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Bioelectrochemical enhancement of methane production from highly concentrated food waste in a combined anaerobic digester and microbial electrolysis cell

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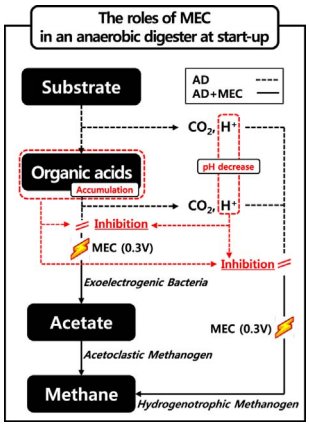
GRAPHICAL ABSTRACT



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ABSTRACT

A microbial electrolysis cell (MEC) is a promising technology for enhancing biogas production from an anaerobic digestion (AD) reactor. In this study, the effects of the MEC on the rate of methane production from food waste were examined by comparing an AD reactor with an AD reactor combined with a MEC (AD + MEC). The use of the MEC accelerated methane production and stabilization via rapid organic oxidation and rapid methanogenesis. Over the total experimental period, the methane production rate and stabilization time of the AD + MEC reactor were approximately 1.7 and 4.0 times faster than those of the AD reactor. Interestingly however, at the final steady state, the methane yields of both the reactors were similar to the theoretical maximum methane yield. Based on these results, the MEC did not increase the methane yield over the theoretical value, but accelerated methane production and stabilization by bioelectrochemical reactions.

1. Introduction

Anaerobic digestion (AD) produces methane gas by the biodegradation and reduction of highly concentrated organic waste (Guo et al., 2013). However, AD is affected by substrate characteristics, operation temperatures, pH, alkalinity, ammonium ions, C/N ratio,

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volatile fatty acids (VFAs), nutrients, organic loading rate (OLR), reactor type, and toxicity (Wang et al., 2016; Rajagopal et al., 2013; Hobbs et al., 2017). Therefore, AD reactors exhibit unstable methane production and organic degradation (Moset et al., 2014; Appels et al., 2008). In particular, highly concentrated organic matter, such as food waste, inhibits methane production and stabilization via accelerated VFA accumulation and a decrease in pH (Hobbs et al., 2017). Lu et al. (2008) and Adekunle and Okolie (2015) showed that, for highly concentrated or complex organic matter, such as food waste and livestock wastewater, byproducts (complex heterocyclic compounds) or non-degradable VFAs form during hydrolysis, thus making it the rate-limiting step. Chen et al. (2008) reported that the methane production by an AD reactor is mainly inhibited by a decrease in pH and VFA accumulation at start-up, and this inhibition continues until the steady state is reached. Latif et al. (2017) also reported that a low pH is associated with various issues, including acid requirements, VFA accumulation, loss in methane production, and the inhibition of methanogenesis. Owing to the decreased pH and the accumulation of VFAs at start-up, an AD reactor often requires 2–9 months to become stabilized (Lauwers et al., 1990).

Various researchers have investigated ways to improve the methane production rate and stabilization time. For example, one traditional method involves phase separation between acidogenesis (or hydrolysis) and methanogenesis to minimize interspecific competition and to increase the reaction rate at the rate-limiting step. Gough et al. (2013) reported that the methane production rate could be increased using separation by thermophilic acidogenesis at 55 °C and mesophilic methanogenesis at 35 °C; Lopez et al. (2014) obtained similar results.

The recently developed microbial electrolysis cell (MEC), a microbial electrochemical technology, uses bioelectrochemical reactions to improve biogas production in an AD reactor by the rapid degradation of highly concentrated organic wastes, VFAs, toxic materials, and non-degradable organic matter (Zhang and Angelidaki, 2014). MECs supply a low voltage (0.2–0.8 V) to the AD reactor for bioelectrochemical reactions, in which exoelectrogenic bacteria decompose organic matter and release electrons at the anode (Eq. (1)). These electrons then move to the cathode in a closed circuit and are consumed, thereby producing CH_4 (Eq. (2)) and H_2 (Eq. (3)) (Logan et al., 2008).

$$\text{Anode: } C_2H_4O_2 + 2H_2O \rightarrow 2CO_2 + 8H^+ + 8e^- \quad E^0 = -0.28 \text{ V vs. SHE} \tag{1}$$

$$\text{Cathode: } CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O \quad E^0 = -0.24 \text{ V vs. SHE} \tag{2}$$

$$2H^+ + 2e^- \rightarrow H_2 \quad E^0 = -0.42 \text{ V vs. SHE} \tag{3}$$

When a MEC was used with a single AD reactor, there was rapid degradation of not only the highly concentrated organic matter, but also the VFAs, toxic materials, and non-degradable matter (Zhang et al., 2013). The microbial activities and the rate of methane production were also increased by the bioelectrochemical reactions (Ding et al., 2016). Several studies have confirmed that the MEC results in greater methane production than that of an AD reactor; methane yields achieved using a MEC are 0.31–0.41 L-CH_4/g-COD (chemical oxygen demand), which is close to the theoretical maximum methane yield at 35 °C (Bo et al., 2014; Tartakovsky et al., 2011; Xafenias and Mapelli, 2014; Yin et al., 2016).

