Influence of Organic Loading Rate on the Performance of a Two-Phase Pressurized Biofilm (TPPB) System Treating Food Waste

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Abstract

A two-phase pressurized biofilm (TPPB) system, including a continuously stirred tank reactor (CSTR) and a pressurized biofilm anaerobic reactor (PBAR), was used to produce high calorific biogas without additional upgrading equipment. The influence of organic loading rate (OLR) on biogas and methane production performance was investigated. Three different OLR levels (4, 5, and 6 g-COD/L/d) were applied to the PBAR in sequence. The headspace pressure of PBAR was controlled at 1.0 MPa. Biogas production, gas composition, and process stability parameters were measured. Results found that the highest methane yield of 332.8 mL/g-COD was obtained at OLR of 5 g-COD/L/d. As compared to approximately 90% methane concentration at OLR of 3.1 g-COD/L/d, the methane content in produced biogas was only 76% at OLR of 5.0 g-COD/L/d. The pH value in the pressurized reactor has an important impact on the quality of produced biogas. Further study should focus on the solution strategies of maintaining suitable pH under higher pressure and higher OLR.

Keywords: anaerobic digestion, organic loading rate, pressure, TPPB system, food waste

Introduction

In China approximately 90 million tons of food waste (FW) is generated annually [1]. For restaurant waste (RW)

specifically, the average daily RW production of China's urban population is 0.10-0.15 kg/d. China's total national production of RW was estimated to reach 40 million tons per year (0.11 million tons per day). Until now, there are 118 RW treatment facilities (including facilities under construction and planning facilities) in Chinese cities, with a processing capacity of 20,000 tons per day. This means

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that more than 80% of the generated RW cannot be treated effectively. According to the 13th five-year plan, by 2020 the processing capacity of RW will be up to 36,000 tons per day (equivalent to 30% of daily RW production). RW in particular is a problematic issue in today's China.

Anaerobic digestion (AD) has been recognized as an environmentally friendly and economic solution for the treatment of organic waste. In the AD process, organic substrate is broken down in an anaerobic condition to produce biogas, the composition of which mainly consists of methane (50-65%) and carbon dioxide (35-50%). As compared to landfilling, incineration, and composting, AD was the most environmentally friendly way to dispose of FW [2].

Biogas produced from AD can be used to produce heat and power, and grid/vehicle-quality natural gas (bio-natural gas) after upgrading. For a small-scale AD plant (biogas flows lower than 2,000 m^3/d), the upgrading equipment for biogas is either not available or not cost-effective. In 2011, an autogenerative high-pressure digestion (AHPD) reactor was described to upgraded biogas without additional upgrading equipment, where high CH_4 content of 90% at a pressure of 0.3-9.0 MPa was obtained [3]. Chen et al. [4] further developed a two-phase pressurized anaerobic digestion (TPPAD) system to convert maize/grass silage into high-quality biogas (CH_4>75%). Our previous study found that at an organic loading rate (OLR) of 3.1 g-COD/L/d, high-calorific biogas (higher calorific value of produced biogas was 36.2 MJ/m^3) was obtained via AD of food waste by using a two-phase pressurized biofilm (TPPB) system [5]. As OLR is an important parameter for evaluating the efficiency of the AD system, in this study, we will further investigate the effect of organic loading rate on the performance of a two-phase pressurized biofilm (TPPB) system treating food waste. The process stability, biogas, and methane yield, biogas composition, and first-order reaction rate constant (k) for the semi-continuous pressurized reactor will be discussed.

Materials and Methods

Substrates and Inoculum

In this study, food waste (FW) was collected from a canteen of China University of Petroleum Beijing (CUPB). The plastic bags, bones, and chopsticks were removed before FW was crushed to a mean particle size of 3 mm. Then FW was stored at 4ºC prior to use. Inoculum used in this study was obtained from a running mesophilic anaerobic reactor digesting various organic wastes in a laboratory of the Institute of New Energy, CUPB. Total solids (TS), VS/TS ratio, and pH were 22.73±0.05%, 92.42±0.06%, and 6.86±0.06 for FW, and 1.33±0.01%, 43.56±0.96%, and 7.76±0.01 for inoculum, respectively [5].

