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A bioelectrochemical reactor containing carbon fiber textiles enables efficient methane fermentation from garbage slurry

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ABSTRACT

A packed-bed system includes supporting materials to retain microorganisms and a bioelectrochemical system influences the microbial metabolism. In our study, carbon fiber textiles (CFT) as a supporting material was attached onto a carbon working electrode in a bioelectrochemical reactor (BER) that degrades garbage slurry to methane, in order to investigate the effect of combining electrochemical regulation and packing CFT. The potential on the working electrode in the BER containing CFT was set to −1.0 V or −0.8 V (vs. Ag/AgCl). BERs containing CFT exhibited higher methane production, elimination of dichromate chemical oxygen demand, and the ratio of methanogens in the suspended fraction than reactors containing CFT without electrochemical regulation at an organic loading rate (OLR) of 27.8 gCODcr/L/day. In addition, BERs containing CFT exhibited higher reactor performances than BERs without CFT at this OLR. Our results revealed that the new design that combined electrochemical regulation and packing CFT was effective.

1. Introduction

A huge amount of garbage is produced annually in Japan and the recycling of it is of significant social interest (Haruta et al., 2005). Anaerobic digestion such as methane fermentation is an attractive strategy with which to cope with garbage and to recover energy sources such as methane gas (Bruni et al., 2010).

To improve the efficiency of the digestion of garbage and methane production, various processes such as the packed-bed system have been exploited (Ueno et al., 2007). The packed-bed system, which is packed by supporting material, enables the efficient degradation of organic wastes and supports methane production from them. The packed-bed system using carbon fiber textiles (CFT) as the supporting material attained a higher organic loading rate (OLR) and methane production rate than those attained by reactors without CFT (Sasaki et al., 2009). The numerous advantages of the packed-bed system over other types of bioreactors are supported by the fact that CFT acts to maintain a high amount of microorganisms, particularly methanogens on CFT (Sasaki et al., 2010a). Methanogenic archaea are important in the final process of methane fermentation (Krakat et al., 2010). Therefore, the stable proliferation of methanogens within the reactor is a key element for the stable operation of a methane fermentor. In our previous study, we realized the efficient degradation of organic solid waste such as garbage slurry and rice straw by using the packed-bed system (Sasaki et al., 2010a,b).

A bioelectrochemical reactor (BER) can be used to control the electric flow and influence microbial metabolism (Thrash and Coates, 2008; Villano et al., 2010). It has been demonstrated that the electric flow caused by the cathodic reaction from the electrode resulted in increased methane production from garbage slurry and increased methanogens attaching to the carbon electrode at a high OLR, whereas the electric flow caused by the anodic reaction decreased them (Sasaki et al., 2010c). In addition, direct or indirect formation of methane from electrical current has been reported (Park et al., 1999; Cheng et al., 2009, 2011).

In this study, CFT was attached to one side of a carbon electrode in a BER to combine the characteristics of both the packed-bed system and the BER. CFT was placed on the side facing the reference electrode where the electrical reaction mainly occurred. Our aim is to investigate the reactor performance of the newly designed BER containing CFT and to examine the effect of combining electrochemical reduction, i.e., cathodic reaction, and packing CFT in our reactors. Methanogenic populations were analyzed because the effect of electrochemical reduction or packing CFT has been demonstrated to have significant impacts on methanogenic populations (Sasaki et al., 2010a,c).

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2. Methods

2.1. Feed material

A mixture of artificial garbage slurry (AGS) and rice straw was used as a model of organic solid waste. The composition of the AGS was as follows (in g/L): commercial dog food (Vita-one, Nihon Pet Food, Tokyo, Japan), 100; KH_2PO_4, 1.1; K_2HPO_4, 1.7; $NiCl_2{\cdot}6H_2O$, 0.004; and $CoCl_2{\cdot}6H_2O$, 0.005. The characteristics of AGS were as follows: dichromate chemical oxygen demand (CODcr), 122.3 gCODcr/L, and suspended solid (SS), 53.3 g/L. Rice straw, which was produced as the waste, was obtained from a Japanese farm. As pretreatment, the AGS and rice straw were shredded to less than 2 mm to increase the surface availability for microbial attack (Hartmann et al., 2000). The characteristics of rice straw were as follows: CODcr, 0.8 gCODcr/L, and SS, 0.7 g/L. The volume of AGS to be added to the cathodic working chamber once a day was determined and gradually increased during the operation. In addition, a fixed amount, i.e., 0.8 g/L (0.2 g/250 ml working volume) of rice straw was added once a day throughout the operation because rice straw that included lignin was difficult to digest.

