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Effects of loading rate and temperature on anaerobic co-digestion of food waste and waste activated sludge in a high frequency feeding system, looking in particular at stability and efficiency

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HIGHLIGHTS

- Food waste (FW) was co-digested with waste activated sludge (WAS).
- A CSTR with a high feeding frequency (HFF) was employed.
- The synthetic effects of temperature and OLR on the HFF system were analyzed.
- The specific methanogenic activity increased after long term acclimation.
- Co-digestion of FW and WAS performed well in HFF system at a rather high OLR.

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ABSTRACT

A continuously stirred tank reactor (CSTR) with a high feeding frequency (HFF) of once every 15 min was employed in order to ease the loading shock frequently occurred in digester with a low feeding frequency. The effects of the organic loading rate (OLR) and temperature on the co-digestion of food waste and waste activated sludge was evaluated in a 302-day long-term experiment. Due to the high hydrolysis rate, the maximum CH_4 yield in a thermophilic reactor was 407 mL CH_4/gVS_{added}, a value that was significantly higher than the 350 mL CH_4/gVS_{added} that occurred in a mesophilic reactor. Although the alkalinity declined when HRT was shorted than 10 d, caused by the decrease of conversion ratio from protein to ammonium, the increase of specific methanogenic activity helped HFF system to achieve stable performance at an OLR of 11.2 (HRT 7.5 d) and 30.2 gVS/L/d (HRT 3 d) under mesophilic and thermophilic conditions, respectively.

1. Introduction

In China, increasing rates of food waste (FW) and sewage sludge production have exceeded 10% in recent years, due to industrial development and urbanization (Yang et al., 2014, 2015a; Zhang et al., 2015). Among conventional technologies such as those involved with landfilling, incineration and composting, anaerobic digestion (AD) is considered the most advantageous for organic waste treatment, because it reduces the quantity of the waste and recovers energy in the form of biogas (Hartmann and Ahring, 2006; Iacovidou et al., 2012; Kim et al., 2011).

AD is a complex biochemical process involving the cooperation of a diverse assemblage of bacteria responsible for hydrolysis, acidogenesis, acetogenesis and methanogenic archaea (Batstone et al., 2002; Jang et al., 2015). However, methanogens grow more slowly than bacteria; this may readily lead to an imbalance between acidification and methanation. The labile organic fraction of FW, the most readily biodegradable organic waste, may hydrolyze too quickly and cause process failure due to the acidification of AD (Kawai et al., 2014; Zhang et al., 2015). A large amount of hard biodegradable cells and extracellular biopolymers in the waste activated sludge (WAS) generally limits hydrolization during the AD process and may lead to low biogas production (Pastor et al., 2013; Zhang et al., 2014). Therefore, co-digestion—rather than mono-digestion—of FW and WAS has been demonstrated to be more efficient and stable because of the dilution of toxic compounds, the improvement in nutrient balance and the synergistic effect of the microorganisms (Dai et al., 2013; Lo et al., 2010; Prabhu and Mutnuri, 2016).

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Temperature is a critical factor that affects reaction rate, stability and microbial activity during AD. Compared with mesophilic digestion, current research generally suggests that thermophilic digestion is a better choice for reducing volatile solids and deactivating pathogens in the treatment of organic waste; however, it is more sensitive to loading shock (Cavinato et al., 2013; Labatut et al., 2014; Pender et al., 2004). Zamanzadeh et al. (2016) reported that although the extent of solubility could be achieved in the thermophilic digester treatment of FW rather than in the mesophilic digester, the high level of VFAs that occurred in the thermophilic condition decreased the stability of the digester and also reduced the methane yield. Nges and Liu (2010) also found that VFA concentration during the digestion of WAS was higher under thermophilic digestion than under mesophilic digestion when the hydraulic retention time (HRT) was the same. On the other hand, Gou et al. (2014) obtained a different result; namely, that during the co-digestion of FW and WAS, acidification caused by the severe accumulation of VFAs occurred earlier and at a lower OLR in a mesophilic reactor than in a thermophilic reactor when the OLR was increased by shortening the HRT. Although the comparison between thermophilic and mesophilic digestion has been studied in much researches, more attention has been paid to the performance of digesters and the characteristic of microbial communities (Dinsdale et al., 1996; Gou et al., 2014; Jang et al., 2016; Labatut et al., 2014; Zamanzadeh et al., 2016). In our previous batch study, we found that the specific methanogenic activity (SMA) from individual VFAs displayed different features under mesophilic and thermophilic conditions, related to the accumulation of VFAs during the AD process (Li et al., 2015). Therefore, varying the SMA may be used as a tool for achieving a deeper understanding of digester performance and stability. To date, little research has focused on varying the SMA as a way of changing a key operational condition in a long-term experiment.

