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Anaerobic digestion of thin stillage of corn ethanol plant in a novel anaerobic baffled reactor

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ABSTRACT

In this study, the performance of a conventional anaerobic baffled reactor (ABR) and a novel configuration of hybrid ABR for the treatment of thin stillage was evaluated. The hybrid ABR achieved the chemical oxygen demand (COD) removal, sulfate removal and methane yield of 97–94%, 94–97% and 294–310 mL CH_4 g^{-1} $COD_{removed}$, respectively at organic loading rate (OLR) of 1–3.5 kg COD m^{-3} d^{-1}. On the other hand, the value of COD and sulfate removal and methane yield for the conventional ABR were 75–94%, 67–76% and 140–240 mL CH_4 g^{-1} $COD_{removed}$, respectively at OLR range of 1.1–1.8 kg COD m^{-3} d^{-1}. The enhanced performance and robustness of the novel ABR was demonstrated to be the result of incorporation of solid/liquid/gas separators into the configuration of the conventional ABR, leading to reduced biomass washout, higher solid retention time and significantly improved phase separation.

1. Introduction

Bioethanol is the most widely used biofuel, which is mainly produced from sugar based crops such as corn and sugarcane (Arapoglou et al., 2010; Harun et al., 2010) with increasing annual production volume of 3.4 million gallons to 14.3 million gallons per year from 2004 to 2014 (Koza et al., 2017). Each liter of ethanol produced can generate up to 20 L of thin stillage, an aqueous by-product from the distillation of ethanol with chemical oxygen demand (COD) of approximately 100 g L^{-1} (Wilkie et al., 2000). The current treatment of thin stillage relies on evaporation and drying, accounting for 46.8% of total energy consumption of the bioethanol plant (Khalid et al., 2011).

Alternative technologies for thin stillage treatment such as anaerobic digestion have been proposed for the removal of organic materials and improving the energy balance of the process, given that the biogas produced, presents an alternate energy source for the plant (Wilkie et al., 2000). Different types of anaerobic digesters have been applied for the treatment of thin stillage with organic loading rate (OLR) range of 2.9–29 kg COD $m^{-3}d^{-1}$ and COD removal of 82–99% (Agler et al., 2008; Andalib et al., 2012; Dereli et al., 2014; Lee et al., 2011; Schaefer and Sung, 2008).

Anaerobic baffled reactor (ABR), which is a compartmentalized reactor and thus can foster optimal environmental conditions for methanogenic and acidogenic bacteria in a two-phase system (Fang, 2010) has not previously been employed for the digestion of thin stillage. Sulfate in the influent stream will lead to sulfidogenesis and sulfur removal primarily in the first compartment of the ABR due to lower Gibbs free energy of the reaction compared to methanogenesis and as a result, mainly biogas from the first compartment contains the hydrogen sulfide (Saritpongteeraka and Chaiprapat, 2008). Given that sulfides can inhibit the activity of methane producing bacteria (Alkan-Ozkaynak and Karthikeyan, 2011) and thin stillage has a relatively high sulfur content of approximately 500 mg L^{-1} (Alkan-Ozkaynak and Karthikeyan, 2011), the two-phase configuration of ABR is advantageous. The other advantage of ABR is a long solid retention time (SRT) (42–612 d (Grobicki and Stuckey, 1991)). Two phase systems enhance the stability of the system to fluctuation in environmental conditions such as temperature and pH (Zhu et al., 2015). ABR has been successfully used for treating different wastewater such as soybean protein processing (Zhu et al., 2008), whisky distillery (Akunna and Clark, 2000), pulp and paper mill black liquor (Grover et al., 1999) and high sulfur rubber latex wastewater (Saritpongteeraka and Chaiprapat, 2008).

Conventional ABR has not been applied and evaluated for anaerobic digestion of thin stillage to the best of our knowledge, and its performance and operation has yet to be explored. The low biomass growth rate and high biomass washout are the main problems of conventional ABR (Barber and Stuckey, 1999). Since the introduction of conventional ABR, different modifications to its

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configuration have been suggested in order to improve the stability and treatment efficiency of the reactor including the use of carrier to support the growth of microorganisms (Faisal and Unno, 2001) and using compartments of different sizes (Elreedy et al., 2015; Malakahmad et al., 2011) or using more number of compartments (Boopathy, 1998). The carrier anaerobic baffled reactor (CABR) was introduced to support the growth of biomass to decrease the wash-out and increase the biomass concentration inside the reactor. Modifications of ABR configuration are well documented in the literature (Barber and Stuckey, 1999; Zhu et al., 2015). The drawback of using carriers is the cost of carriers as well as the blockage caused by accumulated sludge (Zhu et al., 2015). Moreover, building an ABR with a large first compartment as a settler or an ABR with more number of compartments results in a higher construction cost compared to a conventional ABR. In the present study, a novel hybrid ABR in which a solid/liquid/gas separator is incorporated into the configuration of conventional ABR, is evaluated for anaerobic digestion of thin stillage. The suggested modifications in this study are easy and practical to perform on an existing reactor without imposing any considerable cost. It has been hypothesized that this novel configuration enables handling a higher OLR at a higher removal efficiency due to reduced sludge wash out and enhanced phase separation and robustness compared to the conventional ABR. To verify this hypothesis, the performance of the novel hybrid ABR was evaluated and compared with the conventional ABR with respect to robustness, sludge washout, sulfate and COD removal efficiency and biogas production.

