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Research article

A comparative experimental study of the anaerobic treatment of food wastes using an anaerobic digester with a polyamide stirring rake or a stainless-steel stirring rake

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A B S T R A C T

A low treatment capacity and unstable operation are the main drawbacks of the anaerobic digestion of food wastes. The present work improved the efficiency and stabilization of the anaerobic digestion of food wastes using digesters with a polyamide stirring rake (DPSR) and compared it to a traditional digester with a stainless-steel stirring rake (DSSSR). The DPSR had a higher reliability and produced 3.97 times the methane yield of DSSSR in batch experiments at high loading rates (105 VS/L). Uniform design experiments were applied to investigate the relationship between methane yield and the stirring factors of the DPSR. A regression analysis of the uniform design indicated that stirring factors synergistically affect methane yield. The experiment verifying the optimal conditions showed that in the DPSR with 82 r/min stirring intensity and 10 min/d stirring time, the first 20 days of methane yield (392.1 mL/g VS) achieved to 85.26% of the theoretically derived methane yield. In brief, in the anaerobic digestion of food wastes for high methane production and stable operation, the DPSR was more beneficial for the anaerobic digestion of food wastes than the DSSSR.

1. Introduction

The catering industry provides a staggering amount of food wastes (FW) in many countries (Chen et al., 2014; Zhang et al., 2016; Derqui and Fernandez, 2017). For example, the restaurants in Beijing generate more than 2000 tons of FW each day (Kong et al., 2016). Anaerobic digestion (AD) is an ideal technology to realize energy recovery and FW reduction (Rajagopal et al., 2013; Fiore et al., 2016). However, FW are characterized by a high volatile solids to total solids (VS/TS) ratio (Zhang et al., 2007; Prabhu and Mutnuri, 2016). A large amount of water is needed to regulate the VS of feedstock, which increases operating costs and decreases the treatment capacity of the digester (Pantaleo et al., 2013). Moreover, the pH of the substrate may considerably decrease through the AD process due to the release of organic acids (Latif et al., 2017). This decrease in pH is one of the main limits to the AD of food wastes (Deepanraj et al., 2015). Increasing the loading rate of VS for the digester and alleviating the acidification thus become indispensable for the AD of FW.

Various factors including temperature, the pH of the substrate, heavy metals, and ammoniacal nitrogen affect the AD process (Ariunbaatar et al., 2015; Zhang et al., 2015). Great efforts have been made to improve the performance of AD, such as the selection of the optimal substrate (Bouallagui et al., 2009), decreasing the loading rate of feedstock (Capsontojo et al., 2017), the pretreatment of substrates (Carlsson et al., 2012), and reducing the particle size (Silvestre et al., 2015). The continuously stirred tank reactor (CSTR) is a common digester design. The feedstock is mixed continuously to maintain the solids in suspension and to form a homogenous mixture. The mixing mode and intensity are important control measures for the CSTR, and many investigations have shown that they have direct effects on biogas yields (Lindmark et al., 2014). Although the stirring rake has been used for decades in digesters

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(Mataalvarez and Vitoreslozano, 1986), few efforts have been put into optimizing the stirring rake itself. The effects of mixing are important for producing the most viscous substrate (Wang et al., 2017). In this study, two stirring rakes with different structures were compared in terms of their influences on the AD of food wastes. Digesters with stainless steel stirring rakes (DSSSR) are usually used with medium concentrations of organic loading. DSSSRs become unstable when organic loads increase. However, in most cases, the AD of FW requires stable running of a viscous substrate. A polyamide stirring rake not only offers an agitation function but also provides a good microenvironment for the growth of anaerobic microorganisms. This could help improve the stability and efficiency of anaerobic digestion.

This paper describes comparative experiments on the AD of FW using digesters with a polyamide stirring rake (DPSRs) and DSSSRs. Mathematical models were built to describe the correlation between the loading rate and methane yield in the DPSR. Then, a uniform design and regression analysis was applied to optimize the operation conditions (stirring intensity and duration) of the DPSR. Finally, the performances of the AD process were verified at optimal conditions.

2. Materials and methods

2.1. Preparation of feedstock and inoculums

Food wastes were collected from a local restaurant (Tianjin, China). The impurities in the waste, such as wood, metal, glass and plastics, were manually removed. The wastes were then shredded to particles 5 mm in diameter and were stored at −20 °C. Before the beginning of the experiment, the feedstock was thawed overnight at 30 °C. Seed sludge was collected from a mesophilic liquid AD system that was fed with food wastes. The sludge was starved for one week at 37 °C to remove the easily degradable volatile solids prior to the beginning of the experiment. The sludge was then centrifuged at 5000 rpm for 20 min. The supernatant was removed, and the sediment was collected to be used as inoculum. The inoculum inside the AD system was 4 g VS/L.