Anaerobic Reactors and Experimental Procedure

The flow diagram of the two-phase pressurized biofilm (TPPB) system is shown in Fig. 1. Hydrolysis-acidification was performed in a CSTR with working volume of 5.0 L. The reactor performed at 37ºC and the stirring rate was kept at 120 rpm. Hydraulic retention time (HRT) of the reactor was maintained at six days. The organic loading rate (OLR) of smashed food waste in the acidogenesis phase was controlled to 5 g-VS/L/d.

For the methanogenesis phase we used a 4.0 L pressurized biofilm anaerobic reactor (PBAR) with working volume of 3.0 L. Biomedia pellets in PBAR were pre-incubated with inoculum and food waste for microbial enrichment under anaerobic conditions (37ºC). The OLR was increased gradually from 3.1 g-COD/L/d [5] to 4, 5, and 6 g-COD/L/d. The corresponding HRT was 7, 5, 3.85, and 3.75 days, respectively. The headspace pressure of PBAR was maintained at 1.0 MPa.
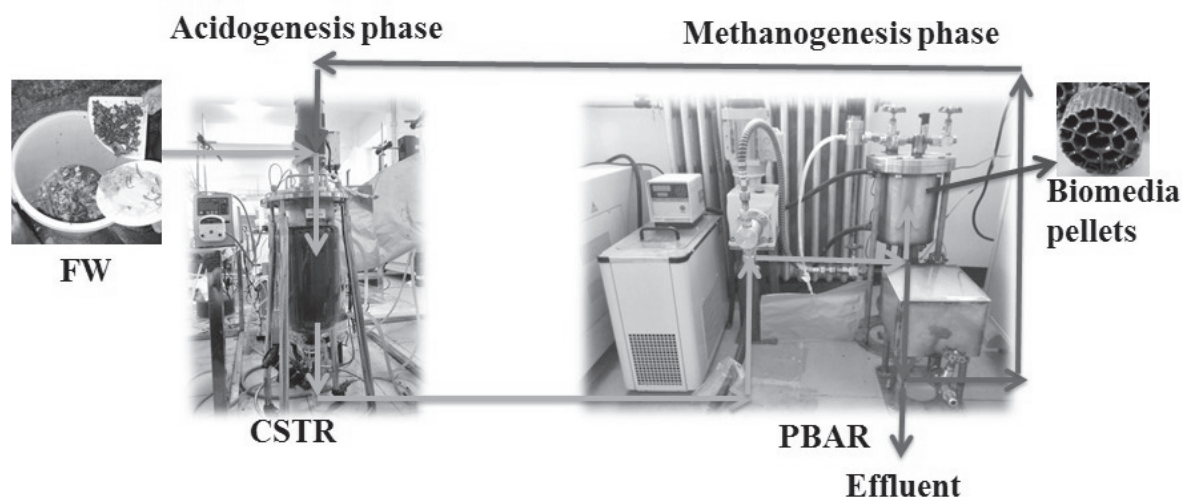

Fig. 1. Flow diagram of the two-phase pressurized biofilm (TPPB) system.

Analysis Methods

Biogas samples were taken every two days to measure the gas composition. A gas chromatograph (FULI 9790II, China) equipped with a thermal conductivity detector was used and helium (He) was the carrier gas. The temperature of the injector, oven, and detector were 150, 130, and 160°C, respectively. Biogas production was determined by a wet gas flow meter (LMF-1, China).

The concentrations of total solids (TS) and volatile solids (VS) were measured according to standard methods [6]. The pH was determined by using a pH meter (PB-10, SARTORIUS Company, Germany). Total volatile fatty acids (VFA) and total inorganic carbon (TIC) were detected by using a Mettler Toledo T70 (Switzerland). Chemical oxygen demand (COD) was measured with a HACH test kit using a COD analyzer (CM-02, SHUANGHUI-JINGCHENG Company, China). Higher calorific values (HCV) and lower calorific values (LCV) of produced biogas were measured according to Li et al. [5].

