Process Performance and Kinetic Characteristic of Anaerobic Digestion Focusing on Swine Manure Content

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Abstract—This study investigated the process performance and kinetics of mono-, and co-digestion of swine manure and corn straw focusing on swine manure content in the total substrate. Batch anaerobic digestion tests were conducted at mesophilic condition. First-order model and Logistic model were used to assess the effect of swine manure content on degradation efficiency, biogas production rate and lag phase and predict biogas production potential. The results indicated that process stability and biogas production, degradation efficiency and biogas production rate increased while lag phase time decreased with the increase of swine manure content. Additionally, swine manure content of R4 showed the best AD performance, and according to the analyzed results and kinetic analysis, it suggested that the appropriate value of swine manure content might be 70%.

Keywords-anaerobic digestion; swine manure; corn straw; correlation; kinetics

I. INTRODUCTION

Substantive investigations have been conducted on the anaerobic digestion (AD) of swine manure mainly centered on analyses of process performance, microbial community shift and kinetics under different operational conditions, using mono-digestion or co-digestion of swine manure [1, 2]. Factors affecting degradation efficiency, process stability and biogas production include pH, temperature, organic loading rate, mixed ratio [3-5], and some inhibitory factors of AD byproducts, including ammonia nitrogen and VFAs are also studied. In addition, pretreatment is a promising method to improve AD efficiency, especially in co-digestion of swine and crop straw. Moreover, researches about kinetics of mono-digestion and co-digestion swine

manure focused on ADM1-based modelling, first-order models, Transfer function model, Cone models [6] and modified Gompertz model [7]. However, use of model mainly depends on operational conditions.

However, no previous study has investigated the influence of swine manure content on process performance and kinetics in AD of swine manure, or focused on the detailed correlation analyses of parameters. Hence, in order to achieve a comprehensive understanding of process performance and mechanism of parameter interacting during AD process of mono-, and co-digestion of swine manure with corn straw, particularly aim on demonstrating the correlation between kinetics and substrate characteristic and providing theoretical basis for further study, the objectives of the present study was to investigate the correlation between biogas production and process parameters, influence of substrate characteristic on kinetic parameters, hydrolysis rate. The predicted biogas potential was also showed.

II. MATERIALS AND METHODS

A. Substrates and Inoculum

Air-dried corn straw crushed into 2- to 3-mm pieces, fresh swine maure and inoculum produced from a household mesophilic anaerobic reactor were collected from a local village in Yangling, China. The physicochemical properties of feedstocks were analyzed (Table 1).

TABLE 1. CHEMICAL CHARACTERTZATION OF
SUBSTRATES USED IN THE DIGESTERS

	TS [a] (%)	VS [a] (%)	TOC[a] (g/kg VS)	C/N	pH
SM	53.58±3.31	84.45±4.66	26.66±1.13	17.85±0.21	6.4±0.12
CS	96.55±6.34	90.66±5.56	46.5±2.17	82.3±1.51	ND[b]
Inoculum	6.59±1.51	75.4±4.12	ND[b]	ND[b]	8.4±0.18

Note: a, Dry basis; b, Not determined
SW: swine manure; CS: corn straw; TOC: total organic carbon

B. Anaerobic Digestion

Laboratory-scale batch anaerobic digestion was conducted at mesophilic condition (37±1°C) in 1L glass bottles with a 700 mL working volume. Each digester had a TS content of 8% and a substrate to inoculum ratio (S/I) of 2.5:1. Five experimental treatments were set: R1 (mono-digestion of corn straw, no swine manure was added), R2, R3, R4 (co-digestion with swine manure content of 30%, 50% and 70% (TS basis), respectively), R5 (mono-digestion of swine manure, no corn straw was added).

C. Kinetic Study

First-order model (Eq. (1)) [6] has been widely used in previous studies when the hydrolysis reaction was the rate-limiting step of anaerobic digestion process. It was used to predict methane yield from anaerobic digestion [6, 8]. In this study, a first-order model was used to describe the hydrolysis rate of different anaerobic digestion phases. It showed a straight line with a slope whose magnitude is the hydrolysis rate constant.

$$M_{(t)} = M_{max} \cdot [1 - exp(-kt)] \qquad (1)$$

Where $M_{(t)}$ is the accumulative biogas production (mLg^{-1}VS) at an anaerobic digestion time t (d), $M_{(max)}$ is the maximum accumulative biogas production at the end of anaerobic digestion process, and k is the observed hydrolysis constant (d^{-1}). The value of k was estimated by a linear regression fit.

