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Enhanced digestion of waste activated sludge using microbial electrolysis cells at ambient temperature

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ABSTRACT

This study examined the effects of the microbial electrolysis cell (MEC) reactions on anaerobic digestion of waste activated sludge from municipal wastewater treatment under ambient temperature conditions (22–23 °C). Two lab-scale digesters, a control anaerobic digester and an electrically-assisted digester (EAD – equipped with a MEC bioanode and cathode) were operated under three solids retention times (SRT = 7, 10 and 14 days) at 22.5 ± 0.5 °C. A numerical model was also built by including the MEC electrode reactions in Anaerobic Digestion Model No.1. In experiments, the EAD showed reduced concentration of acetic acid, propionic acid, n-butyric acid and iso-butyric acid. This improved performance of the EAD is thought to be achieved by direct oxidation of the short-chain fatty acids at the bioanode as well as indirect contribution of low acetic acid concentration to enhancing beta-oxidation. The VSS and COD removal was consistently higher in the EAD by 5–10% compared to the control digester for all SRT conditions at 22.5 ± 0.5 °C. When compared to mathematical model results, this additional COD removal in the EAD was equivalent to that which would be achieved with conventional digesters at mesophilic temperatures. The magnitude of electric current in the EAD was governed by the organic loading rate while conductivity and acetic acid concentration showed negligible effects on current generation. Very high methane content (~95%) in the biogas from both the EAD and control digester implies that the waste activated sludge contained large amounts of lipids and other complex polymeric substances compared to primary sludge.

1. Introduction

In municipal wastewater sludge treatment, anaerobic digestion is typically operated under mesophilic conditions at temperatures ranging from 35 to 40 °C (Metcalf & Eddy et al., 2004). To maintain this temperature requirement for large sludge volumes, a substantial amount of energy is therefore required. However, low temperature conditions below 35 °C slow down the biosolids destruction with reduced rates of microbial growth and biogas production (Connaughton et al., 2006). As a result, lower temperature digesters require a substantially long solids retention time (SRT) for adequate performance. For example, a digester operated at 24 °C or lower would require an SRT of longer than 20 days to digest municipal wastewater sludge under well-mixed conditions (Reynolds and Richards, 1995; Metcalf & Eddy et al., 2004; Bolzonella et al., 2005). However, there are a number of benefits of operating digestion systems at a lower temperature, such as reduced energy input and significantly reduced digester construction cost without heating systems and insulation walls, allowing for small wastewater treatment facilities to operate sludge digesters. Since low temperature conditions substantially decrease the rate of sludge digestion, the primary objective of this study was to enhance the rate of volatile suspended solids (VSS) and chemical oxygen demand (COD) removal using an electrically-assisted digester (EAD) at ambient temperature conditions (22–23 °C).

In anaerobic digestion, the destruction of biosolids is achieved through a series of biological reactions (Fig. 1). Under mesophilic conditions, the hydrolysis of carbohydrates and proteins is relatively quick, requiring 1–3 days; while lipids require 6–8 days for hydrolytic decomposition (Grady et al., 2011). Many studies have reported that if digester influent contains a large amount of complex lipids, the hydrolysis step starts to govern the overall rate of biosolids destruction (Ariunbaater et al., 2014; Izumi et al., 2010; Ma et al., 2011; Valo et al., 2004). Hydrolyzed soluble organics

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Nomenclature[1]

ADM1	Anaerobic Digestion Model No.1
CE	Coulombic efficiency (−)
COD	chemical oxygen demand (mg/L)
ΔH_{CH4}	heat of combustion of CH_4 (890.8 kJ/mol)
EAD	electrically-assisted digester
E_{ap}	applied electric voltage (V)
F	Faraday constant (96,485 C/mol)
FID	flame ionization detector
GC	gas chromatography
I	electric current (A)
LCFA	long chain fatty acid
MEC	microbial electrolysis cell
n_{CH4}	amount of CH_4 produced (mol)
R	Gas constant (8.314 J/mol/K)
r_E	energy recovery from the EAD (−)
SRT	solids retention time (d)
TCD	thermal conductivity detector
TSS	total suspended solids (mg/L)
V	volume of sludge (L)
VSS	volatile suspended solids (mg/L)
WAS	waste activated sludge
W_E	electric energy consumed to drive the MEC reactions (J)
W_{CH4}	energy recovered as CH_4 from the EAD (J)

