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Solid-state anaerobic co-digestion of hay and soybean processing waste for biogas production

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HIGHLIGHTS

- Solid state anaerobic digestion (AD) of soybean processing waste (SPW) and hay.
- Co-digestion of SPW and hay enhanced methane production.
- Partial mixing of inoculum with feedstock did not impact cumulative methane yield.
- Leachate recirculation accelerated start-up of partially premixed AD reactors.

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ABSTRACT

Co-digestion of soybean processing waste (SPW) and hay in solid-state anaerobic digestion (SS-AD) for biogas production was investigated. Effects of the SPW to hay ratio, feedstock to effluent (inoculum) ratio, premixing of effluent with feedstock, and leachate recirculation on biogas production via SS-AD were studied. The highest methane yield of 258 L/kg VS was obtained with a SPW/hay ratio of 75:25 and feedstock/effluent (*F*/*E*) ratio of 3, which was 148% and 50% higher than that of 100% SPW and 100% hay, respectively. Increasing the *F*/*E* ratio from 1 to 5 decreased methane yield, however the highest volumetric methane yield (16.2 $L/L_{reactor}$) was obtained at an *F*/*E* of 3. There was no significant difference in methane yields between premixing 50% and 100% of the effluent. Leachate recirculation significantly accelerated the SS-AD start-up process when effluent was not completely premixed.

1. Introduction

Anaerobic digestion (AD) has been extensively used to convert organic waste streams from various sources, such as agricultural, industrial, and municipal solid waste, to biogas. The AD process can operate in both liquid and solid states in terms of total solid (TS) content. In general, the TS content of liquid AD (L-AD) systems ranges from 0.5 to 15%, while solid-state AD (SS-AD) systems usually operate at TS contents of higher than 15% (Rapport et al., 2008). Comparisons between L-AD and SS-AD indicate that L-AD has higher reaction rates and shorter retention times, while the advantages of SS-AD are smaller reactor volume requirements, less energy input for heating, no processing energy needed for stirring, minimal material handling, and less total parasitic energy loss (Guendouz et al., 2008). Problems related to the floating and stratification of fibrous material in L-AD does not occur in SS-AD (Chanakya et al., 1999; Kaparaju and Angelidaki, 2008). In comparison to the effluent of L-AD, the effluent of SS-AD (digestate) is much easier to handle because of its lower water content, and it can be used as fertilizer or pelletized for fuels (Li et al., 2011a). Brown et al. (2012) compared SS-AD and L-AD of lignocellulosic feedstocks for biogas production and found insignificant differences in methane yield. However, they revealed that the volumetric methane productivity of SS-AD was 2- to 7-fold greater than that of L-AD.

Co-digestion is the simultaneous digestion of a mixture of two or more substrates and offers many advantages, including ecological, technological, and economic benefits, compared to digestion of a single substrate (Rughoonundun et al., 2012). The purpose of co-digestion is usually to balance nutrients (C/N ratio and macro- and micronutrients) (Girault et al., 2012; Liu et al., 2012) and dilute inhibitors/toxic compounds, thus enhancing methane production (Xu and Li, 2012; Luste et al., 2012; Xia et al., 2012). However,

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combining two or more feedstocks requires careful selection to improve efficiency of the AD process (Álvarez et al., 2010).

The start-up phase of an AD system is the most critical step in the process (Pandey et al., 2011), especially for large-scale batch digesters. The feedstock to inoculum (*F/I*) ratio, on a volatile solid (VS) basis, is one of the most important factors for the start of a balanced microbial community. Feedstock/effluent (*F/E*) ratio is used for studies in which the effluent from L-AD was used as both the inoculum and nitrogen source. However, the effect of *F/E* ratio on biogas may vary due to differences between AD systems, such as operating temperature and type of feedstock. In a study on the SS-AD of corn stover, the highest biogas yield was obtained at an *F/E* ratio of 2.43 under mesophlic condition and 4.58 under thermophilic conditions, respectively (Li et al., 2011b). In a different study with an *F/E* ratio of 2, the co-digestion of 90% yard waste and 10% food waste performed well but the reactor failed with 80% yard waste and 20% food waste (Brown et al., 2012). In general, high *F/E* ratios can cause overproduction of volatile fatty acids (VFAs) resulting in low pH. The methanogens are subsequently inhibited by the low pH, and the AD reactor can fail. On the other hand, as effluent provides a nitrogen source for SS-AD, low *F/E* ratios might lead to ammonia inhibition, especially when high-ammonia inoculum is used (Li et al., 2011b). As a result, an optimal *F/E* ratio should be determined for different AD systems.

Soybean processing usually generates two streams of by-products: (1) high quality protein, fiber-rich stream; and (2) a low quality waste stream. In this research, the second stream, defined as soybean processing waste (SPW), was used as a feedstock. SPW usually consists of soybean straw, beans, soybean oil residue, and diatomaceous earth used in the oil bleaching process. Although this mixture of materials has relatively limited applications in industry, it could be a good feedstock for biogas production in the SS-AD process due to its high organic matter content. However, the high protein content of SPW results in a low C/N ratio, thus when SPW is digested alone, ammonia may accumulate creating toxic conditions for the AD microbes, which could lead to low biogas yield (Wang et al., 2013). Hay is a mixture of grass, legumes or other herbaceous plants that has been cut, dried, and stored for use as animal fodder and animal bedding. The spent hay is usually spoiled and considered a waste stream. As spent hay has a high C/N ratio and TS content, it could be co-digested with SPW to improve biogas yield. However, the optimum SPW/hay ratio needs to be determined.