A continuously stirred tank reactor (CSTR) is a common choice for organic waste digestion, given that the higher total solid (TS) and organic content of organic waste makes it difficult to achieve continuous feeding, especially at low OLR and long HRT in lab scale research. Therefore, most studies attempt a feeding frequency of once to several times per day in order to control the digester at suitable OLR and HRT without unreasonably diluting the feedstock (Dai et al., 2013; Di Maria et al., 2016; Gou et al., 2014). This low feeding frequency may have caused a heavier loading shock during the short feeding period, leading to fast acidification, especially under thermophilic conditions. Whether the instantaneous loading shock aggravated the deterioration of the reactor, and whether stable performance could be achieved at a high OLR by easing this instantaneous loading shock, are issues to be investigated. There are still no clear answers to these questions.

High frequency feeding (HFF) CSTR (approximately continuous feeding) was employed in this study in order to weaken the instantaneous loading shock caused by substrate feeding. The synergistic effects of OLR and temperature on the HFF methane fermentation process using FW and WAS as co-substrates was investigated to confirm the optimal operational conditions for stable performance. Meanwhile, the variation of methanogenic activity was analyzed by means of SMA tests to obtain a deep understanding of VFA accumulation.

2. Materials and methods

2.1. Feedstock and seed sludge

The FW used in this study was synthesized according to the composition of food waste in the cafeteria of Xi'an University of Architecture and Technology. It consisted of 15% rice, 10% noodles, 10% pork, 5% chicken, 5% egg, 20% cabbage, 20% potato, 13.8% carrot 1% oil and 0.2% table salt, basing on wet weights. The WAS was taken from a wastewater treatment plant (WWTP) in Xi'an. The FW and WAS were mixed at a ratio of 4:1, in order to obtain higher biogas production (Dai et al., 2013; Jang et al., 2016). The mixture was then crushed for 10 min using a blender and diluted with tap water to obtain feedstock with a TS content of approximately 9.5%. This TS content was slightly higher than that used in other studies (Gou et al., 2014; Fitamo et al., 2016; Voelklein et al., 2016), but this TS level in our study helped to achieve a high OLR. The seed sludge was taken from a full-scale mesophilic digester (volume: 12,000 m^3; HRT: 20 d; CH_4 in biogas: >55%) used to treat sewage sludge in the same WWTP. The physicochemical properties of the feedstock and seed sludge are listed in Table 1. The concentrations of (mg/L) of the microelements were as follows: Fe, 0.1; Co, 30; Ni, 23; B, 1.3; W, 0.31; Se < 0.01; Mo, 3.1; Mn, 20; Cu, 1.9; Zn, 37; Na, 1.7; K, 0.05; Ca, 0.13; Mg, 0.46; N, 0.45; P, 0.001; and S, 0.75.

2.2. Reactor configuration and experimental procedure

The long-term experiment was conducted via CSTR with a working volume of 3 L, as shown in Fig. 1. Water jacket and thermostatically controlled water baths were used to control the temperature of the reactor at 35 and 55 °C, respectively. The feedstock was pumped from a substrate tank, which was maintained at 4 °C to CSTR by a peristaltic pump that was run almost continuously (once every 15 min).

For a stable start-up, a reactor was seeded with 3 L of seed sludge and fed at a lower OLR of 1.30 gVS/L/d. Meanwhile NH_4HCO_3 was added to digester during the first 7 days to maintain the pH at a suitable range. After a steady state was achieved, the OLR was increased from 2.76 to 42.8 gVS/L/d by shortening the HRT from 30 d to 2 d as summarized in Tables 2 and 3. In order to obtain valid data, the duration of each stage was always at least 2 HRTs or more.

2.3. Specific methanogenic activity test (SMA)

In order to determine the kinetics of methane production from the individual VFAs, SMA tests were conducted using 120 serum bottles. The seed sludge was directly taken from the reactor under HRTs of 20 and 7.5 d before use, without any pretreatment. Sodium acetate, sodium propionate and sodium butyrate were mixed with 50 mL of seed sludge individually at concentrations of 0.5, 1, 3, 5 and 8 gCOD/L. The serum bottles were purged with nitrogen gas for 2 min to remove the oxygen, and they were then put into a water bath at temperatures of 35 and 55 °C, respectively. After

Table 1
Physicochemical properties of feedstock and seed sludge.

Parameter	Unit	Seed sludge	Feedstock
TS	g/L	20.9 ± 1.3	91.3 ± 3.2
VS	g/L	7.96 ± 0.52	79.7 ± 3.1
T-COD	g/L	21.3 ± 2.1	126.7 ± 5.6
S-COD	g/L	1.05 ± 0.33	45.3 ± 2.3
pH		7.54 ± 0.02	5.34 ± 0.38
Alkalinity	$gCaCO_3/L$	2.23 ± 0.14	/
Acetic acid	gCOD/L	0.32 ± 0.11	0.98 ± 0.47
Propionic acid	gCOD/L	0.09 ± 0.02	0.03 ± 0.01
Butyric acid	gCOD/L	0.11 ± 0.04	ND
Valeric acid	gCOD/L	0.08 ± 0.01	ND
C	%	/	41.1 ± 0.9
H	%	/	7.61 ± 0.01
O	%	/	46.6 ± 1.2
N	%	/	4.52 ± 0.16
S	%	/	0.35 ± 0.03

Notes: ND means not be detected; '/'means not applicable.

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