Bioresource Technology 245 (2017) 1162–1167

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Enhanced methane production and wastewater sludge stabilization of a continuous full scale thermal pretreatment and thermophilic anaerobic digestion

Dongwoo Han[a], Chang-Yeol Lee[b], Soon W. Chang[c], Dong-Jin Kim[d,*]

[a] R & D Center, ENTECS Co., Ltd. 229 (Ok-dong), Pyeongdongsandan-ro, Gwangsan-gu, Gwangju 62416, Republic of Korea
[b] Chemicals R & D Center, SK Chemicals 310 Pangyo-ro, Bundang-gu, Seongnam, Gyeonggi 13494, Republic of Korea
[c] Department of Environmental Energy & Engineering, Kyonggi University, Suwon, Gyeonggi 16277, Republic of Korea
[d] Department of Environmental Sciences and Biotechnology & Institute of Energy and Environment, Hallym University, Chuncheon, Gangwon 24252, Republic of Korea

ARTICLE INFO

Keywords:
Methane production
Sludge hydrolysis
Thermal treatment
Thermophilic anaerobic digestion

ABSTRACT

A continuous full scale thermophilic anaerobic digestion (AD) of wastewater sludge in conjunction with thermal pretreatment was developed for enhanced CH_4 production as well as sludge stabilization and reduction. Continuous thermal sludge treatment obtained 45.5, 51.7, and 26.1% of hydrolysis based on TS, VS, and COD at 160 °C for 30 min. After AD, TS, VS, and COD removal efficiencies reached 54.7, 60.4, and 59.2%, respectively, at 3.50 kg VS/m^3·d. Maximum CH_4 yield (0.35 m^3 CH_4/kg VS_{add}) was obtained at 2.49 kg VS/m^3·d and less, and the yield decreased with increasing sludge load while net available energy production increased. Continuous thermal sludge treatment and thermophilic AD enhanced CH_4 production and solids reduction and showed stable performance for full scale application.

1. Introduction

The amount of sludge generation is continuously increasing due to the expansion of wastewater treatment facilities and the introduction of advanced wastewater treatment processes. As the landfill site for sludge disposal becomes difficult to secure in many countries, however, much attention has been paid to sludge volume reduction, recycling, and conversion to energy. For the purpose, sludge AD has been widely applied for the production of sustainable energy (methane) as well as for the stabilization and reduction of sludge. AD is a slow process and it needs a large volume digester. It is well recognized that sludge hydrolysis is the rate limiting step of the AD. Therefore, sludge pretreatment has been incorporated for sludge hydrolysis and it increased not only the rate of AD but also the yield of methane production (Bougrier et al., 2006; Kim and Youn, 2011; Kim, 2013).

Thermal sludge treatment has been extensively investigated for pretreatment and many full scale plants are in operation (Kepp et al., 2000). Commercial pretreatment technology, such as Cambi process, incorporates sludge heating up to 170 °C by direct steam injection and pressures higher than the vapor pressure for sludge hydrolysis by thermal expansion to atmospheric pressure. Sludge is further treated by mesophilic AD after the thermal treatment (Bougrier et al., 2006; Kepp et al., 2000; del Rio et al., 2011).

Mesophilic AD has been widely used because of its operation stability and lower energy requirement than thermophilic AD. However, thermophilic AD has strength in disinfection of pathogens, enhanced methane production rate, and requirement of less digester volume due to reduced hydraulic (sludge) retention time (Climent et al., 2007; Gebreeyessus and Jenicek, 2016).

