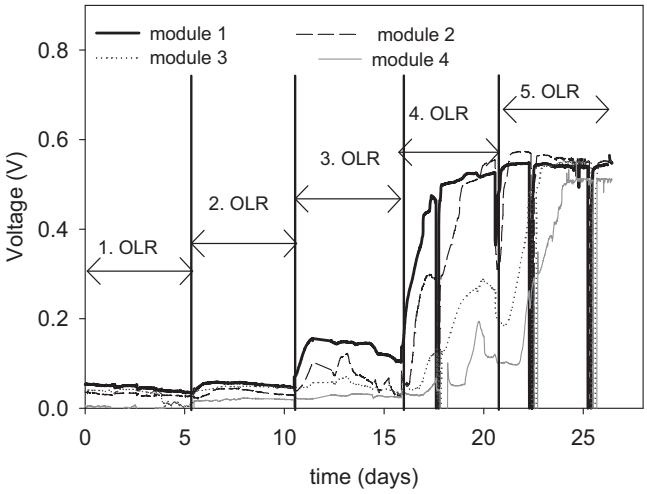

Fig. 2. Voltage generation from each module at different OLRs (0.036–0.572 g sCOD L^{-1} d^{-1}).