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Improved biogas production from rice straw by co-digestion with kitchen waste and pig manure

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ABSTRACT

In order to investigate the effect of feedstock ratios in biogas production, anaerobic co-digestions of rice straw with kitchen waste and pig manure were carried out. A series of single-stage batch mesophilic (37 ± 1 °C) anaerobic digestions were performed at a substrate concentration of 54 g/L based on volatile solids (VS). The results showed that the optimal ratio of kitchen waste, pig manure, and rice straw was 0.4:1.6:1, for which the C/N ratio was 21.7. The methane content was 45.9–70.0% and rate of VS reduction was 55.8%. The biogas yield of 674.4 L/kg VS was higher than that of the digestion of rice straw or pig manure alone by 71.67% and 10.41%, respectively. Inhibition of biogas production by volatile fatty acids (VFA) occurred when the addition of kitchen waste was greater than 26%. The VFA analysis showed that, in the reactors that successfully produced biogas, the dominant intermediate metabolites were propionate and acetate, while they were lactic acid, acetate, and propionate in the others.

1. Introduction

Anaerobic digestion has become an established and proven technology for the treatment of organic wastes such as municipal solid waste, industrial organic waste, animal manure, and agricultural residues. The main advantage of this process is that the product can be used as a vehicle fuel or for co-generation of electricity and heat, and thus, can lead to reductions in greenhouse gas emissions. In China, rice straw (RS) is one of the most abundant agricultural residues, with quantities estimated between 180 and 270 million tons based on dry content in 2007 (Yanli et al., 2010). Large amounts of RS, however, are burned or discarded resulting in environmental pollution. Numerous studies have been carried out using agricultural residues as mono-substrates for biogas production (Khalid et al., 2011; Salminen and Rintala, 2002); however, the direct utilization of rice straw by microorganisms is difficult because of their unbalanced nutritional properties (C/N) and recalcitrant lignocellulosic structure (Himmel et al., 2007). Therefore, attention has been increasingly focused on improving biogas production of lignocellulosic materials through various pretreatments (Taherzadeh and Karimi, 2008).

Kitchen waste (KW) is an easily biodegradable organic matter with high moisture, carbohydrate, lipid, and protein contents. The major limitation of anaerobic digestion of KW alone is the rapid accumulation of volatile fatty acids (VFAs) followed by a pH drop in the reactor, which inhibits methanogenic bacteria (Boualla-gui et al., 2005; Misi and Forster, 2001). Thus, much effort has been invested in avoiding VFA inhibition to ensure the effective anaerobic digestion of KW; these approaches include co-digestion with dairy manure (El-Mashad and Zhang, 2010), using waste activated sludge to adjust C/N (Astals et al., 2011), adding trace elements to accelerate the growth of methanogens and methane formation (Deng and Hägg, 2010; Qiang et al., 2012), and employing two-stage or three-stage systems (Lokshina et al., 2003).

For agricultural residues, co-digestion is considered more cost effective than pretreatments. Addition of nitrogen-rich substrates such as animal manure could balance the C/N of carbon-rich biomass (e.g., rice straw) and further increase the biogas yield and volumetric biogas production rate (Comino et al., 2010). There have been many studies on the co-digestion of KW and pig manure (PM); however, there is little information available concerning co-digestion of these two substrates with RS. The objective of this study was, therefore, to assess the feasibility of co-digestion of RS with KW and PM in terms of biogas production and system stability, as well as the potential for reducing environmental pollution and producing clean and sustainable energy.

2. Materials and methods

2.1. Collection and pretreatment of substrates and inoculums

Rice straw (RS) was obtained from a rural area in Guangzhou, China. The collected RS was chopped and then ground into small

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Table 1
Main characteristics of substrates and inoculum.

Characteristic	Unit	Digested sludge	Kitchen waste	Rice straw	Pig manure
Moisture content	%	95.72	79.77	6.28	72.84
Total solids (TS)	%(w)	4.28	20.23	93.72	27.16
Volatile solids (VS)	%(w)	2.95	18.16	83.18	20.12
VS/TS	%	69	90	89	74
pH	-	8.10	4.40	5.60	7.80
VFA	mg L^{-1}	2228	NA	NA	NA
NH_4^+–N	mg L^{-1}	1668	NA	NA	NA
Lignin	%/TS	NA	NA	23.34	NA
Cellulose	%/TS	NA	NA	34.96	NA
Hemicellulose	%/TS	NA	NA	16.70	NA
TC	%/TS	NA	43.7	47.0	39.4
TN	%/TS	NA	3.0	1.0	2.3
C/N	–	NA	14.6	47.0	17.2
Calorific value	kJ kg^{-1}TS	NA	1.36×10^4	1.58×10^4	1.63×10^4

Note: NA (no analysis), w (wet base)

particles less than 1 mm in size. KW was collected from a university canteen and consisted mainly of residual vegetables, meat, rice, and noodles. Once collected, the waste was shredded into particles with an average size of 5.0 mm and then kept at 4 °C. Fresh pig manure (PM) was collected from a pig farm. After removing visible bristles, the PM was stored at 4 °C. The C/N ratios of RS, KW, and PM were 47.0, 14.6, and 17.2, respectively, which were all outside the optimum C/N range of 20–30 (Deublein and Steinhauser, 2008).

