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Research Note

Development of a cartridge design anaerobic digestion system for lignocellulosic biomass

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A novel cartridge design anaerobic digestion system was developed for the treatment of lignocellulosic biomass. This new design is composed of a novel anaerobic digestion chamber with three replaceable feedstock cartridges. This design has multiple advantages, e.g. high stability, easy to operate, and no liquid waste, over conventional anaerobic digestion systems. In a seven-month test, maize straw was employed as the feedstock, and the system was operated in three scenarios: no rotation of cartridge; rotation with 14 g dry maize straw in each cartridge; and rotation with 28 g dry maize straw in each cartridge. Results showed that biogas production from this system was comparable to solid-state anaerobic digestion units, and the rotation of cartridges significantly improved the stability of methane yield and reduced hydrogen sulfide in biogas. Digestion effluent was completely reused in the rotation tests.

1. Introduction

There has been growing interest in using anaerobic digestion to treat lignocellulosic biomass such as crop residues and yard wastes, and in the meantime, generate biogas for energy production (Sawatdeenarunat, Surendra, Takara, Oechsner, & Khanal, 2014). However, current design of either liquid anaerobic digestion (L-AD, works with less than 15% total solids content) or solid-state anaerobic digestion (SS-AD, works with greater than 15% total solids content (Li, Zhu, Wan, & Park, 2011)) have met with considerable challenges and usually requires pretreatment of feedstock (Zheng, Zhao, Xu, & Li, 2014). Floating of lignocellulosic biomass has been a big problem for L-AD systems. Size reduction and mechanical mixing alleviate this problem but can be energy consuming (Surendra & Khanal, 2014). Digestion effluent presents another challenge for L-AD. Since L-AD operates with a relatively low total solids content, a large amount of water is usually added prior to digestion, thus generating a lot of effluent. Land application of L-AD effluent as a liquid fertiliser is one option. However, there are health concerns regarding pathogens and heavy metals presented in effluent (Sheets, Yang, Ge, Wang, & Li, 2015). Food safety has become a hallmark of U.S. regulations, which may influence farmer perception of using effluent fertilisers for crops intended for human consumption. Consequently, many large AD

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operations have limited outlets for effluent disposal (USFDA, 2011). Composting of AD effluent is another option. However, odour emission is a concern and prior to composting, effluent needs to be dewatered, which is an energy intensive process. Therefore, strategies for reducing L-AD effluent are urgently needed.

On the other hand, the major criticism of SS-AD is instability (Brown, Shi, & Li, 2012; Sheets et al., 2015). Due to the high total solids content, mixing of feedstock and inoculum may be incomplete, which could lead to accumulation of inhibitors such as volatile fatty acids and free ammonia, and eventually may cause digester failure (Fagbohungbe et al., 2015; Karthikeyan & Visvanathan, 2012; Li, Park, & Zhu, 2011; Wang, Xu, & Li, 2013; Zhu, Yang, & Li, 2014). Instability also refers to the unstable biogas production. Batch systems are commonly adopted for SS-AD, however, feedstock degradation rate varies over the batch digestion process and so does biogas yield (Liew, Shi, & Li, 2012). A previous study showed that SS-AD of giant reed, a typical lignocellulosic biomass, had fluctuating daily biogas yield with peak values achieved on day 12 at a feedstock/effluent mixing ratio of 2.0 (Yang & Li, 2014). Instability of SS-AD gives rise to challenges in system management and biogas utilisation.

This study aimed to develop a novel system to resolve the aforementioned challenges in both L-AD and SS-AD by improving biogas stability and reducing effluent generation in anaerobic digestion of lignocellulosic biomass. A key component of the new design is a cartridge design anaerobic digestion chamber. The objectives of this study were: 1) to examine the bench-scale new anaerobic digestion system and to obtain preliminary data; and 2) to compare system performance with three different operating strategies.

