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Comparison of different liquid anaerobic digestion effluents as inocula and nitrogen sources for solid-state batch anaerobic digestion of corn stover

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ABSTRACT

Effluents from three liquid anaerobic digesters, fed with municipal sewage sludge, food waste, or dairy waste, were evaluated as inocula and nitrogen sources for solid-state batch anaerobic digestion of corn stover in mesophilic reactors. Three feedstock-to-effluent (*F*/*E*) ratios (i.e., 2, 4, and 6) were tested for each effluent. At an *F*/*E* ratio of 2, the reactor inoculated by dairy waste effluent achieved the highest methane yield of 238.5 $L/kgVS_{feed}$, while at an *F*/*E* ratio of 4, the reactor inoculated by food waste effluent achieved the highest methane yield of 199.6 $L/kgVS_{feed}$. The microbial population and chemical composition of the three effluents were substantially different. Food waste effluent had the largest population of acetoclastic methanogens, while dairy waste effluent had the largest populations of cellulolytic and xylanolytic bacteria. Dairy waste also had the highest C/N ratio of 8.5 and the highest alkalinity of 19.3 g $CaCO_3$/kg. The performance of solid-state batch anaerobic digestion reactors was closely related to the microbial status in the liquid anaerobic digestion effluents.

1. Introduction

Anaerobic digestion (AD) converts organic wastes into biogas via microbial consortia under oxygen-free conditions, making AD one of the few technologies that both produce energy and treat waste streams. An AD process involves four major phases, hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each of which is mediated by a unique functional group of microbes (Yu and Schanbacher, 2010). Thus, highly activated microbial consortia and their concerted functioning directly contribute to an efficient AD process. The balance of nutrients is also critical for the AD process. A carbon-to-nitrogen (C/N) ratio of 20–30 allows optimal biogas production, while an excess of nitrogen or carbon sources can lead to inhibition (Forster-Carneiro et al., 2008).

Depending on total solids (TS) concentrations in the feedstocks, AD systems can be categorized into two types: liquid AD (L-AD) and solid-state AD (SS-AD). L-AD systems typically operate with a TS concentration of 0.5–14.0% and, in the US, are mainly used for treatment of animal manure and wastewater sludge. In the past decade, L-AD systems have been successfully used for the processing of liquid wastes such as animal manure and food processing waste into bioenergy. A barrier for wide application of L-AD technology is the high cost of handling its effluent, which can account for more than 30% of the operating costs for L-AD systems (Mata-Alvarez et al., 2000). In contrast, SS-AD systems generally operate with 15–40% TS, which is suitable for treating the organic fraction of municipal solid waste (MSW) and lignocellulosic biomass (Li et al., 2011a). Problems related to the floating and stratification of fibrous material in L-AD can be solved with SS-AD (Nordberg and Edstro, 1997) and the volumetric loading capacity and volumetric productivity can also be increased with SS-AD (Guendouz et al., 2010). Due to the low water content, SS-AD generates a compost-like end product which can be used as a soil amendment. SS-AD technology represents over 54% of the total installed AD capacity for treating MSW in Europe (Bolzonella et al., 2003). However, SS-AD still suffers from some drawbacks as discussed below. First, most SS-AD systems need up to six units of recycled digestate (end product) or leachate to blend with one unit of fresh feedstock for inoculation (Rapport et al., 2008) and, second, an SS-AD process can take three times longer than an L-AD process to achieve comparable system performance (Martin et al., 2003). Moreover, SS-AD systems for treating lignocellulosic biomass may encounter a C/N imbalance, because the feedstock is rich in carbohydrates but typically lacks nitrogen sources. The C/N ratios of lignocellulosic biomass, such as corn stover and wheat straw, could range from 40 to 130 (Wu et al., 2010), which are far beyond the commonly recommended C/N ratio of 20–30 for anaerobic digestion (Forster-Carneiro et al., 2008).

In order to improve the performance of SS-AD technology, an integrated anaerobic digestion system (iADs) has been developed

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to handle a mixture of L-AD effluent and solid organic wastes (e.g., crop residues, food waste, municipal yard waste) in an SS-AD process (Li et al., 2011c). Activities of microbial consortia and chemical composition of L-AD effluent greatly affect AD performance especially during the start-up of lignocellulosic biomass digestion (Griffin et al., 1998). Compared with aerobic waste activated sludge (Kim and Speece, 2002), manure (Forster-Carneiro et al., 2007) and rumen fluid (Lopes et al., 2004), L-AD effluent is a better inoculum source as indicated by its more balanced microbial consortia and higher methanogenic activity. In addition, L-AD effluent also serves as a nitrogen source which helps the SS-AD system reach an optimal C/N ratio. The most recent studies have demonstrated that iADs can performs well (i.e., a stable pH level) by treating a variety of lignocellulosic biomass inoculated with L-AD effluent (Li et al., 2011b; Liew et al., 2011; Zhu et al., 2010). The iADs can potentially lower operation costs by reducing or even eliminating the need for handling L-AD effluent and producing a compost-like end product that can be marketed as a soil amendment (Li et al., 2011a).

However, the effects of inoculating with different L-AD effluents for SS-AD of lignocellulosic biomass have not been reported. An optimal feedstock-to-effluent (*F*/*E*) ratio is also needed for iADs to achieve concerted microbial consortia and C/N balance. In this study, the effectiveness of different L-AD effluents in providing inoculum and nitrogen sources for SS-AD of corn stover was evaluated. Different *F*/*E* ratios were also tested for each L-AD effluent to optimize the performance of SS-AD.