The residue left on a 1-mm sieve of material taken from an anaerobic digester fed with pig manure was used as the seed sludge. The characteristics of the three substrates and inoculums are listed in Table 1.

2.2. Experimental design

The digester used in this study was a 2.5-L filter bottle with a working volume of 2 L and consisted of a sampling outlet, a gas sampling port, and a feed inlet. It was sealed using a rubber stopper in which there was a pipe to extract biogas. The digester was connected to a gas collection system consisting of a saturated brine displacement bottle and a brine gathering bottle. Prior to operation, the reactors were purged with nitrogen gas for 5 min to ensure anaerobic conditions. Thereafter, the digesters were placed in a water bath at 37 ± 1 °C. Each digester was manually mixed twice a day. The experiments were terminated when no significant gas production was observed.

All of the reactors were started at an initial substrate concentration of 54 g VS/L. The substrate, inoculum, and water were added according to the desired experimental conditions (Table 2). All batch digesters were run in duplicate.

2.3. Analytical methods

Total solids (TS) and total volatile solids (VS) were determined using standard techniques (APHA, 1998). Biogas production was measured by water displacement. Heat values were determined using a WGR-1 heat value analyzer made by Changsha Bente Instrument Corporation. The C/N analysis was conducted using a Vario EL element analyzer made by Elementar Analysensysteme GmbH. The pH was determined with a pHS-3C pH meter made by Shanghai Precision & Scientific Instrument Co., Ltd. Biogas analysis was performed with an Agilent 6890 GC (Agilent Technologies, USA) with a thermal conductivity detector (TCD) and a 2-m stainless column packed with Porapak Q (50/80 mesh). The operational temperatures at the injection port, column oven, and detector were 100, 70, and 150 °C, respectively. Argon was used as the carrier gas at a flow rate of 30 mL/min. Liquid samples were centrifuged at 10,000 rpm for 15 min at room temperature and filtered with a 0.45-μm membrane filter for the ammonia nitrogen and VFA concentrations analysis (Li et al., 2010). Ammonia nitrogen was measured in a HACH DR/2800 Spectrophotometer. VFA C_2–C_5 and alcohol concentrations of the supernatant were measured after acidification with 6-mol/L HCl using an Agilent 6820 GC equipped with a flame ionization detector (FID) and a 30 m × 0.25 mm × 0.25 μm capillary column (DB-FFAP). The temperatures of the injection port and detector were 250 °C and 300 °C, respectively. The initial temperature of the column oven was 50 °C for 5 min; this was followed by a ramp of 10 °C/min to the final temperature of 250 °C, which was then maintained for 5 min. Nitrogen was used as the carrier gas at a flow rate of 1 mL/min. Lactic acid was quantified using a high-performance liquid chromatograph (Waters 2695, USA) with a refractive index (RI) 2414 detector and a Shodex KC-811 S-DVB gel Column. 0.1% H_3PO_4 was used as the mobile phase at a flow rate of 0.7 mL/min at 50 °C.

Experimental data were analyzed and curves were drawn using the Origin software version 7.5.

3. Results and discussion

3.1. Biogas production

Fig. 1 illustrates the daily biogas production of reactors A, B, C, G, H, and I. Reactors A, B, and I performed successfully without inhibition by VFAs. In the other reactors, inhibition was observed at the beginning of digestion. Reactors C and G could recover by adjustment of the pH, whereas reactors D, E, F, and H failed completely. The plots of the failed reactors D, E, and F are not shown, but are similar to that of reactor H. Furthermore, reactors A, B, and I displayed very similar trends in biogas production. Daily biogas production increased rapidly on the first day, and reached a peak of 30–50 mL/(g VS d) within 14–16 days. Thereafter, biogas production started to decrease rapidly and maintained low levels until the end of the experiment.

Table 2
Experimental design.

Reactors	KW:PM:RS (based on VS)	C/N of co-substrate	KW (g)	PM (g)	RS (g)	Water (g)	Inoculum (g)	Total weight (g)
A	0:2:1	21.7	0.0	358.2	43.2	398.6	1200	2000
B	0.4:1.6:1	21.2	79.1	286.6	43.2	391.1	1200	2000
C	0.8:1.2:1	20.7	158.2	214.9	43.2	383.7	1200	2000
D	1.2:0.8:1	20.2	237.4	143.3	43.2	376.2	1200	2000
E	1.6:0.4:1	19.7	316.5	71.6	43.2	368.7	1200	2000
F	2:0:1	19.2	395.6	0.0	43.2	361.2	1200	2000
G	0: 0: 1	47.0	0.0	0.0	129.5	670.5	1200	2000
H	1: 0: 0	14.6	593.4	0.0	0.0	206.6	1200	2000
I	0: 1: 0	17.2	0.0	537.3	0.0	262.7	1200	2000
Blank	–	–	0.0	0.0	0.0	0.0	1200	1200