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Optimization of micro-aeration intensity in acidogenic reactor of a two-phase anaerobic digester treating food waste

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ABSTRACT

Micro-aeration is known to promote the activities of hydrolytic exo-enzymes and used as a strategy to improve the hydrolysis of particulate substrate. The effect of different micro-aeration rates, 0, 129, 258, and 387 L-air/kg TS/d (denoted as LBR-AN, LBR-6h, LBR-3h and LBR-2h, respectively) on the solubilization of food waste was evaluated at 35 °C in four leach bed reactors (LBR) coupled with methanogenic upflow anaerobic sludge blanket (UASB) reactor. Results indicate that the intensity of micro-aeration influenced the hydrolysis and methane yield. Adequate micro-aeration intensity in LBR-3h and LBR-2h significantly enhanced the carbohydrate and protein hydrolysis by 21–27% and 38–64% respectively. Due to the accelerated acidogenesis, more than 3-fold of acetic acid and butyric acid were produced in LBR-3h as compared to the anaerobic treatment LBR-AN resulting in the maximum methane yield of 0.27 L CH_4/g VS_{added} in the UASB. The performance of LBR-6h with inadequate aeration was similar to that of LBR-AN with a comparable hydrolysis degree. Nevertheless, higher aeration intensity in LBR-2h was also unfavorable for methane yield due to significant biomass generation and CO_2 respiration of up to 18.5% and 32.8% of the total soluble hydrolysate, respectively. To conclude, appropriate micro-aeration rate can promote the hydrolysis of solid organic waste and methane yield without undesirable carbon loss and an aeration intensity of 258 L-air/kg TS/d is recommended for acidogenic LBR treating food waste.

1. Introduction

During the acidogenic phase of an anaerobic digestion, a large consortium of microorganisms that are capable of solubilizing organic substrates such as carbohydrates, proteins and lipids, work together and produce organic acids (i.e., lactic, acetic, butyric and propionic acids, etc.). Among the organic acids produced, butyric acid (HBu) and acetic acid (HAc) are known to be better precursors of methane production (Yang et al., 2003; Montero et al., 2010), especially HAc, which is regarded as the most important product, contributing 65–95% of methane production (Weber et al., 1984); in contrast lactic acid can seriously inhibit hydrolysis and methanogenesis (Zhang et al., 2007; Li et al., 2008). Therefore, conversion of organic matters into HAc and HBu in the hydrolytic-acidogenic stage will improve the overall energy yield (Yang et al., 2003) and increase the process rate. Techniques employed to enhance the solubilization of organic substrates into volatile fatty acids (VFAs) include pH control (Yu and Fang, 2003; Cysneiros et al., 2008), addition of enzymes/microbes (Cirne et al., 2008) and physicochemical/thermal pretreatments (Hartmann and Ahring, 2006).

In the recent studies, several authors documented the advantage of incorporating micro-aeration in the hydrolytic-acidogenic reactors for solubilizing the sludge and other organic substrates. Jagadabhi et al. (2010) found that the production of VFAs from the leach bed reactor (LBR) fed with energy crops increased from 2.2 to 9.0 g/L by the application of micro-aeration at 1 L/min. Zhu et al. (2009) demonstrated that the hydrolysis rate was improved by 30.9–57.7% with the provision of sufficient micro-aeration regime of 5 min aeration in every 4 h at a flow rate of 0.7 L/min as compared with those treatments with insufficient aeration (5 min/24 h) and complete anaerobic conditions. In contrast, Nguyen et al. (2007) reported that the hydrolysis rate of municipal solid waste was not improved with the aeration for 2 h at 1 L/min after 4 h interval; however, a positive effect on the performance of methanogenic phase was observed.

Although, these studies have compared the micro-aeration intensity and effectiveness in the hydrolysis of various organic substrates, the relationship between micro-aeration and acidification rate has not been completely understood in terms of the extent and types of VFAs produced in LBR. Furthermore, the composition

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of VFAs would affect the performance of subsequent methanogenic reactor. Despite the reported advantages of micro-aeration, the residual oxygen in the acidogenic leachate from LBR may inhibit the activity of methane-forming bacteria and decrease the methane yield. Therefore, the objective of the present study was to study the effect of different intermittent micro-aeration rates on the solubilization and speciation of VFAs in the anaerobic hydrolytic-acidogenic LBR reactor coupled with an up-flow anaerobic sludge blanket (UASB) reactor. Material balance based on metabolites and by-products distribution in the LBR and the methane production in the UASB of the two-stage LBR-UASB system was used as the reference for the selection of optimum micro-aeration intensity.

2. Materials and methods

2.1. Anaerobic digesters and materials

Four identical sets of laboratory scale LBR-UASB systems were used for the experiments. The working volume of acidogenic LBR and methanogenic UASB were 4.6 L and 10.0 L respectively. The detailed configurations of reactors were presented in our previous report (Xu et al., 2011). Synthetic food waste (FW) with a total solids (TS) content of 38.5 ± 1.0% with volatile solids (VS) content of 97.1 ± 0.2% (VS/TS) was used as the substrate (Wong et al., 2009). Anaerobically digested sludge (ADS) collected from the Shek Wu Hui wastewater treatment plant, Hong Kong, with 5.2% TS and 86.1% VS/TS was used as the inoculum for acidogenic reactor.

