Waste Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Performance evaluation of a novel anaerobic digestion operation process for treating high-solids content chicken manure: Effect of reduction of the hydraulic retention time at a constant organic loading rate

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ARTICLE INFO

Article history:
Received 4 June 2016
Revised 15 March 2017
Accepted 20 March 2017
Available online xxxx

Keywords:
Anaerobic digestion
Chicken manure
Ammonia inhibition
Hydraulic retention time
Kinetics
Biomass yield

ABSTRACT

A novel feeding strategy was adopted in this study and the effect of reduction in hydraulic retention time (HRT) on the anaerobic digestion of chicken manure (CM) with a constant organic loading rate of 6.0 gVS/L/d was investigated. The lab-scale CSTR was operated at 38 °C and HRT_{CM} was reduced from 52 days to 5 days. At HRT_{CM} of 20–45 days, the reactor was relatively stable in terms of the volumetric biogas production rates and specific biogas production (SBP), which were 2.2–2.4 L/L/d and 338.3–418.7 mL/gVS_{added}, respectively. However, process instability and VFA accumulation occurred when the HRT_{CM} was reduced to 10 days due to excess microbes washout. The reduction in HRT_{CM} to 5 days caused SBP to decrease to 198.7 mL/gVS_{added} and the acetic acid content to exceed 6000 mg/L. The biomass balance model showed that the biomass concentration at HRT_{CM} of 20–52 days (0.473–0.615 gVSS/L) was notably higher than that at HRT_{CM} of 5–10 days (0.173 gVSS/L).

1. Introduction

With the development of large-scale intensive chicken farming, large amounts of wastes are produced in China yearly. Given that the organic matter in chicken manure (CM) is easily biodegradable, methane fermentation is considered an alternative method to minimize waste and recover bioenergy (Nie et al., 2015; Niu et al., 2013). To improve the utilization efficiency and reduce the investment costs of biogas plants, a relatively high organic loading rate (OLR) is often adopted (Dalkılıc and Ugurlu, 2015; Zhang et al., 2014). However, CM is rich in nitrogen, and excessive ammonia produced by hydrolysis at high OLR exerts a toxic and inhibitory effect on microbial activity and leads to failure. Volatile fatty acids (VFA) accumulation mostly occurred as a result of ammonia inhibition (Chen et al., 2008b). Niu et al. (2013) reported that the biogas yield from the mesophilic methane fermentation of CM alone was decreased by 25.0%, and VFA concentration reached 15,000 mg/L with a total ammonia nitrogen (TAN) of 10,000 mg/L. For a mesophilic–thermophilic two-stage anaerobic system, the VFA concentrations in the acidogenic reactor increased to 16,964 mg/L and the biogas production rate decreased from 554 mL/gVS_{added} to 426 mL/gVS_{added} with TS (total solids) loading of 8.25%. A maximum bearing OLR of 6.0 gVS/L/d was reported by Nie et al. (2015), who found that the biogas yield for mesophilic fermentation of CM decreased from 350 mL/gVS_{added} to 270 mL/gVS_{added} with a TAN of 6900 mg/L. Hence, to avoid inhibition of ammonia and maintain operation stability, the OLR should be lower than 6.0 gVS/L/d (Nie et al., 2015).

To prevent the inhibition of ammonia for biogas plants treating CM at high OLR, diluting the substrate by adding water is an effective method. However, adding water to the substrate shortens the hydraulic retention time (HRT). For a large-scale biogas plant, a short HRT is desired to reduce digester volume, investment costs (Schmidt et al., 2014) and improve net electrical energy recovery (Di Maria et al., 2015). In addition, the HRT as a key parameter in biogas processes that influences the anaerobic digestion (AD) operation stability, biogas production, biomass concentration and kinetic model parameters (Dareioti and Kornaros, 2014; Kukkonen, 2014; Schmidt et al., 2014). Dareioti and Kornaros

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http://dx.doi.org/10.1016/j.wasman.2017.03.034
0956-053X/

