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Research article

Anaerobic co-digestion of foodwaste with liquid dairy manure or manure digestate: Co-substrate limitation and inhibition

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ABSTRACT

Process instability has been a challenge to anaerobic digestion of foodwaste at higher organic loading rates. Co-digestion is one of the measures to improve stability. This study conducted batch experiments to compare liquid dairy manure and dairy manure digestate as a co-substrate for anaerobic digestion of foodwaste. The batch co-digestion experiments showed a two-stage biogas production process, which could be simulated with a modification of the Gompertz model. The specific biogas yields derived with the two-stage biogas production model was further simulated against the co-substrate ratios with substrate limitation – inhibition models for identifying the optimal co-substrate ratio. The Haldane model was the best to simulate co-substrate limitation – inhibition kinetics in anaerobic co-digestion of foodwaste. A higher ratio of dairy manure could result in co-substrate inhibition to biogas production due to recalcitrance of cellulose and toxicity of lignin and lignin derivatives. Kinetic modeling shows that the optimal volatile solids (VS) ratio of liquid dairy manure is 16.6%, at which the maximum specific methane yield is 0.54 L/g VS. Semi-continuous co-digestion of 88% foodwaste and 12% liquid dairy manure at a hydraulic retention time of 14 d attained 94% of the simulated maximum methane yield. Although co-digestion of foodwaste and manure digestate resulted in lower biogas yields than co-digestion with liquid dairy manure, manure digestate is still an attractive co-substrate that has several operational advantages compared with liquid dairy manure.

1. Introduction

Laboratory anaerobic digestion studies have demonstrated high biochemical methane potential of foodwaste. Process instability, however, has been a challenge to long-term, continuous anaerobic digestion of foodwaste, especially at a higher organic loading rate and under thermophilic conditions (Banks et al., 2012; Braguglia et al., 2018; Kawai et al., 2014; Komilis et al., 2017; Zhang et al., 2012, 2015). The process instability and failure has been mostly attributed to fast acidification, ammonia inhibition to acetoclastic methanogens and subsequent accumulation of volatile fatty acids, and inadequate availability of trace elements. The high contents of non-fiber carbohydrate and fat of foodwaste may lead to fast acidification. Ammonia accumulation is attributed to its high protein content. Consequently, successful long-term mono-digestion of foodwaste has been limited to organic loading rates typically less than 4.5 g VS/L/d unless an enhancement measure such as co-digestion is taken (Braguglia et al., 2018; Komilis et al., 2017).

Animal manure has been the most common co-substrate for foodwaste digestion (Komilis et al., 2017). Earlier studies on co-digestion of foodwaste and liquid dairy manure (Agyeman and Tao, 2014; Usack and Angenent, 2015; Zarkadas et al., 2015) reported stable operation and synergistic effects at organic loading rates as high as 6.2–12 g VS/L/d, which were attributed to balanced biochemical composition, buffered pH, and supplementation of micronutrients from co-substrates. Because of the high fiber content of liquid dairy manure (LDM), anaerobically digested dairy manure (ADDM) from digesters without an extended hydraulic retention time can have higher residual biomethane potential. Based on the measured biochemical composition of LDM and ADDM at a dairy farm (Table 1), it was estimated with an equation developed by Angelidaki and Sanders (2004) that the ADDM would have a biomethane potential close to that of the LDM. The higher biomethane potential of ADDM was mainly attributed to the increased content of crude protein and non-fiber carbohydrate due to microbial growth in the digesters. Moreover, the ADDM had higher nutrient concentrations than LDM (Table S1), which could be attributed to

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Table 1
Characteristics of substrates and inoculum used in this study.[a]

	Main substrate	Co-substrate		Inoculum	
	Foodwaste	LDM	ADDM[b]	Digested manure[c]	Digested sludge
pH	4.8	7.7	7.9	7.6	7.5
Total solids (g/L)	272.5	123.0	45.5	48.5	26.1
VS/TS (%)	92.1	84.6	68.2	67.4	55.4
Biochemical composition (% TS)					
Crude protein	27.8	16.9	31.9	30.0	31.8
Crude fat	22.4	6.1	3.7	5.3	3.3
Non-fiber carbohydrate	35.1	7.5	11.6	7.9	4.9
Lignin	2.8	10.6	16.2	9.5	5.6
Cellulose	0.9	23.4	7.9	3.4	1.6
Hemicellulose	3.2	21.9	8.0	11.4	14.3

[a] Average of two samples.
[b] ADDM after a screw press.
[c] ADDM passing a 0.5-mm sieve.

microbial assimilation and mineralization of nutrients. ADDM also has greater alkalinity than LDM (Akhiar et al., 2017; Tao et al., 2016). Therefore, ADDM can even be a better co-substrate than LDM.

Synergistic effects of co-digestion on methane production have been reported at different co-substrate ratios, whereas overdosing of a co-substrate may result in disappearance of the synergies and even antagonistic effects. The decreased performance of co-digestion, even after extended acclimatization periods, has been attributed to the effects of a co-substrate that contains inhibitory or toxic compounds such as ammonia and other inorganic salts (Regueiro et al., 2015; Usack and Angenent, 2015). The optimum co-substrate ratio is typically determined through laboratory experiments at discrete substrate combinations or by modeling without consideration of co-substrate inhibition (Cook et al., 2017; Owamah and Izinyon, 2015; Usack and Angenent, 2015).