2.2. Experimental design

Experiments were performed for a total of 17 days at 35 °C with two replicates for each treatment to obtain reproducible results. Intermittent micro-aeration was applied using an air pump connected to the bottom of the LBRs with a flow rate of 1.0 L/min; and the operation was controlled using timers. Four micro-aeration frequencies were evaluated, i.e., aeration for 12 min every 6 h (LBR-6h), 3 h (LBR-3h), 2 h (LBR-2h) and no aeration (LBR-AN) resulting in corresponding micro-aeration rates of 129, 258, 387 and 0 L-air/kg TS/d, respectively.

Each LBR was initially packed with a mixture of 1.0 kg FW and 0.2 kg of anaerobically digested sludge (ADS). Additionally, 10% wood chips (in volume basis) were added as the bulking agent to facilitate the liquid leaching (Xu et al., 2011). Then 1.0 L of tap water was added into each LBR on Day 0. Leaching occurred naturally and the leachate was collected at the bottom of the reactors daily. Half of the collected leachate was diluted with equal volume of tap water and adjusted to pH 6.0 using sodium carbonate before recycling back into the LBR. The remaining half of the collected leachate was fed into the UASB reactor for methanogenesis.

2.3. Analytical methods

The volume of biogas produced from the UASB reactor was measured using a wet gas flow meter (BSD-0.5, Shanghai, China) and concentration of methane in the biogas generated was determined using a gas chromatograph (GC-HP7890) equipped with a thermal conductivity detector. Total solids (TS) and volatile solids (VS) content of the FW and seed sludge were determined by oven drying at 105 °C for 24 h and igniting at 550 °C for 16 h in a muffle furnace, respectively. Total organic carbon (TOC) content of the FW and digestate were determined by dichromate oxidation method (Nelson and Sommer, 1982). The total Kjeldhal nitrogen (TKN) content of the FW and digestate were determined by digestion and spectrophotometric determination of ammonium-nitrogen (NH_4^+-N) according to the APHA Standard Method 4500-N_{org} C (APHA, 2005).

Acidogenic leachate from the LBR and methanogenic leachate from the UASB reactor were collected everyday and analyzed. The pH and ORP were measured with a pH/ORP meter (Orion 920, Thermo). The concentration of chemical oxygen demand (COD), NH_4^+-N and TKN were analyzed according to the Standard Methods 5220C, 4500-N_{org} C and 4500-NH_3 F, respectively (APHA, 2005). For the analysis of VFAs, leachates were filtered through 0.45 μm cellulose acetate membrane filter paper and 0.9 mL was transferred to GC vials with the addition of 0.1 mL formic acid. The concentrations of acetic acid, propionic acid, *n*-butyric acid, *iso*-butyric acid, *n*-valeric acid and *iso*-valeric acid were determined using a HP 6890 Series gas chromatograph (Hewlett Packard) equipped with flame ionization detector and Econo-Cap EC1000 (15 m × 0.53 mm × 1.20 μm) column. The sample injection volume was 1 μL. The temperatures of the injector and detector were maintained at 200 °C and 250 °C, respectively, while the column temperature was programmed with an initial temperature of 120 °C for 5 min, increasing to 160 °C at a rate of 5 °C/min, and holding at 160 °C for 5 min to ensure complete VFAs volatilization. The sum of acetic acid, propionic acid, *n*-butyric acid, *iso*-butyric acid, *n*-valeric acid and *iso*-valeric acid concentrations are reported as total VFAs (tVFA).

3. Results and discussion

3.1. Performance of LBRs with varied micro-aeration intensities

3.1.1. Changes in pH, ORP and volume of leachate

Recycling of acidogenic leachate back to LBR and adjusting the pH of the recycling leachate to 6.0 enhanced the hydrolysis as shown in our previous study (Xu et al., 2011). Therefore, 50% of the acidogenic leachate was mixed with equal volume of tap water, adjusted the pH using sodium carbonate and then recycled back to the LBR in order to recycle part of the hydrolytic enzymes and reduce the acid crisis. The volume of leachate produced in LBR ranged from 480 to 520 mL for most of the period (Fig. 1a), and the differences in decomposition rate among the four treatments influenced the percolating property resulting in varied levels of leachate production.

The pH of LBRs ranged from 3.8 to 4.2 in the first 3 days, and then gradually increased. During the whole digestion process, pH of LBRs' leachate that was recycled to LBR was daily adjusted to 6.0, thus the pH fluctuated around 6.0. The pH in four LBRs was approaching the range of 5.5–6.5 after about one week of digestion. At the beginning of digestion, ORP of digestate was around 56 mV and decreased gradually along the digestion period. By the end of digestion, ORP decreased to the level between −200 mV and 300 mV. The ORP values showed a contrasting profile to that of the pH profile as reported by Zhu et al. (2009). ORP is negatively associated with pH if only the half reaction $[H^+]/[H_2]$ is accounted. In LBRs with micro-aeration, ORP increased to 125–215 mV on the second day and then decreased immediately to the level between −150 mV and −300 mV in the following one week, whereas ORP in LBR-AN decreased gradually right at the beginning of digestion. The initial increase followed by a rapid decrease of ORP can be attributed to the stimulation of facultative microorganisms, which leads to the accelerated consumption of oxidants. Nevertheless, the ORP level in LBR-2h was higher than others indicating comparatively higher level of oxidants in this reactor.

3.1.2. Changes in COD, TKN and NH_4^+-N contents of leachate

As presented in Fig. 2a, COD concentrations of the first day digestion ranged from 7.9 to 9.3 g/L, which was followed by the