Kinetic Model

A simple model was used in this study to describe the biogas and methane production process [7-8]:

$$y/(y_m\text{-}y) = k \times C_0/\text{OLR} = k \times \text{HRT} \quad (1)$$

…where y is the methane yield of substrate (mL CH_4/g-COD), y_m is the maximal methane yield of a given substrate (mL CH_4/g-COD), C_0 is the feeding concentration of substrate (g-COD/L), OLR means the organic loading rate (g-COD/L/d), k stands for the first-order reaction rate constant (1/d), and HRT is the hydraulic retention time (d).

Data Analysis

Single-factor ANOVA was used with significance levels of 0.01 and 0.05 ($\alpha = 0.01$ and 0.05) to determine the significance of differences in the biogas composition, volumetric methane productivity, and biogas and methane production for different operations. Data analysis was determined by SPSS statistics 16.0 (IBM, USA). Graph and data processing were completed by OriginPro 9.0 (OriginLab, USA).

Results and Discussion

Process Stability in Methanogenesis Phase

The parameters of pH, VFA, TIC (alkaline buffer capacity), and VFA/TIC ratios in the methanogenesis reactor are shown in Table 1. Under the headspace pressure of 1.0 MPa, with the OLR increasing from 3.1 g-COD/L/d to 5.0 g-COD/L/d, the pH value, VFA concentration, and VFA/TIC ratio was found to be 7.05-7.18, 1.27-2.59 g/L, and 0.14-0.3 1, respectively, which were in a suitable range of methane production by anaerobic digestion; when the OLR increased to 6.0 g-COD/L/d, the pH dropped to 6.84±0.12 and the corresponding VFA concentration and VFA/TIC ratio were found to be 3.74±0.58 g/L and 0.47±0.08, respectively. According to Li et al. [9], a preferred VFA/TIC ratio under 0.4 was essential and could be used to judge reactor stability. If the ratio of VFA/TIC is less than 0.4, the reactor should be stable. Thus, the PBAR was stable under OLR of 5.0 g-COD/L/d. Based on the finding of Wonneberger et al. [10], the pH value in a pressurized reactor had the strongest impact on the methane content of the produced gas. A preferred pH value for AD ranged from 7.2 to 7.8. The drop in pH could inhibit the methanogenesis and disrupt the biogas and methane production performance of the anaerobic reactor. Therefore, the methanogenesis reactor showed an unstable trend at OLR of 6.0 g-COD/L/d. Generally speaking, this system can be operated at higher OLR of 5.0 g-COD/L/d steadily. The corresponding HRT was found to be 3.85 days.

Table 1. Process stability in methanogenesis reactor (standard deviation was obtained based on eight continuous data during steady states).

	Li et al. (2016)		This study	
OLR (g-COD/L/d)	3.1	4.0	5.0	6.0
Headspace pressure (MPa)	1.0	1.0	1.0	1.0
Duration (days)	15	19	23	27
HRT (days)	7	5	3.85	3.75
pH value	7.05±0.05	7.18±0.08	7.09±0.06	6.84±0.12
VFA (g/L)	1.50±0.32	2.59±0.36	1.27±0.71	3.74±0.58
VFA/TIC ratio	0.27±0.07	0.31±0.04	0.14±0.09	0.47±0.08
TIC (g-CaCO$_3$/L)	5.72±0.44	8.48±0.73	9.18±0.71	7.87±0.43

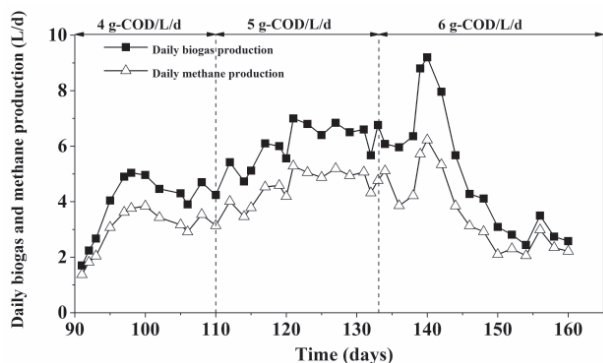Fig. 2. Daily biogas and methane production in methanogenesis reactor at different OLRs.