2. Materials and methods

2.1. Feedstock and inoculum

Maize straw collected from the Illinois State University Farm at Lexington, IL, USA, in October 2015 was used as the feedstock in this study. Maize straw was air dried to less than 15% moisture content, and then ground to pass a 5 mm sieve (Mighty Mac, MacKissic Inc., Parker Ford, PA, USA). The physical and chemical properties of maize straw are listed in Table 1. Effluent taken from a mesophilic liquid anaerobic digester (fed with municipal sewage sludge, operated by Bloomington Normal Water Reclamation District, IL, USA) was used as the inoculum. Digestion effluent provides nutrients and already adapted digestion microbes. The inoculum was activated in a 37 °C incubation chamber for one week prior to use.

Table 1 – Properties of feedstock and inoculum.

Properties, %	Maize straw	Inoculum
Crude protein	4.30 ± 0.32	0.210 ± 0.02
Hemicellulose	24.95 ± 0.33	0.89 ± 0.03
Cellulose	46.16 ± 0.46	1.54 ± 0.13
Lignin	5.90 ± 0.21	N.A.
Phosphorus	0.08 ± 0.01	N.A.
Potassium	1.65 ± 0.09	N.A.
Total solids[a]	88.16 ± 0.81	3.68 ± 0.01
Volatile solids[a]	79.67 ± 0.80	1.92 ± 0.00

[a] Note: wet basis. All others are dry basis. N.A.: Not available.

2.2. Anaerobic digestion system design and operation

A schematic design of the cartridge anaerobic digestion system is shown in Fig. 1. This novel anaerobic digestion chamber has three replaceable cartridges, a clarifier, and an ammonia stripper. The solids removal and ammonia stripping units were not operated in this study. This system has feedstock packed in the replaceable cartridges only, whereas conventional L-AD or SS-AD systems have feedstock evenly distributed inside the digester. The digestion chamber (L × W × H: 23 cm × 15 cm × 15 cm) was made of transparent plastic and had an inner size of 4 L. The three cartridges (L × W × H: 3.8 cm × 15 cm × 14 cm, 0.8 L each) were made of perforated plastic with 0.24 cm diameter holes and 25% open area. Maize straw was loaded into the three cartridges. In addition, 1 L inoculum and ~1.8 L DI (deionised) water was added to the chamber, which left about 0.5 cm head space (150–200 mL, or <5% of the digestion chamber volume). The digestion chamber was put into a 37 °C incubator. A 5 L biogas bag (CEL Scientific, Santa FeSprings, CA, USA) was attached to the top of the digestion chamber, and biogas was collected and analysed every 2–3 days. When a biogas bag was replaced, the digestion liquid was recirculated for 5 min using a pump with a flow rate of 0.2 L min^{-1}. Digestion liquid was taken out from the top layer close to the right side of the chamber, and was injected into the bottom layer close to the left side of the chamber. This recirculation promoted mass transfer in the digestion chamber and also evened out the distribution of inhibitors.

This system was operated in the following three scenarios:

1) Each cartridge was filled with 14 g dry maize straw and all three cartridges were put into the chamber at the same time. This scenario was referred to as "no rotation". Volatile solids (VS) concentration in this scenario was 8.4 g L^{-1}.
2) One cartridge was filled with 14 g dry maize straw and put into the chamber to start the anaerobic digestion process. Then 10 days later, a second cartridge filled with 14 g dry maize straw was added, and followed by a third cartridge added into the chamber after another 10 days. On day 30,

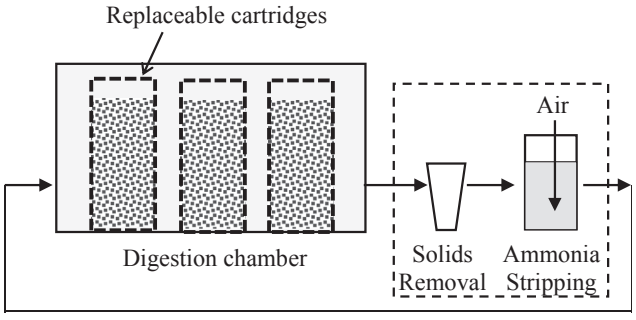

Fig. 1 – Schematic design of the novel anaerobic digestion system. The units in the dashed box were not operated in this study.