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Anaerobic digestion of brewery primary sludge to enhance bioenergy generation: A comparison between low- and high-rate solids treatment and different temperatures

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ABSTRACT

Anaerobic digestion of brewery wastewater solids in the form of primary sludge was investigated for its potential as a source of energy (methane). We operated a low-rate (hydraulic retention time (HRT) = solids retention time (SRT)) continuously stirred anaerobic digester (CSAD) and a high-rate (SRT > HRT) anaerobic sequencing batch reactor (ASBR) in parallel for 250 days. We found that high-rate anaerobic digestion was beneficial for solids-rich waste flows even during a long-term operating period that included a shock load of nonbiodegradable total solids. The ASBR biomass achieved a higher specific methanogenic activity compared to the CSAD biomass (0.257 ± 0.043 vs. 0.088 ± 0.008 g CH_4-COD g^{-1} VSS d^{-1}), which aided in stability during the shock load with total solids. The methane yield for the ASBR was 40–34% higher than for the CSAD (0.306 vs. 0.219 l CH_4 g VS^{-1} fed for days 1–183 and 0.174 vs. 0.130 l CH_4 g VS^{-1} fed for days 184–250, respectively). Finally, we operated an ASBR for an additional 295 days to evaluate the effect of temperature variation on system stability. A stable performance was achieved between the operating temperatures of 22–41 °C.

1. Introduction

Anaerobic digestion (AD) has been an alternative method for the treatment of industrial organic wastewaters for over 40 years (McCarty, 2001). With the rising cost of nonrenewable fuels and political pressure to shift society toward renewable energy, interest in production of heat and/or electricity from biogas (i.e., combined heat and power) has been rekindled. In fact, electricity from biogas (not including landfill gas) increased in Europe by 61.5% from 2006 to 2007, and it has also increased in non European countries (EurObserv'ER, 2008). Specifically, high-rate AD of brewery wastewater has considerably reduced the biochemical oxygen demand (BOD) loading to municipal treatment plants and has produced up to five times the amount of energy required for the entire brewery wastewater treatment process (including post-treatment), offering substantial economic savings (Bocher et al., 2008; Getz et al., 2008; Shao et al., 2008). Compared to conventional (aerobic) treatment, AD requires less energy for its operation, produces less sludge, is more resilient, and offsets nonrenewable boiler fuels (Lettinga, 1995; Speece, 1983). In addition, wastewater from the brewing industry typically has variable pH, high chemical oxygen demand (COD) content, and variable levels of nutrients, making it difficult to treat with traditional aerobic methods (Ince et al., 2001; Yan and Tay, 1996). Indeed, the largest brewer in the US, Anheuser-Busch InBev, Inc., operates anaerobic digesters for wastewater treatment at ten of its 12 breweries in the US (Getz et al., 2008).

Anaerobic bioreactors for soluble wastewaters in the brewery industry are almost exclusively based on high-rate systems that extend the solids retention time (SRT) compared to the hydraulic retention time (HRT) by retaining biomass (Klass, 1984; Sung and Dague, 1995). Examples of high-rate anaerobic digester systems include upflow anaerobic sludge blanket (UASB) (Lettinga et al., 1980), anaerobic baffled reactor (ABR) (Bachman et al., 1985), anaerobic migrating blanket reactor (AMBR) (Angenent and Sung, 2001), and anaerobic sequencing batch reactor (ASBR) (Sung and Dague, 1995) systems. Many breweries utilize a wastewater treatment scheme in which after a screening step, the remaining solids (particle size <1 mm) are fed along with soluble organic components to high-rate upflow anaerobic bioreactors. In this case, these solids are mostly carried through in the effluent along with excess methanogenic biomass (referred to as secondary residuals) because the biodegradation of solids in these high-rate bioreactors

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is low due to the short residence times. In a previously published paper, we digested these secondary residuals in mesophilic (35 °C) and thermophilic (55 °C) CSAD reactors (Bocher et al., 2008). We showed that a mesophilic, low-rate AD system with a minimum HRT of 10 days increased the methane production by up to 8.1% when compared to soluble wastewater treatment alone. In addition, the volatile solids (VS) concentration of the secondary residuals stream was reduced by 43%, greatly reducing the sewer fees that are based on BOD and total suspended solids (TSS) from the anaerobic bioreactor effluent.

Instead of feeding solids to high-rate upflow bioreactors, some breweries employ an alternative wastewater solids management strategy in which primary clarification after the screening step generates a separated-slurry stream with particle size <1 mm (i.e., primary sludge). Because of the presence of particulates, such as yeast cells and (hemi)cellulosic particles (i.e., grain, fines, trub, hops, and rice) in primary sludge, a successful treatment strategy must allow the residence time of the solids to be long enough to provide for biological hydrolysis. Generally, most solids-rich slurries, such as waste activated sludge (WAS, up to ~45 g total solids (TS) l^{-1}), require long residence times and are treated with low-rate CSAD bioreactors. This is because of anticipated problems with long-term TS accumulation in high-rate digesters, which could lower the VS/TS ratio, and thus the biological activity (Wang et al., 2009). However, studies on the anaerobic digestion of solids-rich swine waste (Angenent et al., 2002) and WAS (Chang et al., 1994; Wang et al., 2009) have shown that high-rate treatment in ASBRs can accommodate solids. The ASBR employs perhaps the simplest method of solids retention because in the sequence of steps leading up to substrate addition, biomass is allowed to settle before decanting effluent (Sung and Dague, 1995).

