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Anaerobic digestion characteristics of pig manures depending on various growth stages and initial substrate concentrations in a scaled pig farm in Southern China

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HIGHLIGHTS

- AD character of pig manures from different growth stages was evaluated.
- SNM presented 28.2% and 32.1% higher methane production rate than GSM and GFM.
- GFM obtained the lowest methane yield due to low C/N ratio and high VFA/TIC.
- Modified Gompertz model shows better fit than first order model on describing AD.

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ABSTRACT

The characteristics of anaerobic digestion of pig manure from different growth stages were investigated. According to growth stage, batch experiments were performed using gestating sow manure (GSM), swine nursery with post-weaned piglet manure (SNM), growing fattening manure (GFM) and mixed manure (MM) as substrates at four substrate concentrations (40, 50, 65 and 80 gVS/L) under mesophilic conditions. The maximum methane yields of MM, SNM, GSM and GFM were 354.7, 328.7, 282.4 and 263.5 mL CH_4/gVS_{added}, respectively. Volatile fatty acids/total inorganic carbon (VFA/TIC) ratio increased from 0.10 to 0.89 when loading increased from 40 to 80 gVS/L for GFM. The modified Gompertz model shows a better fit to the experimental results than the first order model with a lower difference between measured and predicted methane yields. The kinetic parameters indicated that the methane production curve on the basis of differences in biodegradability of the pig manure at different growth stages.

1. Introduction

With the development of large-scale and intensive pig farming, large amounts of wastes are produced in China (Huang et al., 2011; Tian, 2012). In 2009, the amount of pig manure reached approximately 209.3 million tons. This large amount of animal manure has lead to many unpleasant environmental consequences when this waste has been abandoned in fields or near factories (Kafle and Kim, 2013). Therefore, how to settle the problem has being a hot gambit. With inherent energy and fertilizer values of pig manure, anaerobic digestion is considered the best method to minimize waste and recover bioenergy (Jiang et al., 2011; Pöschl et al., 2010). Recently, researcher has investigated the characteristics of anaerobic digestion for treating animal manures and results have shown that the methane yield and production kinetics are influenced by different factors, including substrate characteristics and substrate concentrations (Chandra et al., 2012; Otero et al., 2011; Rincón et al., 2010).

On the basis of growth stage, pigs are commonly raised and fattened in three separate breeding units, which are mainly classified as gestating sow (GS), swine nursery (SN) with post-weaned piglets, and growing fattening (GF) buildings in intensive large-scale pig farms in China. This feeding pattern is similar to that in France and Sweden (Combalbert et al., 2012; Eriksson et al., 2005). The composition of manures at different growth stages is highly dependent on conditions under which animals are kept in farms (SN, GS or GF). One hand, the manure extracted from different pig houses has different components due to the different nutrient metabolic capacity of SN, GS or GF. On the other hand, the pigs' feed formulas and the pig feed additive (antimicrobial agents) at different growth stages are quite different, which lead to the different composition

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of SNM, GSM or GFM (Boyd et al., 2002; Canibe et al., 2007; Dewey et al., 1999; Lallai et al., 2002). Some studies reported that the biogas production characteristics are significantly affected by manure composition, such as antibiotics, heavy metals and ammonia content in raw manure (Dewey et al., 1999; Guo et al., 2012b; Lallai et al., 2002).

Apart from the substrate composition, substrate concentration is also an important factor for influencing the efficiency of anaerobic digestion (Chae et al., 2008; Raheman and Mondal, 2012; Rincón et al., 2010). Increased substrate concentration can result in an increase in volumetric methane yield during anaerobic digestion (Sanchez et al., 2005). However, anaerobic systems can also fail because of accumulation of VFAs, total ammonia (TAN) and free ammonia (FAN) in these systems with overloaded fermentation concentration (Niu et al., 2013; Sanchez et al., 2005). The effect of fermentation concentrations on anaerobic digestion has been well reported in several studies (Chae et al., 2008; Raheman and Mondal, 2012). However, the available information on the characteristic of anaerobic digestion at various initial substrate concentrations is quite limited in terms of different compositions of manure extracted from different pig-raising stages.

This study aimed to investigate the characteristics of anaerobic digestion of pig manure depending on various growth stages and initial substrate concentrations in a large-scaled pig farm in Southern China. The methane yields of GSM, SNM, GFM, and MM at four substrate concentrations were determined. The characteristics of digestates at various VS concentrations of each manure sample from different growth stages were also evaluated. Furthermore, the modified Gompertz model and first-order kinetic model were introduced to fit the experimental results and predict the methane yields of each manure sample in anaerobic digestion.