2. Materials and methods

2.1. Feedstock and L-AD effluents

Corn stover was collected from a farm operated by the Ohio Agricultural Research and Development Center in Wooster, OH, USA (40°48′33″N, 81°56′14″W) in October 2009. Upon receipt, the corn stover was dried to a moisture content of less than 10% and then ground to pass a 9 mm sieve (Mighty Mac, MacKissic Inc., Parker Ford, PA, USA). Three kinds of L-AD effluents, municipal sewage sludge effluent (MSSE), food waste effluent (FWE), and dairy waste effluent (DWE) were obtained from three semi-batch mesophilic liquid anaerobic digesters operating at hydraulic retention time of 28 days by Schmack Bioenergy (Akron, OH), Bridgewater Dairy farms (Northwest Ohio), and quasar energy group (Wooster, OH), respectively. FWE was dewatered by centrifugation (3000 rpm for 15 min) to increase its TS content from 3.9% to 9.9%. Characteristics of the corn stover and three L-AD effluents are shown in Table 1.

2.2. Solid-state batch anaerobic digestion

Each SS-AD reactor (1 L) was loaded with a mixture of corn stover and one type of L-AD effluent, at an *F*/*E* ratio of 2, 4, or 6 (based on volatile solids). Deionized water was added to obtain a TS content of 22% for all SS-AD reactors. Reactors with only 700 g of L-AD effluent (TS around 10%) were run as controls. Each reactor was sealed with a rubber stopper and placed in a 37 ± 1 °C walk-in incubator for 30 days (Cui et al., 2011; Liew et al., 2011). Biogas was collected in a 5-L gas bag (CEL Scientific Tedlar gas bag, Santa Fe Springs, CA, USA) attached to the outlet of the reactor. Composition and volume of the biogas were measured daily for the first 10 days and every 2–3 days afterwards. All tests were conducted with duplicates in batch mode.

2.3. Analytical methods

Samples of corn stover, L-AD effluents, and reactor contents, taken at the beginning and end of the SS-AD process, were characterized. The TS and volatile solid (VS) contents were analyzed according to the Standard for the Examination of Water and Wastewater (Eaton et al., 2005). Total carbon and nitrogen contents were determined by an elemental analyzer using helium as carrier gas (Vario Max CNS, Elementar Americas, Mt. Laurel, NJ, USA) and were used to calculate the C/N ratio. Wet samples were combusted at 800 °C to form CO_2, NOx and water, and then a thermal conductivity detector was used to measure the carbon and nitrogen concentration. In this study, the C/N ratios ranged from 14 to 26 at different *F*/*E* ratios. Total ammonia nitrogen (TAN) was determined by a modified distillation and titration method (ISO 5564, 1984) using 4% boric acid instead of 2% boric acid. Total volatile fatty acids (VFAs) and alkalinity were measured following a titration procedure (McGhee, 1968) using an auto-titrator (Mettler Toledo, DL22 Food & Beverage Analyzer, Columbus, OH, USA). Five grams of solid sample were mixed with 50 mL of deionized water then filtrated with four layers of cheese cloth, and the filtrate was used for titration. Crude protein content was obtained by determining total organic nitrogen (total nitrogen minus ammonia nitrogen) then multiplying by a factor of 6.25 (Hattingh et al., 1967). Crude lipids were analyzed in duplicate by automated extraction from about 1.5 g of dry solids using Soxhlet extraction with a methanol:chloroform ratio of 1:2 as solvent (Soxtec Avanti 2050, Foss Tecator, Hamburg, Germany). Cellulose and hemicellulose contents were determined using a two-step acid hydrolysis process according to the NREL Laboratory Analytical Procedure (Sluiter et al., 2010). Monomeric sugars (glucose, xylose, galactose, arabinose, and mannose) and cellobiose were measured by

Table 1
Characteristics of feedstocks and L-AD effluents.

Parameters	Corn stover	MSSE	FWE	DWE
Total solids (%)	92.2 ± 0.7	10.6 ± 0.3	9.9 ± 0.1	10.2 ± 0.3
Volatile solids (%)	87.5 ± 1.0	6.7 ± 0.2	6.8 ± 0.0	7.4 ± 0.1
Total carbon (%)	43.6 ± 1.1	4.3 ± 0.3	4.3 ± 0.3	3.8 ± 0.4
Total nitrogen (%)	0.5 ± 0.0	0.6 ± 0.0	0.7 ± 0.1	0.4 ± 0.0
Carbon to nitrogen (C/N) ratio	79.7 ± 3.7	6.6 ± 0.3	6.2 ± 0.1	8.5 ± 0.1
pH	N/D	8.2 ± 0.0	8.2 ± 0.0	8.7 ± 0.0
Alkalinity (g CaCO3/kg)	N/D	14.4 ± 0.5	10.7 ± 0.0	19.3 ± 0.4
Total volatile fatty acid (g/kg)	N/D	4.9 ± 0.0	4.9 ± 0.2	3.9 ± 0.0
TAN (gN/kg)	N/D	4.2 ± 0.0	2.0 ± 0.0	2.9 ± 0.0
Cellulose (%)[a]	41.0 ± 0.0	2.7 ± 0.3	1.0 ± 0.0	20.0 ± 0.6
Hemicellulose (%)[a]	22.2 ± 0.5	3.6 ± 0.7	1.3 ± 0.1	17.1 ± 1.1
Lipids (%)[a]	N/D	10.6 ± 0.4	24.5 ± 4.0	3.6 ± 0.9
Crude Protein(%)	N/D	20.8 ± 2.4	44.4 ± 5	13.1 ± 2.9

[a] Based on VS while the rest are based on total weight; N/D, not determined; FWE was dewatered by centrifugation.