2.2. Cathodic BERs containing CFT

All experiments of cathodic BERs containing CFT were performed according to the method of Sasaki et al. (2010c), using an H-type two-glass-chamber (Fig. 1). In short, we utilized a three-electrode system, which included a working electrode, a reference electrode, and a counter electrode. The cathodic working chamber and anodic chamber were separated by a proton exchange membrane (Nafion 117; DuPont Co. Wilmington, DE, USA). A carbon plate (25 × 75 × 2 mm) was used as the working electrode and the counter electrode. On the carbon plate of the working electrode, CFT (25 × 75 × 2.4 mm) was attached to the side of the reference electrode using silicon glue. An Ag/AgCl reference electrode was inserted into the cathodic working chamber. All reported potentials on the working electrode pertain to the Ag/AgCl reference electrode (type: saturated KCl). Using a potentiostat (PS-08, Tohogiken, Japan), the potential of the working electrode was electrochemically regulated to −1.0 V or −0.8 V (vs. Ag/AgCl), i.e., a level lower than the oxidation–reduction potential for methane fermentation, to ensure a cathodic reaction at the working electrode. Two types of BERs (at −1.0 V or −0.8 V) containing CFT were prepared in triplicate. There were also three reactors containing CFT in which the potential at the working electrode was not electrochemically regulated as control 1. In addition, two BERs at −0.8 V without CFT were operated as control 2. As a result, four types of reactors ((1) with CFT, at −1.0 V; (2) with CFT, at −0.8 V; (3) with CFT, without electrochemical regulation [as control 1]; (4) without CFT, at −0.8 V [as control 2]) were prepared. The working volume of each chamber was 250 ml. The medium used in the anodic chamber was 100 mM NaCl. The contents of reactors were thoroughly mixed using a magnetic stirrer.

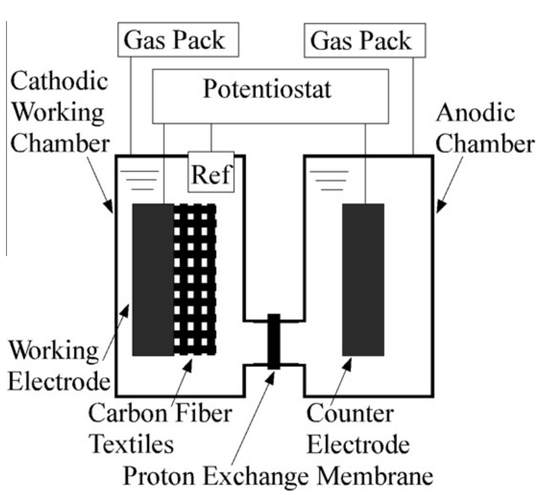

Fig. 1. Schematic diagram of cathodic BER containing CFT. Ref, reference electrode. Configuration of the control reactor without electrochemical regulation (control 1) was the same. A BER (at −0.8 V) without CFT (control 2) was also prepared as a control.

2.3. Operation of reactors

First, the same volume (250 ml) of sludge from the methane fermentor (55 °C) degrading organic solid waste (Sasaki et al., 2010c) was injected into each working chamber after it was filled with nitrogen gas (gas phase). Next, all chambers were sealed with a silicon stopper. The cathodic working chambers and the control reactors without electrochemical regulation (control 1) or without CFT (control 2) were operated in semicontinuous mode at 55 °C as follows: once a day, a predetermined volume was discharged and the same amount of fresh AGS and 0.8 g/L of rice straw was added. The OLR was increased by increasing only the input amount of AGS; however, the input amount of rice straw was fixed. The pH in the working chamber was adjusted to 7.2 by adding 1 N NaOH.

Fig. 2 summarizes the time schedule for the OLR and the hydraulic retention time (HRT) in cathodic BERs containing CFT and control reactors without electrochemical regulation (control 1) or without CFT (control 2). From days 0 to 44, the OLR was increased in stepwise fashion by reducing the HRT after the fluctuation in the gas production rate had declined to under ±12.5%. From days 45 to 54 or days 55 to 62, the reactors were operated for a period more than two times the length of the HRT (10 days or 8 days) at an OLR of 27.8 gCODcr/L/day or 32.7 gCODcr/L/day, respectively. All reactors were operated on the above time schedule; however, reactors exhibiting signs of deterioration such as accumulation (>100 mM) of high levels of volatile fatty acids (VFAs) were stopped at that time.

The deterioration of three control reactors without electrochemical regulation and two control reactors without CFT led to

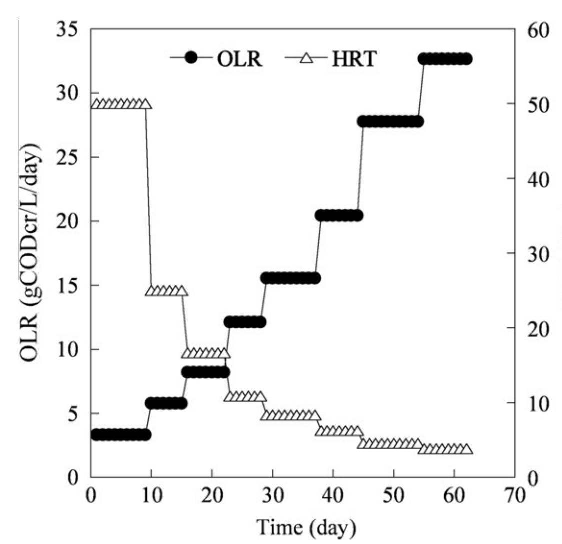

Fig. 2. Time courses of OLR and HRT in working chambers of the cathodic BERs containing CFT, and the control reactors without electrochemical regulation (control 1) or without CFT (control 2). Due to deterioration, controls 1 and 2 were stopped at day 54. Each one of the three BERs (at −1.0 V or −0.8 V) containing CFT was stopped at day 54 for sampling. The remaining two BERs (at −1.0 V or −0.8 V) containing CFT were stopped due to deterioration at day 62.