Fig. 3. Biogas composition in methanogenesis reactor under different OLRs.

Effect of OLR on Biogas and Methane Production

The daily biogas and methane production in the methanogenesis reactor at different organic load rates (OLR) are shown in Fig. 2. With the OLR increasing from 4.0 g-COD/L/d to 5.0 g-COD/L/d, daily methane production was raised from 3.4±0.3 L/d to 4.9±0.4 L/d. When the organic load rate increased to 6.0 g-COD/L/d, daily methane production showed a rising trend and then dropped to 2.7±0.6 L/d, indicating that the methanogenesis reactor was unstable at OLR of 6.0 g-COD/L/d. As shown in Table 1, at OLR of 6.0 g-COD/L/d, the pH value was below 7.0, which also indicated that some inhibition reaction occurred in the methanogenesis reactor. According to Li et al. [5], daily methane production of 2.1±0.3 L/d was found at OLR of 3.1 g-COD/L/d under the headspace pressure of 1.0 MPa. Thus, the highest OLR that can be stable operated was 5.0 g-COD/L/d with highest daily methane production of 4.9±0.4 L/d. Daily biogas production showed the same trend as compared to daily methane production. Highest daily biogas production of 6.6±0.5 L/d was obtained at OLR of 5.0 g-COD/L/d, which was 45% and 84% higher than that of at OLR of 4.0 and 6.0 g-COD/L/d, respectively.

Effect of OLR on Biogas Composition

Biogas composition was influenced by OLR variation (Fig. 3). The methane content decreased from 88.9±1.3% to 75.3±1.4% as OLR rose from 3.1 g-COD/L/d to 4.0 g-COD/L/d. At OLR of 5.0 g-COD/L/d and 6.0 g-COD/L/d, the biogas composition was 75.8±0.8% and 77.1±7.9%, respectively. Similar results were found by Chen et al. [4], where at OLR of 5.1 g-COD/L/d and pressure of 0.89 MPa, the methane content in the methanogenesis reactor was found to be 75%. Lemmer et al. [11] also found that at OLR of 5.0 g-COD/L/d and pressure of 0.9 MPa, methane concentration of 77.3% was obtained using a mixture of grass and maize silage (G/M-silage) leachate as feedstock. Statistical analysis showed that there was no significant difference among methane content at
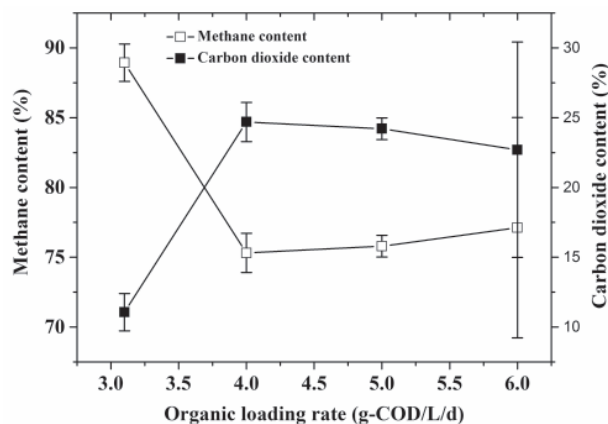
OLRs of 4.0, 5.0, and 6.0 g-COD/L/d. However, methane content at OLR of 3.1 g-COD/L/d was significantly higher ($p = 0.00 < 0.01$) than that of at OLRs of 4.0, 5.0, and 6.0 g-COD/L/d (Table 2). It is worth noting that at OLR of 6.0 g-COD/L/d, higher error bars of methane and carbon dioxide content were obtained, which also indicated an unstable operation in methanogenesis reactor at this OLR. Besides, 0.4-1.3% hydrogen was detected in biogas at this stage, indicating that at OLR of 6.0 g-COD/L/d, the activity of methane-producing bacteria was inhibited and the activity of acid-producing bacteria was enhanced.