The first objective of this study was to compare the effects of two co-substrates for foodwaste digestion, i.e., LDM and ADDM, by means of batch anaerobic co-digestion experiments. Side-by-side comparison of the co-substrates could not only discover a new enhancement measure for anaerobic digestion of foodwaste, but also demonstrate a new strategy for identifying a co-substrate. Based on specific biogas yields in the batch co-digestion experiments at different co-substrate ratios, this study further used co-substrate limitation and inhibition models to simulate the kinetics of co-substrate effects on specific biogas yield. By curve fitting to typical kinetic models, the second objective was to identify the best kinetic model and subsequently estimate the optimal co-substrate ratio for anaerobic co-digestion of foodwaste. Finally, the performance of anaerobic co-digestion at the optimal substrate combination was tested through semi-continuous anaerobic co-digestion of foodwaste and liquid dairy manure.

2. Materials and methods

2.1. Batch experiments on anaerobic co-digestion

Batch anaerobic digestion experiments were conducted in 2-L continuously-stirred mesophilic digesters (Agyeman and Tao, 2014). For each co-substrate (LDM and ADDM), batch co-digestion experiments were conducted at 7 substrate combinations, i.e., foodwaste VS: co-substrate VS in 95%: 5%, 90%: 10%, 85%: 15%, 80%: 20%, 70%: 30%, 60%: 40%, and 50%: 50%, plus two blanks (100% each inoculum). The foodwaste was collected over two weeks from buffet leftovers at a casino in central New York, USA, ground through a 2.5-mm-aperture cutting plate, and stored at −21 °C. The ADDM was the effluent of mesophilic manure digesters at a dairy farm in Skaneateles, New York. A screw press was used at the farm to remove coarse particles from the digester effluent. The LDM was collected from the same farm at the same time as the ADDM. Each digester was inoculated at 21.345 g VS with anaerobically digested sludge and ADDM sieved through 0.5-mm mesh in the same VS ratios as the targeted foodwaste to co-substrate ratios. Substrate to inoculum VS ratio was set at 0.82. The headspace was flushed with nitrogen gas and sealed immediately. The substrates and inocula were characterized by Dairy One Forage Laboratory in Ithaca, New York, USA and the results are given in Table 1 and Table S1. Biochemical composition was determined with the ANKOM Technology and AOAC methods. Elemental content was determined for samples after microwave-accelerated acid digestion, using a Thermo iCAP 6300 inductively coupled plasma radial spectrometer.

After 2 d of acclimation, the digesters were fed with substrates and deionized water to a working volume of 1.8 L and set at temperature 36 °C. Biogas production was recorded every 15 min with Model 1615A digital mass flow gas meters (Omega Engineering, Norwalk, Connecticut, USA), displaying biogas flow rate at temperature 25 °C and pressure 1 atm. Based on the dynamics of biogas production rate, the batch experiments lasted for 25–30 d. Biogas samples (0.1 mL each) were collected weekly with a gas tight syringe and diluted with air in 11.3-mL Restek serum vials for determination of methane content using a Shimadzu GC-2014 gas chromatograph (Agyeman and Tao, 2014). This GC system used a HayeSep-D column to separate N_2O, a Porapak-N pre-column to backflush C_2 compounds, a Porapak-N column to separate CO_2, and a MS-13× column to separate air/CH_4/CO into individual gases. Methane is detected with a flame ionization detector. Helium was used as carrier gas. The temperatures of oven, injector port and detector were 100, 140 and 100 °C, respectively. Measurements were taken in the digesters for pH with a Hach H160 meter connected to an ISFET NMR tube pH probe before feeding and at the end of each batch. Initial and final concentrations of total solids (TS) and VS were determined for each batch according to Standard Methods 2540 B and E (APHA et al., 2012). Samples collected initially and at the end of each batch were centrifuged at 2500 g for 20 min and centrate samples were diluted for determination of total ammonia nitrogen (TAN) concentration with a QuickChem 8500 series automatic flow injection analyzer (LaChat Instruments, Loveland, Colorado, USA), following Standard Method flow injection analysis (APHA et al., 2012).

Both the commonly used first-order and Gompertz models (Equations (1) and (2)) were tested to fit the dynamics of cumulative biogas production in the individual batches. The first-order model fitted the biogas production dynamics in the blanks well (R^2 = 0.960 and 0.996). The Gompertz model fitted the initial biogas accumulation poorly and sometimes put out negative lag phase times. Finally, the Gompertz model was modified (Equation (3)) to fit the biogas production dynamics in the anaerobic co-digestion experiments, which showed two stages of biogas production. The kinetic constants were estimated simultaneously for each batch experiment using the Microsoft Excel 2013 Solver tool.

$$Y_t = Y_m(1 - exp(-kt)) \quad (1)$$

$$Y_t = Y_m exp\left\{-exp\left[\frac{R_m \times e}{Y_m}(\lambda - t) + 1\right]\right\} \quad (2)$$

$$Y_t = Y_{m1}\frac{t}{K + t} + Y_{m2} exp\left\{-exp\left[\frac{R_m \times e}{Y_{m2}}(\lambda - t) + 1\right]\right\} \quad (3)$$

where t = time from adding substrates in a batch (d); Y_t = specific biogas production at t (L/g VS); Y_m = specific biogas yield (L/g VS); Y_{m1}, Y_{m2} = specific biogas yield at the first and second stages (L/g VS); k = first-order digestion rate coefficient (1/d); K = first-stage half saturation time (d); λ = length of lag phase (d); R_m = maximum specific biogas production rate (L/d/g VS); and e = Euler's number = 2.718.