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Bioelectrochemical system stabilizes methane fermentation from garbage slurry

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ABSTRACT

Methanogenic bioreactors, which are packed with supporting material, have attracted attention as an efficient means of degrading garbage. We aimed to increase bioreactor performance by using an electrochemical system to regulate the electrical potential on supporting material. At an organic loading rate of 26.9 g dichromate chemical oxygen demand (CODcr)/L/day, reactors with a potential of −0.6 or −0.8 V, generated by a cathodic electrochemical reaction, showed greater removal of CODcr and methanogenesis than reactors with a potential of 0.0 or −0.3 V, generated by anodic reaction, or control reactors without electrochemical regulation. 16S rRNA gene analysis revealed that the same methanogens were present in all our reactors, but quantitative real-time polymerase chain reaction showed that higher prokaryotic and methanogenic copy numbers were present on cathodic electrodes than on anodic or control electrodes. These results indicate that cathodic electrochemical regulation can support methane fermentation from garbage.

1. Introduction

Recycling the huge amounts of garbage produced every year is very important in the public interest. Anaerobic treatment using methane fermentation is a low cost approach that produces little residual sludge and generates methane gas as a renewable energy source (Ahring, 2003; Forster-Carneiro et al., 2008). In this regard, a packed-bed methane fermentation system is an efficient reactor design for the digestion of organic solid waste (Ueno et al., 2007; Sasaki et al., 2007). The packed-bed reactor is filled with the supporting material that supports microorganisms, which aid in the degradation of organic materials and methanogenesis to allow operation at a high organic loading rate (OLR) (Sasaki et al., 2009). Therefore, controlling microbial activity on the supporting material will enhance the effectiveness of a packed-bed reactor.

Microorganisms can derive energy proportional to the potential energy difference, ΔE^{o} (in volts), between an electron donor and an electron acceptor (Thrash and Coates, 2008; Park et al., 1999). Bioelectrochemical reactors (BERs) are now attracting attention in part because microbial activity in them can be altered or controlled using an external electrochemical system (Thrash and Coates, 2008). In previous studies, BERs were used to regenerate reduced or oxidized iron (Fe(II) or Fe(III), respectively) to support larger numbers of organisms and increase their growth rates (Matsumoto et al., 1999, 2000, 2002; Ohmura et al., 2002). In addition, electrochemically reduced redox dye such as neutral red in a BER was reported to serve as an electron donor for microorganisms (Park et al., 1999).

Within methanogenic bioreactors, electrons are transferred from organic materials to various acceptors (Stams et al., 2003). The addition of Fe(III) as the electron acceptor reportedly increases the consumption rate of volatile fatty acids (VFAs) during methane fermentation (Coates et al., 2005). This suggests that an external electrochemical system can be applied to alter microbial activity in methane fermentation. In fact, utilization of a BER for methane production has already been reported for the treatment of acetate (Cheng et al., 2009). However, BERs have not yet been applied for the treatment of materials comprising large molecules such as the organic solid waste. Methane fermentation from organic solid waste is an anaerobic process carried out by three major groups of microorganisms: hydrolyzing and fermenting bacteria, acetogenic bacteria, and methanogenic archaea (Ahring, 2003). A better understanding of the effect of stimulating the activity of a complex microbial community on methane fermentation would be useful from both a scientific and an engineering point of view.

Our aim in the present study was to investigate the utility of BERs for the stable and efficient operation of a thermophilic, methanogenic bioreactor for the degradation of organic solid waste, and the effect of electrochemical regulation on the structure of the microbial community. Carbon material was used as the electrode and supporting material, because it is good for microbial adhesion

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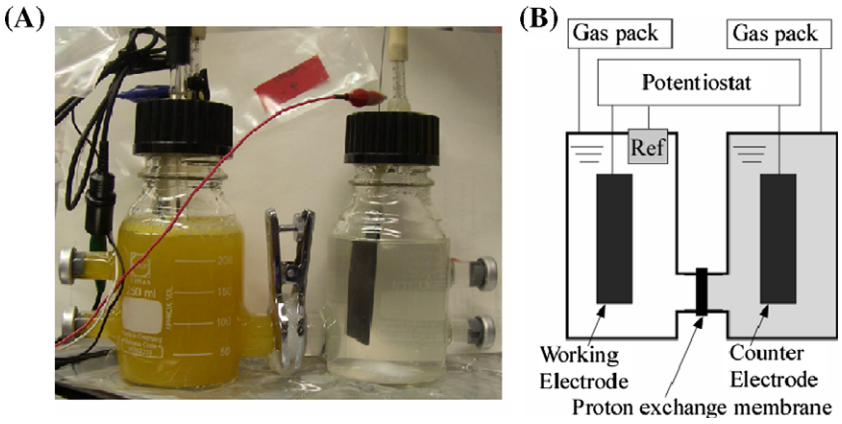

Fig. 1. Photograph (A) and schematic diagram (B) of our BER. Ref: reference electrode.