Usually, the high cost for biogas upgrading is considered a main barrier for further utilization of the AD technology in decentralized appliances [12]. In this study, high calorific biogas was obtained without additional upgrading equipment. According to the calorific value calculation formula [5], lower calorific values (LCV) and higher calorific values (LCV) of produced biogas were in the range of 27.1-27.7 MJ/m^3 and 30.1-30.8 MJ/m^3 at OLRs of 4.0, 5.0, and 6.0 g-COD/L/d, which is more suitable for direct use as fuel. The CH_4/CO_2 ratio in the collected biogas changed from 2.1 to 6.0. The methane was enriched under higher pressure at different OLRs. However, compared to the gas gained with the AHPD technique, methane content of the produced gas in the TPPB system is low [12]. Further study should be done to increase the methane content in the pressurized reactor.

Effect of OLR on Methane Yield and VMP

Effect of OLR on methane yield (MY) and volumetric methane productivity (VMP) are shown in Fig. 4. With the OLR increasing from 3.1 g-COD/L/d to 5.0 g-COD/L/d, the MY and VMP increased, which implied that microorganisms gradually adapted higher OLR conditions. Highest MY of 332.8±24.3 mL/g-COD and VMP of 1.7±0.1 L$_{methane}$/L$_{reactor\ volume}$ were obtained at OLR of 5.0 g-COD/L/d, which was 16.9% and 46.1%,

Table 2. Statistical analysis on the significant differences in methane content and methane yields of FW at different OLRs (standard deviation was obtained based on eight continuous data during steady states).

Methane content				
	3.1 g-COD/L/d	4.0 g-COD/L/d	5.0 g-COD/L/d	6.0 g-COD/L/d
3.1 g-COD/L/d	-	V.S.	V.S.	V.S.
4.0 g-COD/L/d	V.S.	-	N.S.	N.S.
5.0 g-COD/L/d	V.S.	N.S.	-	N.S.
6.0 g-COD/L/d	V.S.	N.S.	N.S.	-
Methane yield				
3.1 g-COD/L/d	-	V.S.	V.S.	V.S.
4.0 g-COD/L/d	V.S.	-	V.S.	V.S.
5.0 g-COD/L/d	V.S.	V.S.	-	V.S.
6.0 g-COD/L/d	V.S.	V.S.	V.S.	-

S. significant difference, V.S. very significant difference, N.S. no significant difference

and 121.1% and 84.2% higher than that of at OLR of 4.0 and 6.0 g-COD/L/d, respectively. Statistical analysis showed that methane yield at OLR of 5.0 g-COD/L/d was significantly higher ($p<0.01$) than that of at OLR of 3.1, 4.0, and 6.0 g-COD/L/d. Generally, the optimal OLR in this study was found to be 5.0 g-COD/L/d. A similar result was obtained by Chen et al. [4], where specific methane yield was 310 mL/g-COD at OLR of 5.1 g-COD/L/d and pressure of 0.89 MPa using maize silage leachate (the COD concentration was 23±0.9 g/L) from acidogenesis-leach-bed-reactor as feedstock. Further research by Chen et al. [13] showed that their two-phase pressurized anaerobic digestion (TPPAD) system can be run up to OLR of 17.5 g-COD/L/d, achieving the best performance at 12.5 g-COD/L/d at two working pressures (0.9 and 1.5 MPa). The lower OLR obtained in this study may be because of the low pH value (approximately 6.8) inside the reactor at higher OLR. Further study should focus on the controlling pH value in the pressurized reactor.
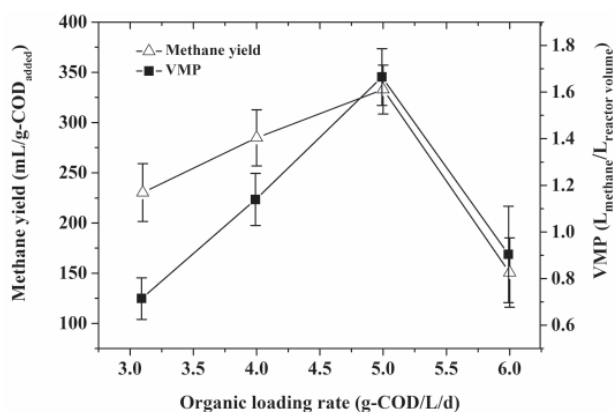
Effect of OLR on *k* Value