2. Methods

2.1. Substrates and inoculum

The pig manure samples used in this investigation were obtained from a large-scale pig farm located in Jiangxi Province, China (28.7°N, 117.1°E). These manure samples were classified according to the different growth stages: GSM, SNM, GFM, and MM (VS_{GSM}:VS_{SNM}:VS_{GFM} = 1:1:1). Before the experiment was conducted, these milled pig manure samples were frozen at −20 °C to prevent biological decomposition. Prior to launch this experiment, the freezing substrates were transferred to a refrigerator at 4 °C for 1 day. The characteristics of different pig manure samples and seed sludge are listed in Table 1.

2.2. Batch digester start-up and experimental design

The batch digestion test was performed in 250 mL serum bottles capped with natural rubber sleeve stoppers. The working volume of the bottle is 180 mL. Different volatile solid (VS) concentrations of the substrates were required to determine the degradation characteristics of different pig manure samples. The total solid (TS) concentration in Chinese biogas plants is lower than German biogas plants with 8–12% TS (Guo et al., 2012a). According to the actual substrate concentrations of Chinese biogas plants, the anaerobic digestion character of pig manure samples at different VS contents (4.0%, 5.0%, 6.5% and 8.0% of VS corresponding to initial substrate concentrations of 40, 50, 65 and 80 gVS/L, respectively) was analyzed in this study. Firstly, according to the substrate concentrations, different amounts of pig manure samples were added into each bottle. Then, 150 mL of inoculum was added and finally appropriate volume distill water was added to the bottle for a final volume of 180 mL. Subsequently, the initial pH of the mixed liquor in each digester was adjusted to 7.0 ± 0.1 by using 1 M HCl or 1 M NaOH (Xie et al., 2011). The headspace of the bottles were flushed with 100% pure nitrogen for approximately 2 min to ensure anaerobic conditions (Kafle et al., 2012). The anaerobic digesters were maintained at 37 ± 1 °C in a temperature-controlled chamber. Assays with inoculum alone were also used as control samples. All of the batch experiments were performed in triplicate and the results were expressed as means ± standard deviation. Biogas and methane produced from the inoculum were subtracted from the sample assays. The digesters were ceased until there was no methane production. After methane production stopped, the digestates were finally sampled for determination of TS, VS, pH, TAN, VFA and TIC.

2.3. Analytical methods and calculation

TS, VS, soluble chemical oxygen demand (SCODcr) and total ammonia nitrogen (TAN) were determined in accordance with the standard methods (APHA, 2005). pH was determined using a digital pH meter (FE20, METTLER TOLEDO, Switzerland). The TIC and VFA content were analyzed by titration with 0.05 M H_2SO_4 to endpoints of pH 5.0 and 4.4 (Rieger and Weiland, 2006). Air-dried material was also used for elemental analysis (C, H, N, S) by an elemental analyzer (Vario EL/micro cube, Germany). The contents of cellulose, hemicelluloses and lignin were measured using an automatic cellulose analyzer (A200i, ANKOM, America). The free ammonia (FAN) concentration was calculated using Eq. (1) (Hansen et al., 1998; Niu et al., 2013):

$$\mathrm{FAN} = \frac{\mathrm{TAN}}{1 + 10^{(p\mathrm{Ka}-p\mathrm{H})}} \tag{1}$$

$$p\mathrm{Ka} = 0.09018 + \frac{2729.92}{T + 273.15}$$

T: the temperature (°C).

The volume of daily biogas production was determined by displacing 75% saturated solution of sodium chloride according to Rincón et al. (2010). The measured biogas volumes were adjusted to the volumes at standard temperature (0 °C) and pressure (101.325 kPa). Biogas composition was analyzed by gas chromatography (GC-2010 plus, SHIMADZU, Japan) with a stainless steel column of TDX-01 (packed with carbon molecular sieve, 2 m × 3 mm) and thermal conductivity detector (TCD). The temperatures of the column oven, injector and detector were 80 °C, 120 °C and 150 °C, respectively. Nitrogen was used as the carrier gas with a flow rate of 30 mL/min. Theoretical methane potential was calculated according Bushwell's formula (Chae et al., 2008).

2.4. Kinetic model

First-order kinetics model has been used to describe the process of methane fermentation of some organic materials (Kafle and Kim, 2013; Kafle et al., 2012; Rincón et al., 2010). Pig manure as a kind of good organic materials, assuming the first-order kinetics can be used to describe the process of methane fermentation of pig manure. The cumulative methane production was predicted in this batch experiment based on Eq. (2).

Apart from the methane yield, the duration of the lag phase (λ) is also an important factor used to determine the efficiency of anaerobic digestion. λ can be calculated using the modified Gompertz model which is a typical "S" style curve equation (Eq. (3)):

$$M(t) = M_{\max} \times (1 - e^{-Kt}) \tag{2}$$

$$M(t) = M_{\max} \exp\left\{-\exp\left[\frac{R_{\max} e}{M_{\max}}(\lambda - t) + 1\right]\right\} \tag{3}$$