2.2. Experimental protocol

A wide range of loading rates (15–105 g VS/L) of FW was tested in batch DPSR and DSSSR experiments to determine the appropriate loading rate of the feedstock. The lengths and maximum radii of both the polyamide stirring rake and stainless-steel stirring rake were 12 cm and 5 cm, respectively. The polyamide stirring rake was made of Polyamide 66. Its bristles were 2.5 cm long. The stainless-steel stirring rake contained six blades. Each blade had an area of 4.5 cm^2. The working volume of both digesters was 2 L. Detailed drawings of the digesters are presented in Fig. 1(a) and (b). The digesters were used in a room with a constant temperature (37 ± 1 °C). The stirring rate during the experiments was 120 rpm for 15 min every day.

After the determination of the appropriate loading rate of the feedstock, a uniform design was applied to determine the relationship between methane production and stirring factors (the stirring intensity and duration of the polyamide stirring rake). The experiments were based on a uniform design with two factors (Kaitai, 2001). The ranges of independent variables were 50–140 rpm/min and 2–20 min/d. A sequential procedure including data collection, polynomial estimation, and a check of model adequacy was followed.

2.3. Analytical methods and data analysis

The total solids (TS), volatile solids (VS), ammonium contents and total chemical oxygen demand (COD) of food wastes and seed sludge were analyzed. All of the analyses were performed in duplicate following the standard methods of the American Public Health Association (Eaton et al., 2005). The pH was determined using a pH meter (SX620, SanXin, China). The C, H, O and N contents of food wastes were determined using an elemental analyzer (Vario Micro cube, ELEMENTAR, Germany). The daily methane production from digesters was measured using a water displacement set-up after the biogas passed through a gas collecting device (Fig. 1) that contained 2 mol/L NaOH solution. Bristles of DPSR (OLR = 90 g VS/L) were observed using a Nikon microscope under the 10 × 4 and 10 × 10 high-power fields.

Regression analysis was used to estimate the quantitative relationship between the methane yield and operation conditions. A least squares method was used to model the parameters for approximating the mathematical models. Origin 8 (Origin Lab Inc., USA) was used to establish and test the mathematical models to examine the data.

3. Results and discussion

3.1. Characteristics of food wastes and seed sludge

The main properties of the food wastes and seed sludge that were used in the experiments are shown in Table 1. The TS (117.0 g/L) and VS/TS (91.5%) of food wastes were in the common range that has been reported by previous studies (Zhang et al., 2007; Nagao et al., 2012; Brown and Li, 2013). The elementary composition of samples by weight was found to be 41.3% C, 4.3% H, 32.2% O, and 3.3% N. The composition $C_{14.4}H_{17.9}O_{8.4}N$ is thus obtained as the empirical formula for food wastes according to the reference method (Rittmann and McCarty, 2012).

Eq. (1) is the oxidation half-reaction for food wastes, written on a one-electron equivalent basis.

$$(1/55.7)C_{14.4}H_{17.9}O_{8.4}N + (21.4/55.7)H_2O \rightarrow (13.4/55.7)CO_2 + (1/55.7)NH_4^+ + (1/55.7)HCO_3^+ + H^+ + e^- \quad (1)$$

Eq. (2) is the reduction half-reaction for CO_2, also written for a one-electron equivalent.

$$(1/8)CO_2 + H^+ + e^- \rightarrow (1/8)CH_4 + (1/4)H_2O \quad (2)$$

Adding Eqs. (1) and (2) provides the overall balanced reaction, Eq. (3), in which no free electrons are present.

$$C_{14.4}H_{17.9}O_{8.4}N + 21.4H_2O + (55.7/8)CO_2 = 13.4CO_2 + NH_4^+ + HCO_3^+ + (55.7/8)CH_4 + (55.7/4) + H_2O \quad (3)$$

Calculations of theoretical methane yield are based on the contents of C, H, O and N in food wastes. The theoretical yield shows that wastes produce the methane potential. According to Eq. (3), the theoretical methane yield of food wastes was 459.9 mL/g VS, which was lower than the 546.1 mL/g VS that was observed in another study (Nielfa et al., 2015). The difference in the feedstock was the cause for this difference. The C/N was 51.8 in Nielfa et al. (2015), whereas the C/N was 12.5 for samples in this study. The high concentration of N indicated that the sample was rich in protein. In fact, it was unfavorable to methane production (Song et al., 2016).