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Effects of feedstock ratio and organic loading rate on the anaerobic mesophilic co-digestion of rice straw and cow manure

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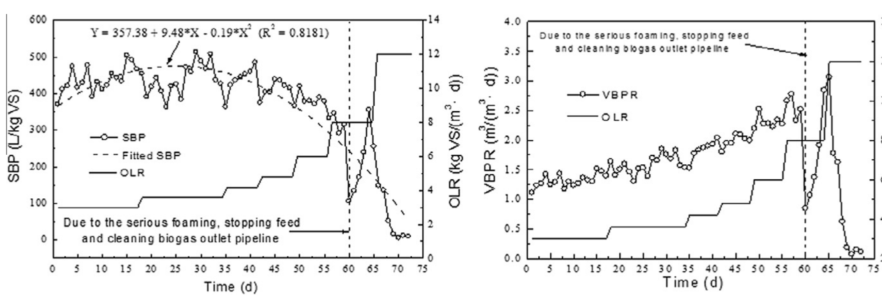
HIGHLIGHTS

- The optimal ratio of rice straw to cow manure was 1:1 based on volatile solids.
- Stable biogas production was obtained at an organic loading rate of 3–6 kg VS/(m^3 d).
- The overloaded system was inhibited by volatile fatty acids rather than ammonia.
- The recommended organic loading rate for the co-digestion is 6 kg VS/(m^3 d).
- Digestion system foaming was observed at an organic loading rate ⩾8 kg VS/(m^3 d).

GRAPHICAL ABSTRACT



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ABSTRACT

In order to investigate the effects of feedstock ratio and organic loading rate (OLR) on the anaerobic mesophilic co-digestion of rice straw (RS) and cow manure (CM), batch tests (2.5 L) were carried out at volatile solid (VS) ratios of 0:1, 1:2, 1:1, 2:1, and 1:0 (RS/CM), and continuous bench experiments (40 L) were carried out at OLRs of 3.0, 3.6, 4.2, 4.8, 6.0, 8.0, and 12.0 kg VS/(m^3 d) with optimal VS ratio. The optimal VS ratio was found to be 1:1. Stable and efficient co-digestion with average specific biogas production of 383.5 L/kg VS and volumetric biogas production rate of 2.30 m^3/(m^3 d) was obtained at an OLR of 6 kg VS/(m^3 d). Anaerobic co-digestion was severely inhibited by the accumulation of volatile fatty acids instead of ammonia when the OLR was 12 kg VS/(m^3 d). Further, significant foaming was observed at OLR ⩾ 8 kg VS/(m^3 d).

1. Introduction

Agricultural residues and animal manure are the two most important types of organic wastes. China, which ranks first in the world in crop residue production, is estimated to produce over 800 million (tons/year) of crop residues (Jiang et al., 2012). In terms of distribution, rice straw (RS) is more popular in southern China than in other locations. Further, the total production of animal manure from large-scale centralized farms is about 837 million tons, of which 382 million tons is cow manure (CM) (Tian, 2012). To make better use of these wasted resources, biogas production has become a national strategy in China in order to (1) control pollution, reduce emissions, minimize the formation of fog and haze, and construct an ecological civilization, (2) provide an

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Table 1
Main characteristics of the substrates and inoculum.

Characteristic	Inoculum	Rice straw	Cow Manure		
			Batch	Continuous a	Continuous b
Total solids (g/kg)	42.8	937.2	140.0	125.4	156.3
VS (% of TS)	69.00	95.26	68.70	73.79	84.71
Ash (% of TS)	31.00	4.74	21.30	26.21	15.29
Carbon (% of TS)	NA	38.19	36.81	NA	41.80
Hydrogen (% of TS)	NA	5.08	4.70	NA	6.11
Oxygen (% of TS)	NA	50.46	24.67	NA	32.99
Nitrogen (% of TS)	NA	0.80	2.30	NA	2.75
Sulfur (% of TS)	NA	0.72	0.36	NA	0.35
C/N	NA	47.5	16.0	NA	15.2
Calorific value(kJ/kg TS)	NA	1.58×10^4	1.59×10^4	NA	NA

Note: NA (no analysis).
Continuous a: continuous digestion with OLR 3.0–4.8 kg VS/(m^3 d).
Continuous b: continuous digestion with OLR 6.0–12.0 kg VS/(m^3 d).