These results indicate that bioelectrochemical reactions increase methane production by improving microbial activities and the efficiency of the removal of organic matter, including VFAs. Previously, Zhao et al. (2014) used a bioelectrochemical system to resolve a high OLR and found that methane production increased by the bioelectrochemical activation of acetoclastic and hydrogenotrophic methanogenesis, without a decrease in pH or VFA accumulation. Gajaraj et al. (2017) reported that MEC-assisted AD systems of 0.3 V and 0.6 V increase the yields of methane from glucose degradation by 9.4 ± 0.4% and 9.4 ± 0.5%, respectively, compared with the yield for an AD reactor. However, these experiments were conducted in small-scale reactors using a low concentration of synthetic substrate, such as acetate and glucose. More recently, Cerrillo et al. (2016) used an AD reactor coupled with a MEC to overcome the organic and nitrogen overload from pig slurry and reported that the AD + MEC combined system was a promising strategy for stabilization against organic and nitrogen overloads. This research was notable as it utilized pig slurry, but the working volume of the reactors was still less than 4 L. Dang et al. (2016) reported that an AD + MEC reactor with a carbon-based electrode could enhance methane production from dog food waste at a higher OLR than that of an AD reactor. However, few studies have examined methane production from municipal food waste using bench-scale AD and AD + MEC reactors to verify the effectiveness of MEC.

Therefore, in this study, the effect of a MEC on the methane production rate and stabilization time from highly concentrated food waste was investigated in relatively large-scale AD and AD + MEC reactors (working volume: 20 L). Based on the study results, the roles of MEC in the AD reactor are discussed, with a focus on the methane production rate and stabilization time of highly concentrated food waste.

2. Materials and methods

2.1. Characteristics of the substrate

Food waste sampled from a food waste treatment plant (FWTP) in the Republic of Korea was used as the substrate; the food waste was pre-treated by filtration using a 150-μm sieve. The pre-treated food waste diluted to 60.3 ± 2.1 g-TCOD (total chemical oxygen demand)/L was injected into each reactor once a day. The total solid (TS), total volatile solid (TVS), total nitrogen (TN), and pH of the feed provided to each reactor were 5.2 ± 0.4%, 3.9 ± 0.3%, 1.2 ± 0.2 g/L, and 5.2 ± 0.7, respectively.

2.2. Setup of the reactors and electrodes

To assess the effects of a MEC on the methane production rate in an AD reactor, experiments were conducted in two sequencing batch reactors (SBR). One reactor was a typical mesophilic single AD reactor and the other was a mesophilic single AD + MEC reactor. The seeding sludge was obtained from an AD reactor of the FWTP and was inoculated to each reactor. Fig. 1(a) shows the configuration of the two reactors, comprising an acrylic cylindrical structure (280 mm diameter × 410 mm height). The total volume of each reactor was 25 L and the working volume was 20 L. The AD + MEC reactor contained six sets of electrodes of 150 mm in width and 300 mm in height; the electrodes were positioned vertically to the rim of the cylindrical reactor. Each electrode was composed of graphite carbon mesh coated with Ni to increase electrical conductivity. For the cathode, a complex metal catalyst solution was prepared by dissolving 30.125 g of $MnSO_4 \cdot H_2O$, 19.75 g of $KMnO_4$, 0.5684 g of iron phthalocyanine (FePc), and 0.5761 g of copper phthalocyanine (CuPc) in 1 L of distilled water and stirring for 2 h. The prepared solution was heated for 1 min and 30 s using a microwave and cooled for 60 s. The same procedure was repeated 5 times, and the solution was subsequently fixed on the graphite carbon mesh as described previously (Song et al., 2014). To minimize the internal resistance and to prevent contact between the electrodes, which were less than 3 mm apart, a piece of non-woven fabric was placed between the anode and cathode (Fig. 1(b)). Titanium wires were used to complete the external circuit and to connect the anodes and cathodes. Each reactor had an agitator to maintain homogeneous conditions and valves to inject the substrate and collect the biogas.

2.3. Operational conditions

The two reactors were operated for 12 months with an OLR of