Bioresource Technology 104 (2012) 150–156

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

High-solid anaerobic digestion of sewage sludge under mesophilic conditions: Feasibility study

Nina Duan, Bin Dong *, Bing Wu, Xiaohu Dai

National Engineering Research Center for Urban Pollution Control, School of Environmental Science and Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, PR China

ARTICLE INFO

Article history:
Received 10 September 2011
Received in revised form 22 October 2011
Accepted 25 October 2011
Available online 3 November 2011

Keywords:
Anaerobic digestion
Sewage sludge
High-solid
Mesophilic

ABSTRACT

Feasibility of high-solid anaerobic digestion of sewage sludge was investigated in single-stage completely stirred tank reactors at 35 ± 1 °C. System stability and the effect of organic loading rate (OLR), sludge retention time (SRT) and total solid (TS) content on the performance of high-solid system was examined. Experimental results showed that, with the concentration of free ammonia nitrogen (FAN) lower than 600 mg l^{-1}, high-solid anaerobic digestion of sewage sludge could maintain satisfactory stability. Slight, moderate and significant inhibition was found with FAN concentration ranging from 250 to 400, 400 to 600 and 600 to 800 mg l^{-1}, respectively. The VFA/TA criteria could not foresee system instability in significant ammonia inhibition system by its traditional ratio grades. High-solid system could support higher OLR (4–6 times as high) and obtain similar methane yield and VS reduction as conventional low-solid system at the same SRT, thus reach much higher volumetric methane production rate.

1. Introduction

Volume and mass of sludge generated in waste water treatment plants (WWTPs) are expected to increase continuously in the next decade, due to increasing population connected to sewage networks, building of new WWTPs and upgrading of existing plants to fulfill the more stringent local effluent regulations. In China, the annual production of sewage sludge (80% moisture content) has reached almost 3000 tons, and 80% of it has not obtained necessary stabilization. Thus, it is essential to develop proper treatment processes to reduce the amount of sludge. One of the most widely used processes is anaerobic digestion or methanisation. It can realize sludge stabilization by converting a part of its organic matter into biogas which is a renewable energy source. This technology has been successfully implemented in the treatment of agricultural wastes, food wastes, and sewage sludge (Chen et al., 2008).

However, the use of traditional anaerobic digester for low-solid sewage sludge is not always feasible in small-scale WWTPs or WWTPs in some undeveloped countries. For example, up to 2010, among the 2500 WWTPs in China, only 50 ones were designed with anaerobic digestion systems, and only 20% of them were well operated. Low-solid anaerobic digestion was not well applied in China mainly due to poor management, unprofessional operation, economical limitation and inadequate planning. However, more than 80% of the sewage sludge in China has already been dewatered before further disposal or treatment, which makes it favorable to be centralized processed. Hence, high-solid anaerobic digestion could be one viable option to solve the sludge disposal problems in undeveloped countries like China or in small-scale WWTPs. High-solid anaerobic digestion is usually characterized by a high TS content of the feedstocks, typically greater than 15% (w/w) (Rapport et al., 2008) and has been claimed to be advantageous over traditional low-solid anaerobic digestion for several reasons, such as smaller reactor volume, lower energy requirements for heating, less material handling, and so on (Guendouz et al., 2008).

So far, a wide range of organic solids found in municipal, industrial, and agricultural wastes have been investigated as feedstocks in high-solid anaerobic digestion, including food wastes (Cho et al., 1995; Lu et al., 2007), agricultural wastes (He et al., 2008; Lissens et al., 2004; Mosier et al., 2005; Pang et al., 2008), and organic fraction of municipal solid wastes (OFMSW) (Bolzonella et al., 2006; Forster-Carneiro et al., 2007; Martin et al., 2003; Sans et al., 1995). However, so far, no reports can be found focusing on high-solid anaerobic digestion of sewage sludge with feeding TS of 20%. Fujishima et al. (1999) has suggested a system in which the dewatered sludge discharged from small-scale plants is collected and sent to a plant with an anaerobic digester. They investigated the effect of moisture content on anaerobic digestion of dewatered sludge, but the TS contents of the fed sludge used in their study were below 11% (w/w), and a long-term effect was not investigated. Nges and Liu, 2010 investigated the effect of solid retention time (SRT) on anaerobic digestion of dewatered sludge in mesophilic and thermophilic conditions in long-term experiments, but the TS content of fed sludge was below 12%. Up to now, there are few studies related

* Corresponding author. Tel.: +86 21 65981794; fax: +86 21 65983602.
E-mail address: tj_dongbin@163.com (B. Dong).

0960-8524/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biortech.2011.10.090

to high-solid anaerobic digestion of sewage sludge with TS above 12% in a long-term operation. In this study, high-solid mesophilic digestion of sewage sludge (feeding TS 20%) was investigated using single-stage completely mixed reactors (semi-continuously operated), the performance of which were compared with reactors fed by TS of 10% and 15%. The effect of OLR, SRT and TS content was examined, with special attention paid to ammonia inhibition and system stability in high-solid state. The aim was to investigate the stability of high-solid anaerobic digestion of sewage sludge and to evaluate its performance.

