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Improve biogas production from low-organic-content sludge through high-solids anaerobic co-digestion with food waste

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HIGHLIGHTS

- More biogas produced by adding food waste to low-organic-content sludge.
- No synergetic effect of co-substrate for biogas production at low solid concentration.
- Excessive acidification is the key risk inhibiting low-solids co-digestion.
- The blend ratio 1:1 of food waste and sludge is optimal for high-solids co-digestion.
- Cumulated free ammonia is the key risk threatening high-solids co-digestion.

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ABSTRACT

Anaerobic co-digestion of sewage sludge and food waste was tested at two different total solid (TS) concentrations. In the low-solids group with TS 4.8%, the biogas production increased linearly as the ratio of food waste in substrate increased from 0 to 100%, but no synergetic effect was found between the two substrates. Moreover, the additive food waste resulted in the accumulation of volatile fatty acids and decelerated biogas production. Thus, the blend ratio of food waste should be lower than 50%. While in the high-solids group with TS 14%, the weak alkaline environment with pH 7.5–8.5 avoided excessive acidification but high concentration of free ammonia was a potential risk. However, good synergetic effect was found between the two substrates because the added food waste improved mass transfer in sludge cake. Thus, 50% was recommended as the optimum ratio of food waste in substrate because of the best synergetic effect.

1. Introduction

Anaerobic digestion is a widely-used process to transform organic waste to bioenergy and simultaneously reduce waste volume and mass before final disposal. Sewage sludge, commonly consisting of primary sludge and excess sludge, is of particular interest for anaerobic digestion because of a large amount of pollutants and nutrients that it offers. Hence, bioenergy recovery from sewage sludge through anaerobic digestion has been seen as a promising method for sludge treatment and disposal all over the world.

However, there still exist two key problems possibly limiting the application of this technology. Sewage sludge has low ratios of carbon to nitrogen (C/N), generally ranged from 6 to 9, which negatively impact the efficiency of anaerobic digestion. Excessive nitrogen and insufficient carbon mean an imbalance diet for microorganisms, and possibly result in ammonia accumulation and subsequent inhibition to microbial activity (Zhang et al., 2015). Besides low C/N ratios, low-organic-content sludge is another negative factor influencing the benefits of anaerobic digestion. This kind of sludge is commonly derived from the wastewater treatment plants (WWTPs) using long sludge retention time or collecting some rainfall, industrial wastewater and wastewater from construction sites. The typical organic contents (expressed as volatile solids content in total solids, VS/TS) in sludge range from 60% to 80%, and the corresponding organic degradation rates are generally from 56% to 65% when sludge retention time (SRT) is 15–30 days (Appels et al., 2008). In contrast, low-organic-content sludge usually leads to much worse performance. For example, the organic degradation rate decreased to only 25–35% when sludge VS/TS was lower than 50% (Liao and Li, 2015). This eliminates the economic feasibility of bioenergy recovery from sludge anaerobic digestion seriously.

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For the sludge with low C/N ratios and low organic contents, the additive food waste, a kind of high-organic-content waste with higher C/N ratios, could be an option to improve biogas production from anaerobic digestion (Zhang et al., 2007). Due to high content of easily biodegradable ingredients, food waste is hydrolyzed rapidly and this possibly leads to the accumulation of volatile fatty acids (VFAs), especially propionic acid (Zhou et al., 2014). When mixed with sewage sludge, food waste produced more biogas without excessive acidification at both mesophilic and thermophilic conditions (Kim et al., 2003), because balance diet and suitable C/N ratios improved microbial activity and avoided the accumulation of intermediate products including VFAs and ammonia (Dai et al., 2013).

However, it is still unknown whether co-digestion with food waste is also an effective option to improve biogas production from low-organic-content sludge, i.e. whether synergistic effect exists between low-organic-content sludge and food waste. In fact, the recommended blend ratio of food waste and sludge varied across the references. For example, Kim et al. (2003) found the optimal mixing ratios of food waste were 39.3% and 50.1% in mesophilic and thermophilic conditions, respectively. Prabhu and Mutnuri (2016) indicated that food waste mixed with sludge in the ratio of 1:2 produced the maximum biogas of 823 ml/g VS added (21 days) with an average methane content of 60%. Kuo-Dahab et al. (2014) verified the increases of biogas production, VS reduction and digester stability with the addition of food waste up to 50% (w/w total feed solids). On the contrary, Dai et al. (2013) reported that biogas production and VS reduction increased linearly with the increasing ratios of food waste during high-solids anaerobic co-digestion of sludge and food waste. The different conclusions were possibly attributed to the different C/N ratios of sewage sludge and food waste used in these researches. It was ever reported that the optimum methane yield of 239 ml/g VS removed occurred at 11% (w/w) of food waste in mixture with a C/N ratio of 15, while methane yield decreased as the fraction of food waste in mixture increased further. The highest VS reduction rate of 93% was achieved at a C/N ratio of 20 followed by 30 and 15 (Siddiqui et al., 2011).