Furthermore, thermophilic digestion needs lower cooling duty after the thermal sludge pretreatment than mesophilic digestion (Climent et al., 2007; Stuckey and McCarty, 1984). Very few studies have been reported on the effect of thermal sludge pretreatment and thermophilic AD on biogas (methane) production and sludge stabilization and most of the thermal pretreatments were performed at low temperature (70 °C) (Climent et al., 2007; Skiadas et al., 2004; Gavala et al., 2003). Gavala et al. (2003) performed thermal sludge pretreatment at low temperature (70 °C) and found no significant differences in biogas production between mesophilic and thermophilic AD in a batch laboratory scale reactor. Skiadas et al. (2004) reported significant increase of biogas production under thermophilic AD after low temperature thermal pretreatment in comparison with untreated sludge. Climent et al. (2007) and Ferrer et al. (2008) found low temperature pretreatment (70 °C) gave positive influence in biogas production under thermophilic AD. Kaparaju et al. (2008) reported enhanced methane production with intermittent mixing during thermophilic AD of

* Corresponding author.
E-mail address: dongjin@hallym.ac.kr (D.-J. Kim).

http://dx.doi.org/10.1016/j.biortech.2017.08.108
Received 30 June 2017; Received in revised form 16 August 2017; Accepted 17 August 2017
Available online 20 August 2017
0960-8524/

manure. Summarizing the literature review, thermophilic AD digestion in conjunction with thermal pretreatment at high temperature (> 130 °C) had not been performed yet in bench scale or pilot scale, especially in a continuous operation.

In this study, thermal sludge pretreatment and thermophilic AD were performed in a full scale plant to examine the effect of high temperature sludge pretreatment on sludge stabilization, biogas (methane) production, and the energy balance of the system. As far as the authors understand this is the first report on continuous thermophilic AD with thermal pretreatment at high temperature. For the thermal sludge pretreatment, indirect heating by heat transfer medium was used. Even though heat transfer efficiency of the indirect heating is lower than the direct heating by steam injection, the system has an advantage that it keeps the thickened sludge concentration constant during the thermal pretreatment and the AD without dilution. The higher concentration of sludge is fed to the digester, the lower volume of anaerobic digester is needed.

The objectives of this study were to find the optimum temperature of thermal sludge pretreatment for sludge hydrolysis and thermophilic AD by indirect heating in a full scale plant and to investigate the effect of thermal sludge pretreatment on sludge stabilization and methane production including energy balance of the full scale (sludge treatment capacity: 5 m^3/d) thermophilic anaerobic digester.

2. Materials and methods

2.1. Thermal sludge pretreatment and thermophilic AD

Excess wastewater sludge was obtained from a rotating drum thickener of a municipal wastewater treatment plant in Namyangju city, Korea. The sludge was screened with a mesh (2 mm) before the thermal pretreatment and its characteristics are shown in Table 1. A stirred autoclave reactor (working volume: 300 L, diameter: 580 mm, height: 1200 mm) was used for the thermal sludge pretreatment at a hydraulic retention time (HRT) of 30 and 60 min and the temperature was controlled at 130–180 °C in a batch experiment to examine the effect of temperature and time on sludge hydrolysis.

In the continuous thermal sludge pretreatment combined with the thermophilic AD, the thickened sludge was continuously pumped into the autoclave reactor (160 °C) at the HRT of 30 min as shown in Fig. 1. The sludge was preheated in the heat exchanger with the thermally treated sludge and further heated in the thermal treatment reactor. The pretreated sludge was continuously fed to the thermophilic anaerobic digester (total volume: 100 m^3, diameter: 4.2 m, height: 7 m) at the HRT of 15–18.8 days and the temperature of 55 °C. The digester was stirred with a screw type mixer.

2.2. Analytical methods

The efficiency of sludge disintegration or hydrolysis by thermal treatment was quantified based on the solubilized total solids (TS), volatile solids (VS), chemical oxygen demand (COD) using the following equation:

$$\text{Sludge hydrolysis} = (S_T - S_0)/(T_0 - S_0) \times 100(\%) \quad (1)$$

where, S_T = Soluble total (volatile) solids and soluble COD of the thermally pretreated sludge, mg/L.

S_o = Soluble total (volatile) solids and soluble COD of the sludge before the treatment, mg/L.

T_o = Total (volatile) solids and total COD of the sludge before treatment, mg/L.