There are three main tendencies in anaerobic modelling for predicting reactor behaviour [14]. Based on kinetic equations such as Monod, an unstructured nonsegregated model (UNM) and an unstructured segregated model (USM) are proposed [7]. First-order reaction rate constant (k) plays an important role on the evaluation of fermentation efficiency and biodegradability. First-order and cone models are used to determine the k values and to describe the batch anaerobic digestion process [15]. In this study, according to Linke [7], a simple model was used to describe the biogas and methane production process in semi-continuous mode. Methane yield y as a function of maximum methane yield y_m, reaction rate constant k, and HRT are described on the basis of a mass balance in a semi-continuous reactor and a first-order kinetic.
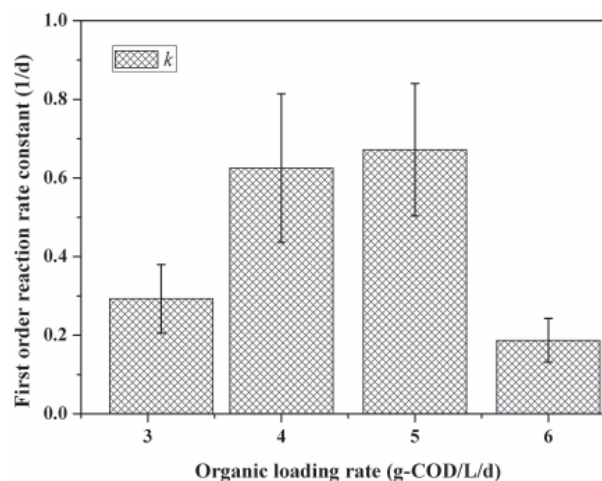

Fig. 4. Effect of OLR on methane yield and volumetric methane productivity.

Fig. 5. Effect of OLR on first-order reaction rate constant (k) values.

According to Eq. (1), first-order reaction rate constant (k) values were calculated at different OLRs. The effect of OLR on k values is shown in Fig. 5 – with OLR increasing from 3.1 to 5.0 g-COD/L/d, the k values increased from 0.29±0.09 1/d to 0.67±0.17 1/d, and then dropped to 0.19±0.06 1/d at OLR of 6.0 g-COD/L/d. According to Li et al. [16], the first-order rate constant (k) for food waste was determined to be 0.18 1/d in the batch biochemical methane potential (BMP) test. Higher k value obtained in the current work may be because of the two-phase anaerobic digestion system and higher methane generation efficiency in the pressurized biofilm anaerobic reactor (Fig. 1). In brief, a suitable OLR in a pressurized reactor for methane production was 5.0 g-COD/L/d. The corresponding HRT was found to be 3.85 days (Table 1).

Conclusion

At OLR of 5.0 g-COD/L/d and HRT of 3.85 days in a pressurized biofilm anaerobic reactor (PBAR), the TPPB system can operate steadily. Highest methane yield of 332.8 mL/g-COD and volumetric methane productivity of 1.7 $L_{methane}/L_{reactor\ volume}$ were obtained at OLR of 5.0 g-COD/L/d, which was 16.9% and 46.1%, and 121.1% and 84.2% higher than that of OLR of 4.0 and 6.0 g-COD/L/d, respectively. The PBAR became unstable at the higher OLR of 6.0 g-COD/L/d because of the accumulation of VFAs and a decrease in pH. Using higher buffer capacity of leachate as feedstock may be an alternative solution.

Acknowledgements

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