Due to the poor water absorption capability of SPW, it becomes a slurry after being mixed with L-AD effluent at 20% total solid (TS) content, making it difficult to load into full-scale, garage-type solid state digesters. Increasing the TS content to a stackable level will cause a higher *F/E* ratio, which might result in acidification and inhibition of methanogens (Park and Li, 2012; Xu and Li, 2012). Due to the high TS content for SS-AD, no agitation is applied during the process, so that contact between bacteria and feedstock is poor, resulting in low biogas yield. Therefore, mixing strategies, such as premixing feedstock with partial inoculum and leachate recycling, may be effective for improving biogas yield.

In order to address the issues discussed above, the objectives of this research were to: (1) study the effects of SPW/hay and *F/E* ratios on the performance of SS-AD, and (2) investigate the effects of premixing and leachate recirculation on the performance of the SS-AD process.

2. Methods

2.1. Feedstocks and effluent

SPW was provided by the facility of *quasar energy group* in Zanesville, OH, USA. It mainly consisted of soybean straw, soybeans, soybean oil extraction residues, and diatomaceous earth used in oil bleaching process. The SPW was kept in a cooler (4 °C) before use. Hay was obtained from a local farm in Wooster, OH, USA, and ground through a 10-mm sieve with a grinder (Mighty Mac, Mackissic Inc., Parker Ford, PA, USA). The ground hay was stored in air tight containers until use. Effluent from a mesophilic liquid anaerobic digester (run by *quasar energy group* in Zanesville, OH, USA) that was fed with biosolids was used as inoculum. Characteristics of the feedstocks and effluent are presented in Table 1.

2.2. Co-digestion of SPW and hay for SS-AD

Batch AD with complete premixing was carried out at five SPW/hay ratios (100:0, 75:25, 50:50, 25:75, and 0:100) at an *F/E* ratio of 3 and at five *F/E* ratios (*F/E* = 1, 2, 3, 4, and 5) at a SPW/hay ratio of 75:25. For evaluation of both SPW/hay and *F/E* ratios, feedstock and effluent were well mixed and loaded into a 2-L reactor that was then sealed with a rubber stopper having a gas outlet connected to 5-L gas bags (CEL Scientific Tedlar gas bag, Santa Fe Springs, CA, USA) (Fig. 1a). Reactors were incubated in a walk-in thermostat chamber at 37 °C for 42 days. All tests were run with duplicate reactors.

2.3. Pre-mixing of feedstocks and effluent

The effects of three methods for pre-mixing feedstocks and effluent on SS-AD performance were investigated in 5-L batch reactors without leachate recirculation (Fig. 1a). An overall *F/E* ratio of 3 and an SPW/hay ratio of 75:25 were used. Prior to placing materials into 5-L reactors, 100%, 50% or 0% of the required effluent was mixed thoroughly with all of the feedstock. The TS of the material with 50% and 0% effluent premixing was 24% and 54%, respectively (Table 2), which resulted in stackable materials that could be loaded by a tractor with a loader and toe pip bucket into garage-type digesters. After the mixture was loaded into the reactor, the remaining effluent (0%, 50%, or 100%, respectively) was immediately added from the top of the reactor to obtain an overall *F/E* ratio of 3 and TS of 17.6, which was more favorable for SS-AD (Table 2). Biogas was collected in a 10-L Tedlar gas bag attached to the outlet of the reactor. The operating procedure and mixing parameters are shown in Fig. 1b and Table 2, respectively.

2.4. Leachate recirculation

Pre-mixing and loading methods of feedstocks and effluent were the same as those in Section 2.3. Batch reactors with a 5-L capacity and leachate recycling system were used (Fig. 1c). The leachate recirculation system included a leachate sump at the bottom of the reactor, a peristaltic pump (Thermo Fisher Scientific™, Master flex 77200-62, Waltham, MA, USA) and plastic tubing connecting the sump to the leachate inlet on the top of the reactor. In order to prevent the feedstock particles from dropping into the sump, a metal grid combined with a 2-mm hardware cloth was

Table 1
Characteristics of feedstocks and inoculum.*

Parameters	Soybean processing waste	Hay	Effluent
Total solids (%)	49.2 ± 0.6	87.8 ± 0.3	7.6 ± 0.2
Volatile solids (%)	35.9 ± 0.5	84.3 ± 0.6	3.8 ± 0.2
Total carbon (%)	24.0 ± 2.3	45.9 ± 0.3	2.6 ± 0.0
Total nitrogen (%)	1.9 ± 0.3	0.6 ± 0.0	0.4 ± 0.0
Carbon to nitrogen ratio	12.5 ± 0.8	76.0 ± 3.5	6.5 ± 0.0
pH	8.8 ± 0.1	6.8 ± 0.0	7.6 ± 0.0

* All numbers are wet basis.