2. Methods

2.1. Substrates and inoculums

Dewatered sewage sludge from Anting WWTP (Shanghai, China) was used as substrate for the present study. The sludge was obtained by collecting primary and excess sludge and dewatered with the aid of a high-molecular flocculant based on polyacrylamide. The total solids (TS) of the dewatered sludge ranged from 19% to 23% (w/w) and volatile solids (VS) accounted for 50–60% of TS. The mesophilic seed sludge collected from an anaerobic digester at Bailonggang WWTP (Shanghai, China) had TS of 2.3% (w/w) and VS was 56.5% of TS. Characteristics of dewatered sludge and inoculums are listed in Table 1. The collected sludge was stored at 4 °C and heated to 35 °C before everyday feeding.

2.2. Reactors and operation

Three identical reactors (numbered R1, R2 and R3), with liquid working volume of 6.0 l, were equipped with helix-type stirrers, which were set at a rate of 60 rpm (rotations per minute) with 10 min stirring and 10 min break continuously. Volumes of produced biogas were measured by wet gas meters every day.

On the first day of the experiments, 6.0 l seed sludge was added to each reactor, which was operated semi-continuously (once-a-day draw-off and feeding) at 35 ± 1 °C. During the start-up period, when the TS concentration of the substrate in the reactor did not reach its designed level, the OLR was increased stepwise with dewatered sludge as feedstock. Once the TS of the substrate in each reactor approached its designed level, the feeding sludge was diluted to its designed TS level (10%, 15% and 20%, respectively) with de-ionized water before feeding.

2.3. Analytical methods

Biogas and substrate samples of the reactors were taken twice a week and analyzed for methane content, pH, TS, VS, volatile fatty acid (VFA), total alkalinity (TA), total ammonia–nitrogen (TAN) and free ammonia–nitrogen (FAN). Methane content of the biogas was measured by a gas chromatograph (GC) (Agilent Technologies 6890N, CA, USA) with a thermal conductivity detector equipped with Hayseq Q mesh and Molsieve 5A columns. To analyze VFAs, the sludge samples from the reactors were centrifuged at 10,000 rpm for 10 min. Then the supernatant was passed through a microfiber filter (0.45 μm) and the filtrate was acidified by formic acid to adjust the pH to approximately 2.0 before VFA was analyzed by a GC (Agilent Technologies 6890N, CA, USA) with flame ionization detector. TS, VS, TA and TAN were determined according to standard methods (APHA, 1995). FAN concentration was calculated in the same way as described by Østergaard (1985). The degradation or removal level based on VS (i.e. VS reduction) was calculated by the same equation as reported by Koch et al. (2009), assuming that the mass of undegradable material (inorganic fraction) is constant:

$$VS_{reduction} = 1 - \frac{VS_{digestate} \cdot (1 - VS_{feed})}{VS_{feed} \cdot (1 - VS_{digestate})} \quad [\%], \tag{1}$$

where $VS_{digestate}$ is the loss on ignition of digestate (% of TS) and VS_{feed} is the loss on ignition of feeding sludge (% of TS).

3. Results and discussion

3.1. Start-up performances

Figs. 1–3 show the performance data of R1, R2 and R3, which were fed with dewatered sludge until each reached its designed TS level (on day 30, 68 and 85, respectively). Then the feeding sludge was diluted to its designed TS level (10%, 15% and 20%, respectively) with de-ionized water before feeding. In the first 17 days, each reactor was operated at an OLR of 4.1 kg VS m^{-3} d^{-3}, which was much higher than that in traditional low-solid digestion system for sewage sludge (Metcalf and Eddy, 2003; Qasim, 1999; Turovskiy and Mathai, 2006). Significant VFA accumulation and sharp increases of VFA/TA ratio were observed, accompanied by decreasing biogas production (days 5–20) and VS reduction (days 12–20), which indicated low stability at high starting OLR, probably due to the small amount of biomass and its poor acclimation to the substrate at the beginning.

As OLR reducing to 2.0 kg VS m^{-3} d^{-3}, methane yield of each reactor showed increasing trend with great fluctuation, probably due to the conversion of accumulative VFAs to biogas. From day 20 to the end of the start-up period (day 30, 68 and 85, respectively), the TA, VS reduction and TAN concentration in each reactor showed increasing trend with TS increasing (the drop of TAN concentration on day 20 may be caused by the initial drop of VS reduction), indicating better buffering capacity and successful recovery of the systems.

It should be noticed that, although the system was inoculated by digestate from traditional low-solid digester treating sewage sludge and experienced intense unstable state (VFA/TA 0.8-1.1) by overloading, it could still successfully recover in continuous operation at OLR 2.0 kg VS m^{-3} d^{-3}, which was still higher than the regular OLR applied in low-solid digesters treating sewage sludge. The results indicated that, as long as pH was not dramatically influenced and was kept in favorable range for methanogens, previous high VFA/TA state was quite recoverable in continuous

Table 1
Characteristics of the substrate and inoculums (TS and VS values reported are averages of three measurements).

Parameters	DS[a] 1 (days 1–55)	DS 2 (days 56–115)	DS 3 (days 116–141)	DS 4 (days 142–160)	DS 5 (days 161–200)	Inoculums
pH	7.4	7.4	7.5	7.4	7.6	7.8
TS (%, w/w)	20.45	22.56	23.08	19.72	22.35	2.31
VS/TS (%)	60.09	60.29	52.48	52.47	51.17	56.51
TAN (mg l^{-1})	783	694	801	752	739	321
FAN (mg l^{-1})	26	23	33	25	38	26

[a] Dewatered sludge.