(Thrash and Coates, 2008). In a three-electrode system, which included a working electrode, a reference electrode, and a counter electrode, the potentials at the working electrodes were maintained at a level higher or lower than the oxidation–reduction potential for methane fermentation to ensure an anodic or cathodic reaction at the working electrode, respectively. We first compared the performances of BERs with different potentials at the working electrodes. We then qualitatively and quantitatively analyzed the microbial communities on the working electrode and in the suspended fraction using terminal restriction fragment length polymorphism (T-RFLP) analysis, cloning analysis, and real-time polymerase chain reaction (PCR).

2. Methods

2.1. Feed material

Artificial garbage slurry was used as a model of organic solid waste. The composition of the artificial garbage slurry was as follows (in g/L); commercial dog food (Vita-one, Nihon Pet Food, Tokyo, Japan), 100; KH_2PO_4, 1.1; and K_2HPO_4, 1.7. $NiCl_2{\cdot}6H_2O$ and $CoCl_2{\cdot}6H_2O$ were added to give Ni^{2+} and Co^{2+} concentrations of 0.10 and 0.12 mg/L, respectively (Tang et al., 2005). To ensure efficient electron transfer, 0.2 mM of 2,6-anthraquinone disulfonate was included in the working unit. The characteristics of the artificial garbage slurry were as follows: dichromate chemical oxygen demand (CODcr), 122.3 gCODcr/L; and suspended solid (SS), 53.3 g/L.

2.2. BERs

Each BER was constructed of two glass vessels (250 mL capacity) with glass tubing and a pinch-clump assembly, and was separated into two units by a proton exchange membrane (Nafion N117, Dupont Co., Wilmngton, DE, USA) (Fig. 1). A carbon electrode ($250 \times 750 \times 20$ mm) served as the supporting material in each unit, and in order to control the potential of the working electrode, an Ag/AgCl reference electrode was inserted into the working unit. Each electrode was connected to a potentiostat (PS-08, Tohogiken, Japan). In each BER, the potential at the working electrode was maintained at 0.0, −0.3, −0.6, or −0.8 V (vs. Ag/AgCl). All voltages reported in this paper are with respect to the Ag/AgCl reference electrode (type: saturated KCl). There was also a control BER in which the potential at the working electrode was not electrochemically regulated. The five types of BERs outlined above were prepared in triplicate. The working volume in each unit was 250 mL. The medium used in the counter unit was 250 mL of 100 mM NaCl.

2.3. Operation of the BERs

Seed cultures were collected from a thermophilic anaerobic digester, in which stable gas production from garbage slurry was being observed. The seed cultures (250 mL) were inoculated into the working units, which were then sealed with a silicon stopper. The contents were thoroughly mixed using a magnetic stirrer, and the initial anaerobic condition was established by replacing the gas phase with nitrogen gas. The temperature of the culture was maintained at 55 °C.

The working units were operated semicontinuously as follows: once a day, a predetermined volume was discharged and the same amount of fresh artificial garbage slurry was added. At the same time, 0.5 N NaOH was added to adjust the pH to about 7.5 in each reactor throughout the experiment. Finally, fresh 2,6-anthraquinone disulfonate was added to give a final concentration of 0.2 mM.

Fig. 2 summarizes the time schedule for the OLR and the hydraulic retention time (HRT) in each working unit. From days 0 to 40, the OLR was increased in stepwise fashion by reducing the HRT after the fluctuation in the gas production rate had

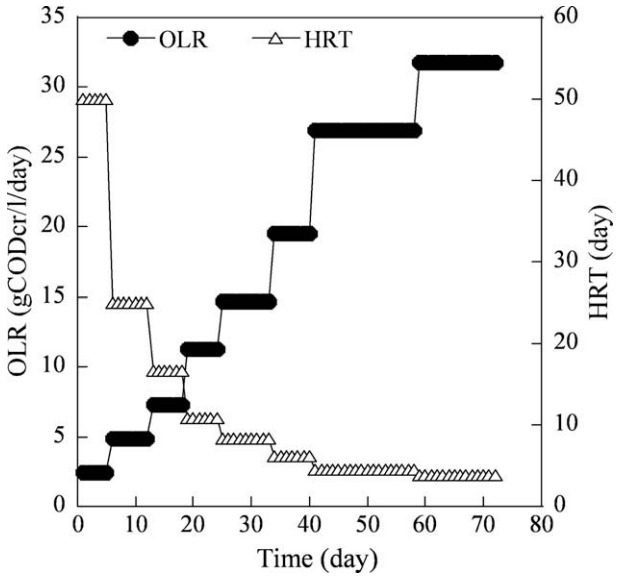

Fig. 2. Time-dependent changes in OLR and HRT. Due to deterioration, the three control reactors were stopped on days 52, 53 or 58, respectively, and two each of reactors set to 0.0 or −0.3 V were stopped on day 46 or 58, respectively. One each of the reactors set to −0.6 or −0.8 V was stopped on day 58 for sampling. The remaining two reactors each set to −0.6 or to −0.8 V operated until day 72.