Besides co-digestion with food waste, high-solids anaerobic digestion (HSAD) was another possible choice to improve the stability and performance of anaerobic digestion because it has high tolerance to VFAs, ammonia and other toxic chemicals (Dai et al., 2013). Due to high-solids feedstock, HSAD has some advantages over low-solids conventional anaerobic digestion (CAD) including smaller digesters, high volumetric biogas production and less energy consumption for heating (Guendouz et al., 2008; Liao and Li, 2015). Nevertheless, high-solids feedstock also generated high concentration of intermediates and correspondingly increased the risk of system imbalance (Liao et al., 2014). As a consequence, the positive effect of co-digestion is possibly counteracted by blocked mass transfer and accumulated inhibitory intermediates under high-solids environment (Liu et al., 2016). Up to date, only limited information has been reported on high-solids anaerobic co-digestion of food waste and sewage sludge. For low-organic-content sludge, it is still not clear whether this process could maintain stable at high organic load rates and exhibit better performance than conventional low-solids anaerobic mono digestion.

Therefore, in this study, two series of batch anaerobic co-digestion experiments were carried out using low-organic-content sludge and food waste as the substrates at low and high solid concentration. The stability and performance of high-solids anaerobic co-digestion were investigated in comparison with low-solids mono digestion, and the effects of additive food waste and solid concentration on co-digestion were further discussed based on a kinetics model.

2. Materials and methods

2.1. Substrate and inoculum

Dewatered sludge was sampled from a local WWTP, in which an anaerobic-anoxic-oxic process was applied and the mixture of excess sludge and primary sludge was first conditioned with polyacrylamide and then dewatered by centrifugation. In seven days, 2 kg dewatered sludge was collected each day and finally 14 kg dewatered sludge was mixed completely in order to eliminate the influence of influent wastewater fluctuation. The sample was stored in a refrigerator at 4 °C before used as the substrate in batch anaerobic digestion experiments.

Food waste was sampled from the staff canteen of this WWTP. The main ingredients included rice, vegetable, meat and oil, and no napkin, cans and polythene bags existed in the samples. The inorganic hard material, mainly composed of bones and shells, was removed before the samples were cracked. In five days, 2 kg food waste was collected each day and finally 10 kg food waste was mixed and cracked together using a soybean milk machine. The sample was also stored in a refrigerator at 4 °C before used as the substrate in batch anaerobic digestion experiments.

The inoculum was the digested sludge discharged from a pilot-scale mesophilic anaerobic digester with an effective volume of 500 L. The digester was also fed with the diluted dewatered sludge with TS 15–20%. The digester had run steadily at a SRT of 30 d for more than one year before these experiments. The digested sludge was stored at room temperature under anaerobic condition for three days to remove the residual biodegradable organic matter.

The sampling procedure was carried out twice for two successive groups of batch experiments (low-solids group and high-solids group). The characteristics of sewage sludge (SS), food waste (FW) and inoculum sludge (IS) were shown in Table 1. The key difference between the low-solids group and the high-solids group was the VS/TS ratios of sewage sludge, which were 41.6% and 49.4%, respectively.

2.2. Batch anaerobic digestion experiments

Batch anaerobic digestion experiments were divided into two groups, which were operated at low solid concentration (L group) and high solid concentration (H group), respectively. In each group, five conditions (A, B, C, D and E) were adopted with different proportions of sewage sludge and food waste in substrate. The arrangement was listed in Table 2. Under each condition, parallel

Table 1
Characteristics of sewage sludge (SS), food waste (FW) and inoculum sludge (IS) in two groups of batch experiments.

	SS	FW	IS
Low-solids groups			
TS (%)	21.1	18.4	13.8
VS/TS (%)	41.6	95.2	47.8
Protein/VS (%)	56.2	33.8	/
Polysaccharide/VS (%)	10.0	42.6	/
Lipid/VS (%)	0.1	6.7	/
C/N	6.5	16.7	6.3
Cl^- (mg/L)	79.6	4327.7	36.8
High-solids groups			
TS (%)	18.5	22.4	13.2
VS/TS (%)	49.4	98.1	52.7
Protein/VS (%)	46.1	37.6	/
Polysaccharide/VS (%)	10.3	42.5	/
Lipid/VS (%)	0.1	6.7	/
C/N	6.5	16.7	6.3
Cl^- (mg/L)	67.1	1397.7	113.0