2. Material and methods

2.1. Thin stillage characterization

The corn thin stillage was obtained from IGPC Ethanol Inc. (Aylmer, ON, Canada). After collection, the thin stillage sample was stored in a refrigerator at 4^{o}C to avoid degradation. Physical and chemical characteristics of the thin stillage used in this study were characterized by a number of different analysis methods. The elemental analysis (K, Ca, Mg, S, Zn, Mn, Fe, Cu, Al and Na) of the thin stillage was conducted at the Minerals Engineering Center at Dalhousie University (Halifax, Nova Scotia, Canada) using inductively coupled plasma optical emission spectrometry (ICP-OES) in which the samples were diluted into 5% nitric acid prior to measurement. COD, biological oxygen demand (BOD), total solids (TS), volatile solids (VS), total suspended solids (TSS), and volatile suspended solids (VSS) analyses were based on Standard Methods (Eugene et al., 2012). The total nitrogen (TN) was determined by HACH analysis kit, and UV–vis spectrophotometer (DR6000, HACH). The thin stillage was filtered before introducing to the reactor due to high solid content. The characteristics of filtered thin stillage such as TS, VS, TSS and VSS were determined according to Standard Methods (Apha, 1985) and other features (TN, Total phosphorus, sulfate and ammonia) were measured by HACH analysis kit.

2.2. ABR start-up

The COD of feed was adjusted by diluting thin stillage with tap water. Souring due to the accumulation of volatile fatty acids (VFAs) often leads to process failure (Chua et al., 1997; Yu et al., 2002). In order to control pH and prevent souring, pH adjustment was done by the addition of $NaHCO_3$ to the feed, leading to an increase in alkalinity and buffering capacity of the system. The stability of an anaerobic system can be determined by VFA/TA (Total alkalinity) ratio. The VFA/TA ratio of 0.1–0.25 is usually desirable without the risk of acidification while the ratio beyond 0.3–0.4 indicates digester upset, and corrective measures are necessary (Li et al., 2014; Liu et al., 2012; Nigam and Pandey, 2009). The downside of $NaHCO_3$ addition is an increase in the operating cost of anaerobic digestion especially in a large scale but the alkalinity supplementation is usually added to the anaerobic digestion plants (Khanal, 2008; Metcalf and Eddy, 2003). On the other hand, the provided phase separation in the hybrid ABR results in enhanced activity of methanogenic bacteria and consequently higher consumption rate of VFAs. Thus, it reduces the risk of acidification/reactor failure and its associated costs.

A lab scale ABR was operated with a total and working volume of 40 L and 27.5 L, respectively (Fig. 1a). The reactor includes four compartments with a working volume of 6.9 L in each compartment. The prepared feed was fed continuously to the ABR using a peristaltic pump (feeding pump) (Cole Parmer, Master flex L/s). A water bath was used to maintain the temperature of reactor constant at 35 °C. The reactor was sealed and the top of each compartment was connected to a 25 L Tedlar® gas sampling bag to collect the produced biogas. The effluent from the ABR was collected in the buffer tank (Fig. 1a) and then recycled to the inlet by a peristaltic pump (recycle pump) to be mixed with the fresh feed. The OLR of the reactor was increased stepwise. The system was monitored on daily basis with respect to VFA and alkalinity and once it reached to stable condition, different parameters such as biogas production rate, COD, sulfate, biomass washout were measured.

2.2.1. Conventional ABR

An initial run was performed in the conventional ABR (Fig. 1b) with a feeding flowrate of 6.55 L d^{-1} and a recycle flowrate of 66 L d^{-1} (Stage I) (overall hydraulic retention time (HRT) of 4.2d and internal HRT of 0.4d). In this study, the overall HRT is considered as the length of time the liquid remain in the reactor (Henze, 2008) while the internal HRT is calculated considering the recycle stream (Serna-Maza et al., 2014).

The OLR of the system was increased stepwise from 0.75 to 1.8 kg COD m^{-3} d^{-1} by increasing the COD of feed from 3450 ± 79 mg L^{-1} to 8150 ± 228 mg L^{-1}. The OLR is calculated based on the COD concentration of wastewater, feeding flowrate and working volume of the reactor (Metcalf and Eddy, 2003). To control the OLR precisely, the feeding flowrate were measured and checked every day. Moreover, for each round of feed preparation, the COD of feed was measured. Due to the accumulation of high concentration of VFA (917 ± 28 mg L^{-1} in the 4th compartment), the operating parameters of system such as feeding and recycle flowrate were changed as well as biomass concentration inside the reactor. Therefore, in order to have a better control on the system, the feeding flowrate was decreased from 6.55 to 2.52 L d^{-1} and the recycle flowrate was increased from 66 to 144 L d^{-1} (recycle ratio (RR) of 57, overall HRT of 11 d and internal HRT of 0.2 d) while the OLR was maintained at 1.8 kg COD m^{-3} d^{-1} by increasing the COD of feed from 8150 ± 228 to 19500 ± 429 mg L^{-1}. The higher recycle flowrate of the effluent provides higher capacity to toxic substrate and high concentration wastewater by diluting the influent and maintaining the buffer capacity (Zhu et al., 2015). Increasing the overall HRT by decreasing the feeding rate increases the COD removal efficiency and consequently decreases the VFA concentration in the reactor (Castillo et al., 2007; Kuşçu and Sponza, 2005; Nachaiyasit and Stuckey, 1997). A high biomass concentration in the reactor indicates a low food to microorganism ratio (F/M) resulting in an increase in COD removal efficiency (Ghangrekar et al., 2005). Thus, at that step of operation, 75 g VSS (3.9 L) from IGPC methanator's sludge was added to the ABR (18.8 g VSS, 980 mL was added to each compartment to increase the sludge amount in each compartment from 69.3 g VSS to 88.3 g VSS), resulting in the increase in the ratio of inoculation volume: compartment volume from 4.6:6.9 to 5.0:6.9. The OLR was increased to 2.9 kg COD m^{-3} d^{-1} stepwise by increasing the COD to 31200 ± 593 mg L^{-1}.