Table 2
Daily amount of substrate feed used in the continuous bench experiments.

OLR (kg VS/(m^3 d))	Daily feed amount (g)		
	Rice straw	Cow manure	Water
3	54	446	1100
3.6	65	535	1000
4.2	76	624	900
4.8	87	713	800
6	108	732	760
8	146	909	545
12	216	1364	20

alternative for natural gas, alleviate energy shortage, and optimize energy structure, (3) help solve the "three agricultural problem" (countryside, agriculture, and peasant) and promote new rural construction, and (4) develop a recycling economy and foster new industries to change the mode of economic development (Jia et al., 2014). AD has been widely used to treat livestock and poultry waste as well as to produce biogas. However, there are some technical obstacles in conducting AD using agricultural straw, particularly dry straw.

Owing to the intrinsic characteristics of straw including unbalanced nutritional properties such as high carbon/nitrogen ratio (C/N), recalcitrant lignocellulosic structure, and floatation in a wet fermentation reactor, numerous studies focusing on nutritional regulation (Weiland, 2010), pretreatment (Hendriks and Zeeman, 2009), and improvement of the fermentation process (Li et al., 2010) have been conducted. Co-digestion with animal manure is considered a more cost-effective method for nutritional regulation compared to the addition of nitrogen-containing chemical reagents such as urea or ammonium bicarbonate. The addition of nitrogen-rich substrates such as animal manure could balance the C/N ratio of carbon-rich straw and further increase the biogas yield (Comino et al., 2010).

There have been many studies on the co-digestion of dry straw and animal manure. Wang et al. carried out a large number of experiments on the co-digestion of dry straw and manure, including the co-digestion of wheat straw with dairy manure and chicken manure, corn straw with dairy manure and chicken manure, and RS with dairy manure, chicken manure, and pig manure (Wang et al., 2012, 2013). Zhang et al. (2013) conducted the anaerobic co-digestion of goat manure with wheat straw, corn straw, and RS under mesophilic temperature conditions. The results of these studies showed that the co-digestion of straw with manure significantly improves biogas production.

However, these co-digestion studies were mostly carried out in batch and bottle experiments. There is little information available on the effect of organic loading rate (OLR) on co-digestion in a continuous bench (or pilot) experiment. In the present study, batch bottle tests have been conducted with the purpose of optimizing feed ratio. In addition, bench continuous experiments using RS and CM as mixed material have been conducted. The purpose of the latter is to investigate the effect of OLR on the process stability using pH, volatile fatty acids (VFAs), ammonia, total alkalinity (ALK), and foaming as process indicators. In addition, the effect of OLR on the co-digestion performance in terms of specific biogas production (SBP), volumetric biogas production rate (VBPR), and methane content has been investigated.

2. Methods

2.1. Substrates and inoculum

RS was obtained from rural Guangzhou, China. The collected RS was chopped and ground into small particles that were less than 1 mm in size. Fresh CM was collected from a cow farm. Collection of CM was conducted in three sets for batch digestion and continuous digestion with OLR of 3.0–4.8 and 6–12 kg VS/(m^3 d), respectively. After removing visible bristles, the CM was stored at 4 °C. The C/N ratios of RS and CM were 47.5 and 15.2–16.0, 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 inoculum. The characteristics of the two substrates and inoculum are listed in Table 1.

2.2. Experimental setup

The digester used for batch testing was a 2.5 L filter bottle, which consisted of a sampling outlet, gas-sampling port, and feed inlet. The bottle was sealed using a rubber stopper with a pipe for extracting the 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.

Continuous AD was conducted in a bench-scale reactor with a total volume of 40 L. The reactor contained five ports for various purposes such as online pH monitoring, mechanical agitation, temperature control, and gas and liquid sampling. To avoid pipe blockage from AD foaming, the loading volume was restricted to 30 L.