For the assessment of methane production potential of the thermally pretreated sludge in a batch mode, four sets of laboratory scale thermophilic anaerobic digesters (10 L working volume) were used (Owen et al., 1979). All the digesters were mixed with a stirrer and incubated at 55 ± 1 °C.

For the analysis, total solids, volatile solids, and COD were measured by the protocols in the Standard Methods (APHA et al., 2005). Soluble components by sludge hydrolysis were prepared after filtering by 0.45 μm PTFE membrane filter and analyzed. Biogas production from the anaerobic digester was continuously monitored with a gas flow meter. Methane and carbon dioxide in the biogas were analyzed by a gas chromatography (GC-14 A, Shimadzu), which was equipped with a thermal conductivity detector, a packed column (Shincarbon ST), and He as the carrier gas (40 mL/min). Biogas (250 μL) was injected to the GC with a gas tight syringe at a split ratio of 3:1. Injector and detector temperatures were set to 230 and 250 °C, and the oven temperature was raised to 30 °C/min from 60 °C to 240 °C.

Table 1
Characteristics of the thickened sludge before and after the thermal sludge treatment at 160 °C for 30 min in a continuous full scale operation.

	Before treatment (mg/L)	After treatment (mg/L)	Degradation (%)
Total solids	56,700 ± 3,650	56,600 ± 4,300	–
Total volatile solids	43,950 ± 2,650	43,680 ± 3,750	–
Total suspended solids	54,410 ± 3,340	29,570 ± 4,090	45.5
Volatile suspended solids	42,470 ± 3,980	20,240 ± 2,250	51.7
Total COD	69,220 ± 6,980	69,310 ± 7,490	–
Soluble COD	537 ± 180	18,170 ± 2,440	26.1*

* Average sludge hydrolysis efficiency based on COD.

3. Results and discussion

3.1. Thermal sludge pretreatment

Fig. 2 shows the effect of temperature (130–180 °C) and time (30, 60 min) of the thermal sludge pretreatment on the sludge hydrolysis. Thermal sludge treatment was carried out in a batch mode. Sludge hydrolysis was measured by the conversions of total suspended solids (TSS) to total dissolved solids (TDS), volatile suspended solids (VSS) to volatile dissolved solids (VDS), and total COD to soluble COD. Thickened excess wastewater sludge (5.7%) was thermally treated at various temperature. The results showed that sludge hydrolysis increased with treatment temperature and time. Maximum sludge hydrolysis was obtained at 180 °C and the efficiencies with the treatment time of 30 and 60 min were 53.1 and 55.5% in TS, 61.0 and 62.9% in VS, and 34.6 and 38.0% in COD, respectively. VS showed the highest hydrolysis efficiency followed by TS and COD. Sludge hydrolysis increment was not significant when the treatment time was increased from 30 to 60 min. In addition, sludge hydrolysis efficiency remained almost constant when the temperature was higher than 160 °C except COD hydrolysis. Therefore, thermal sludge treatment condition for the thermophilic AD was set to 160 °C for 30 min.

Fig. 3 shows the hydrolysis efficiencies of the thickened sludge during the continuous full scale thermal sludge pretreatment at 160 °C for 30 min. It showed that sludge hydrolysis (%) were stable during the whole operation period and the average efficiencies based on TS, VS, and COD were 45.5, 51.7, and 26.1%, respectively. Sludge hydrolysis efficiencies of the continuous thermal treatment were somewhat lower than those of the batch treatment results which were 49.8, 58.3, and 26.8%, respectively, for 30 min treatment. It is mainly caused by the hydraulic characteristics of the two different reactors. In fact, batch reactor takes more treatment time if the time for heating and cooling to the designated temperature is included.

Fig. 4 shows the methane production potential results of the thickened sludge with the thermal sludge treatment at 120 - 180 °C for 30 (A) and 60 min (B). Untreated sludge gave methane production of 0.155 and 0.158 m^3/kg VS_{add}, and the maximum methane productions were 0.278 and 0.283 m^3/kg VS_{add} for 30 and 60 min pretreatment at