(2014) pointed out that the methanogenic reactor shows better stability with HRT of 25 days than that with 20 days, and significant accumulation of VFA occurs at HRT of 20 days. Besides, a short HRT can cause the washout of microbes when the generation times of the microorganisms are shorter than the HRT, which leading to failure of the AD system (Schmidt et al., 2014). Microorganisms (acidogens, acetogens and methanogens) involved in AD process have a distinct generation time (Güelfo et al., 2013; Gerber and Span, 2008; Jaxybayeva et al., 2014). For acidogenesis and acetogenesis, the acid-forming bacteria and acetogenic bacteria have a minimum doubling time of about 30 min and 1.5–4.0 days, respectively (Gerber and Span, 2008; Mosey, 1983). For methanogenesis, hydrogenotrophic methanogens show a short minimum doubling time of 1 h than acetoclastic methanogens (2–3 d) (Gerber and Span, 2008; Thauer et al., 2008).

As previously reported, for a continuous stirred tank reactor (CSTR), a minimum HRT of 10–25 days is obligatory to prevent the washout of slow-growing methanogens (Güelfo et al., 2013; Schmidt et al., 2014). Schmidt et al. (2014) reported that notable deterioration observed for a CSTR that treats simulated thin stillage as the HRT is reduced to 3 days because of the excessive washout of methanogens. Hence, maintain appropriate microorganism concentration and determine the biomass content are important for AD system to execute steadily. In the AD process for treating organic wastewater, biomass content is usually measured as volatile suspended solid (VSS) (Guo et al., 2013). Nevertheless, directly measuring the content of VSS to indicate the biomass concentration for a non-soluble waste e.g. manure based digester feedstock is unscientific (Ghaly et al., 2000). So, some kinetic models, such as the substrate mass balance model, the biomass balance model, have been introduced to calculate the biomass content and evaluate the performance of digesters for treating different types of non-soluble substrates (food waste, pig manure, etc.) (Borja et al., 2002; Guo et al., 2013; Wei et al., 2014; Zhang et al., 2015).

Although some research has been done focusing on the influence of HRT on the performance of AD process, commonly in the previous studies, the reduce in HRT coupled with the increase of OLR (Climenhaga and Banks, 2008; Dareioti and Kornaros, 2014; Di Maria et al., 2015; Qiang et al., 2012). For example, in the anaerobic co-digestion of sludge and FVW (fruit and vegetable waste) system, the OLR increased from 1.46 gVS/L/d to 2.80 gVS/L/d as HRT reduced from 14 days to 10 days (Di Maria et al., 2015). In addition, the noticeable increase in biogas yield caused by the reduced HRT was also a consequence of the increased OLR. Differently from previous research, in this study, a novel operation strategy was adopted. That is, the reactor was feed with stable mass of chicken manure per day to keep a constant OLR (basis on VS), but the HRT decreased gradually by recycle the stripped biogas slurry and adding water. Based on this new feeding strategy, one side, the knowledge about how reduced HRT affects the AD performance is limited. On the other side, there is also no kinetic analysis has been reported on the substrate utilization and the change in biomass concentration the AD of CM with reduced HRT. Hence, the main objective of this study was to identify whether the reduce in HRT relaxed the inhibition of ammonia at a constant high OLR. To clarify these, effect of a decreasing HRT on biogas yield, gas composition, TAN, FAN, VFA and kinetic model parameters was investigated.

2. Material and methods

2.1. Materials and digesters

Fresh chicken manure (CM) was collected from a biogas plant using CM as feedstock, in Chemnitz, Germany. The CM was stored in a sealed-plastic barrel and flushed with 100% pure nitrogen gas, then kept in a cooling room at 4 °C. The original inoculum to start up the fermenter was taken from another digester for treating cattle manure. The biogas production potential of CM was determined by Automatic biogas Potential Test System (AMPTS II, Bioprocess control, Sweden) according to German standard VDI 4630 (VDI, 2006). The characteristics of CM and inoculum are shown in Table 1.