(monosaccharides, amino acids and long-chain fatty acids) are decomposed to short-chain organic acids and hydrogen gas in acidogenesis reactions, such as fermentation and beta-oxidation. Acetoclastic methanogenesis and hydrogenotrophic methanogenesis are the final steps converting acetate and hydrogen gas to methane gas, respectively. At 35 °C, hydrogenotrophic methanogens are known to grow rapidly and convert hydrogen gas to methane in less than 1 day (Grady et al., 2011). Acetoclastic methanogenesis, however, requires a substantially long time as acetoclastic methanogens need 3–5 days (*Methanosarcina* spp.) and at least 12 days (*Methanosaeta* spp.) to sustain growth (Grady et al., 2011), indicating that the time requirement for acetoclastic methanogenesis is even longer at ambient temperature conditions (20–25 °C). The majority of acetoclastic methanogenesis is driven by *Methanosaeta* species which result in the process being another rate-limiting step in anaerobic digestion. When the digester influent contains easily degradable substrates with a relatively small amount of lipids, acetoclastic methanogenesis has been reported to be the dominant rate-limiting step (Ariunbaater et al., 2014; Grady et al., 2011; Rittmann and McCarty, 2001). In domestic wastewater sludge digestion, the influent does not typically contain high levels of complex substrates which results in acetoclastic methanogenesis being the key rate-limiting step.

In this study, microbial electrolysis cell (MEC) technology was integrated into a lab-scale anaerobic digester in order to expedite the rate of biosolids destruction as previously described (Asztalos and Kim, 2015, accepted) but under even lower temperature conditions (22 °C). An MEC consists of a bioanode and cathode that are electrically connected with an external power supplier (Liu et al., 2005b; Rozendal et al., 2006; Logan et al., 2008). Acetate is oxidized by exoelectrogenic bacteria at the bioanode and hydrogen gas is produced at the cathode via electrolytic water reduction. Hydrogenotrophic methanogens quickly convert the produced hydrogen gas into methane gas. The MEC bioanode oxidizes a certain portion of the available acetate in the digester and creates an additional pathway for acetate removal as previous demonstrated in the EAD (electrically-assisted digester) under mesophilic condition (40 °C) (Asztalos and Kim, 2015, accepted). While expedited volatile suspended solids (VSS) and chemical oxygen demand (COD) removals were demonstrated, decomposition of organic acids (acetic acid, propionic acid, butyric acid and valeric acid) in the EAD was not clearly investigated. Experimental examination of such organic acids is necessary to ensure proper destruction of long-chain fatty acids (LCFAs) via beta-oxidation. We also focused on how the electric current is governed in wastewater sludge digestion by finding correlations with potential limiting factors, such as organic loading rate, conductivity and acetic acid concentration. Another aspect of this study is to explain whether the MEC reactions can increase the methane content in biogas production because the MEC cathode reaction creates an extra amount of hydrogen gas and hydrogenotrophic methanogenesis consumes carbon dioxide ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$).

We also built a numerical model similar to Anaerobic Digestion Model No.1 (ADM1) developed by the IWA Task Group (Batstone et al., 2002) with the addition of the MEC component (Asztalos and Kim, 2015, accepted). The numerical model allowed us to examine a variety of components and microbes under various SRT, temperature and electrical current conditions. For example, experimental results on improved digestion performance with the MEC reactions under ambient temperature conditions were compared with conventional digester performance under various temperature conditions using the model. In addition, model simulation results can be used to explain how the MEC electrode reactions affect other biological reactions and contribute to enhancing anaerobic digestion performance. We also used the model to find equivalent temperature increases that would result in the same degree of improvement achieved with the MEC reactions. This application of the model will provide a meaningful conclusion on which option is more beneficial between increasing operation temperature and employing the MEC reactions in anaerobic digestion. Based on this comparison, we will be able to further discuss the energy requirement for the MEC reactions and that for heating wastewater sludge to attain mesophilic conditions.

2. Materials and methods

2.1. Reactor construction

Two lab-scale anaerobic digestion reactors, a control digester and an electrically-assisted digester (EAD), were constructed with MEC components. The reactor bodies were made out of a thick polypropylene block in which a cylindrical hole (6.5 cm diameter and 6.5 cm depth with the effective liquid volume of 180 mL) was drilled. Two end-plates were fastened to the top and bottom of the bodies using metal tie rods and nuts placed along the perimeter of the reactor bodies (Fig. 2). Three carbon fiber brushes (2 cm diameter and 2.5 cm in length; Mill-Rose, OH) were pretreated in a muffle furnace at 450 °C for 30 min (Wang et al., 2009) before they were placed in each digester as bioanodes. A single layer of stainless steel mesh was used as the MEC cathode without the use of any precious metal catalysts (total projected area of 135 cm^2, AISI 304, 100-mesh, McMaster-Carr, OH). The stainless steel mesh was

[1] The symbols in ADM1 are defined in Tables 1 and 2.

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