Here, we investigated whether high-rate AD is an advantageous treatment system for a high-solids brewery stream (primary sludge) without excessive long-term TS accumulation. For this reason, we operated a CSAD and an ASBR in parallel while feeding the same waste for 250 days. We also investigated whether it was possible to digest brewery primary sludge under variable feed conditions (we obtained 21 different substrate batches during the course of our operating run with differing levels of COD and TS), while maintaining a stable digester performance. The short-term effect of relatively fast changes in the operating temperature on hydrolysis and methanogenesis in the ASBR was investigated during an additional operating period of 295 days. Finally, in a previous paper we had suggested that secondary residuals would be advantageous to digest compared with primary sludge from breweries because of a lower variability and because of augmentation of methanogens from the high-rate, soluble wastewater bioreactor to the CSAD (Bocher et al., 2008). We, therefore, also compared the methane yields for CSAD systems at 37 °C treating primary sludge (this study) with those treating secondary residuals (Bocher et al., 2008) to gauge what would be the best route of AD treatment of solids for optimal energy recovery.

2. Methods

2.1. Experimental apparatus

Experiments were conducted in two identical laboratory-scale bioreactors; one operated as a CSAD and one operated as an ASBR by employing a continuous and intermittent mixing scheme, respectively. The reactors were constructed of glass (Midrivers Glassblowing, Inc., St. Charles, MO) with a maximum working volume of 5 l and had a water jacket to maintain constant temperatures with an external heating recirculator (PolyScience Model 210, Niles, IL). A mechanical agitator (Model 5vb, EMI, Inc., Clinton, CT) was equipped with a 62-mm diameter axial flow impeller (Lightnin A-310, Rochester, NY) to stir the reactors at ~300 rotations per minute (RPM). After day 250 of the operating period (period II), the mixing in the ASBR was carried out by biogas recirculation with a peristaltic pump (Cole-Parmer, Vernon Hills, IL). Primary sludge was introduced into the reactors manually. To prevent biogas loss during feeding, the decanting/feeding tube extended midway into the reactor contents. A peristaltic pump (Cole-Parmer, Vernon Hills, IL) was used for decanting effluent. The gas collection scheme of each digester system consisted of a foam separation bottle, a pressurized ball used to eliminate air from being suctioned into the digesters during the decanting of effluent, a bubbler to allow visual detection of gas production, a biogas sampling port, and a gas meter (type 1-l, Actaris Meterfabriek, Delft, The Netherlands). We have given detailed reactor schematics previously, in Bocher et al. (2008) (CSAD and ASBR before day 250) and Agler et al. (2008) (ASBR after day 250).

2.2. Reactor operation

We operated CSAD and ASBR systems for 250 days (period I), followed by operation of the ASBR alone for 295 additional days (period II). At the beginning of period I, we inoculated the bioreactors with 1.0 l of blended anaerobic granular biomass from a mesophilic anaerobic upflow bioreactor (i.e., EGSB-biobed system) treating soluble brewery wastewater (Anheuser-Busch InBev, Inc., St. Louis, MO). We allowed 2 weeks for the biomass to acclimate to 37 ± 1 °C and the mixing schedule before feeding. Solids removed in primary clarifiers from the Anheuser-Busch InBev, Inc. brewery in Baldwinsville, NY was received every 2–3 weeks and was allowed to settle further in our lab upon arrival to achieve ~40 g VS l^{-1} (Table 1). Next, the substrate was stored at −20 °C until use. The ASBR was mixed for 1 min every 30 min with a 1-h biomass-settling period before decanting. Thus, the cycle for the ASBR was: instantaneous feeding step, ~23-h reacting step, ~1-h settling step, and a 2-min decanting step after which the cycle was repeated. Because the HRT and the SRT are uncoupled in ASBRs, the SRT is only meaningful at steady state. True steady state is only achieved after long periods of operation and certainly not during the rapid loading increases performed during our start-up. See our description of steady state in the materials and methods section of Bocher et al. (2008). Thus, for purposes of comparison we will use HRT in this paper to describe loading rates. During the start-up period (period I), we first operated with an HRT of 50 days (0.8 g VS l^{-1} d^{-1}) after which we shortened the HRT in a step-wise manner by a factor of 1.25 on days 52, 91, 124, 149, 201, 219, and 236 to achieve a final HRT of 10 days (4.0 g VS l^{-1} d^{-1}) (Fig. 1) during period I. Loading rate increases were made when total volatile fatty acid (VFA) concentrations and gas production rates were stable (Ahring et al., 1995) and when at least a time period of one HRT had passed, except during the 40-day HRT (operated for 39 days) (Fig. 1). We refer in this paper to pseudo steady-state conditions based on these stable performance parameters.

During period II, the short-term effects of relatively fast temperature variations on the performance of the ASBR were observed. Initially, the HRT was maintained at 15 days from day 250–286 after which it was shortened to 12.8 days for most of the remainder of the study (except for a brief increase in HRT to 20 days during days 533–543) (Fig. 3). At the beginning of period II, a 5 °C temperature decrease was made whenever stable biogas production conditions were obtained (Fig. 2). The temperature was decreased from 37 to 32 °C on day 357, to 27 °C on day 371, and to 22 °C on day 392. The reactor temperature was then increased to 27 °C