A lab-scale continuous stirred tank reactor (CSTR) with a working volume of 10 L (total 15 L) was used in this study. The feeding port of the CSTR was sealed with a rubber bung, and the sealed tube with tube bottom was submerged in the fermentation medium. A stirrer with a stirring speed of 100 rpm was fixed in the middle of the top plate. The reactor was warmed by circulating water supplied by a heating circulator (Proline P8, Lauda DR. R. Wobser GmbH & Co. KG, Germany) and it was maintained at (38 ± 1) °C.

2.2. Experimental procedure

The digester was commissioned in January 2011. In the initial period of this digester, around 9 L inoculum (digested cattle manure) was added to start-up this digester, and the initial OLR was 2.2 gVS_{CM}/L/d. Hence, the digester had been operated for more than 1280 days before this study began using CM as the feedstock. In this study, the digestate was drawn out through an outlet port at the bottom of the reactor, and the new mixed substrate was fed into the digester via the feeding port once daily. Biogas volume was monitored daily by a wet-type gas flow meter (Ritter TG 05, Dr. -Ing. Ritter Apparatebau GmbH & Co. KG, Germany) and the biogas production was corrected to value at standard temperature and pressure (0 °C, 101.325 kPa). The digestate was collected daily in a covered tank at room temperature (around 20 °C). Once a week, the digestate was centrifuged at 10,000 rpm and 10 °C for 10 min (Sorvall™ RC 6 Plus, Thermo Scientific, USA). By centrifugation, around 97% solids fraction was separated from the digestate, and the total solids (TS) content in liquid fraction was around 3% (date not shown). After solid-liquid separation, the solids fraction was dried to a constant weight at 105 °C, then ground to 2 mm (SM 200, Retsch GmbH, Germany), which was used to maintain the TS concentration of the feed mixture (feeding TS ≈ 14%). In order to avoid the ammonia inhibition, the liquid fraction was stripped to remove ammonia firstly at 80 °C and 450 mbar

Table 1
Characteristics of chicken manure (CM) and seed sludge (SS) used in the experiment.

Parameters	CM (this study)	CM (Niu et al., 2013)	SS
TS (% FM)	47.3 ± 0.4	11.2 ± 0.5	4.1 ± 0.3
VS (% FM)	31.2 ± 0.3	8.3 ± 0.8	3.2 ± 0.1
VS (% TS)	65.5 ± 0.2	73.8	78.1 ± 2.7
pH	8.07 ± 0.02		7.36 ± 0.06
TAN (mg/kg FM)	4415.5 ± 216.0	3850 ± 200	526.3 ± 22.9
FAN (mg/kg FM)	1094.1 ± 88.2		15.0 ± 2.1
TIC (mg CaCO3/kgFM)	48090.5 ± 7199		6775 ± 104
VFA (mg CH_3COOH/kgFM)	26632.5 ± 3312		1419 ± 57
C (% TS)	33.08 ± 0.21	35.2 ± 0.45	
N (% TS)	4.91 ± 0.13	5.44 ± 0.24	
H (% TS)	4.28 ± 0.09	4.83 ± 0.05	
S (% TS)	0.83 ± 0.07	0.84 ± 0.10	
O (% TS)[a]	26.64 ± 0.13	30.12 ± 0.18	
C/N	6.74	6.47	
Biogas production potential (mL/gVS)	422.4		

TS: total solids, FM: fresh matter, VS: volatile solids. TAN: total ammonia nitrogen, FAN: free ammonia nitrogen, TIC: total inorganic carbon and VFA: volatile fatty acids, Biogas production potential was achieved by BMP test.

Please cite this article in press as: Zhang, W., et al. Performance evaluation of a novel anaerobic digestion operation process for treating high-solids content chicken manure: Effect of reduction of the hydraulic retention time at a constant organic loading rate. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.03.034