A Logistic model (Eq. (2)) were used to fit the accumulative biogas production data obtained from experiments. The model was used when an inhibitory phenomenon was observed in the anaerobic digestion process and assumed that the methane production reflects the bacterial growth.

$$M_{(t)} = \frac{P_{max}}{1 + exp\left(\frac{4R}{P}(\lambda - t) + 2\right)} \qquad (2)$$

$M_{(t)}$ is the accumulative biogas production (mLg^{-1}VS) at an AD time t (d), P_{max} is biogas production potential (mLg^{-1}VS), R is the maximum biogas production rate (mLg^{-1}VSd^{-1}), and λ is the lag-phase time (d). The values of P_{max}, R and λ were estimated by a non-liner program. SPASS Statistics 20 was used for the analysis of standard deviations and significance of differences and linear and non-liner fitting of models.

III. RESULTS AND DISCUSSION

A. Biogas Production

Variation of daily biogas production and accumulative biogas production of all treatments was shown in Fig.1. Compared with the peak value of each treatment, it found that R1, R2 had one obvious peak value at 19d. R3, R4 had two obvious peaks and the first peak was achieved at 3d and the second peak was achieved at 10d and 8d, respectively (Fig.1a). R5 reached the main peak at 5d. Therefore, starting-up time significantly reduced with the increasing of swine manure content which could be indicated by the time of peak value appeared. These peak values increased from with the rising of swine manure content, ranged from 14.19mLg^{-1}VSd^{-1} for R2 to 26.28 mLg^{-1}VSd^{-1} for R5. Although R1 had a higher peak value of 19.06 mLg^{-1}VSd^{-1} than R2, it showed a longer lag phase and then rapidly decreased and maintain a lower level which could due to the high C/N ratio in R1. In R5, the biogas production rate showed a "sharply rose-declined" tendency with the shortest lag time. Therefore, accumulative biogas production of R5 showed a rapid rising tendency at initial stage of 16 days followed by R4 (Fig.1b). However, though R5 achieved the highest biogas production rate, R4 obtained the highest accumulative biogas production of 434.9mLg^{-1}VS, with an increase of 69.8%, 32.4%, 22.5% and 25.4% than R1, R2, R3 and R5. These could be explained that higher swine manure content in corn straw provides a suitable C/N ratio which is important for AD stability. Furthermore, degradation efficiency could be increased by more easily degradable matters in swine manure and decrease the duration time of AD. Moreover, complex composition of substrate in co-digester contributes to the system stability than mono-digestion of swine manure and corn straw.
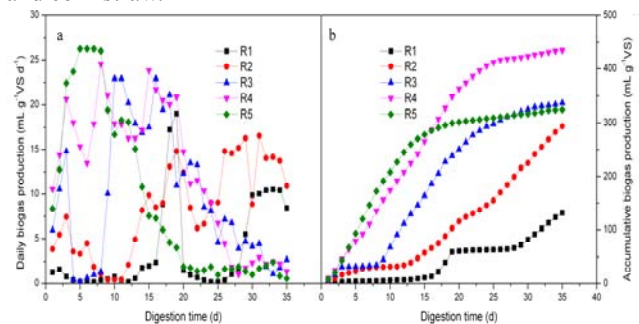

Figure 1 Variation of biogas production during AD process in the digesters

B. Influence of Process Parameters on Methane Yield

AD process is generally divided into four stages, i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis. Each stage includes material metabolism and energy transformation depending on microbial activity. The synergistic effect of process parameters, such as pH, VFA, ammonia nitrogen (AN) and alkalinity (AL) influences the microbial activity, consequently definitely affects methane production. As shown in Table 2, there was a significantly correlation between these parameters and methane. It found

that pH significantly promotes methane production (P<0.01), while VFA shows a negative correlation to methane production with no significant (P>0.05), AN and AL effect methane production positively without significant (P>0.05). It is well known that buffer system do not form in the first few days, a decrease in pH is observed due to the generation of VFA (significantly negative correlation, P<0.01). However, higher VFA concentration might stimulate more AL due to the buffer system. Therefore, a significant positive correlation (P<0.01) between VFA and AL and a negative correlation between pH and AL (P<0.05) were observed. Furthermore, AN is the only nitrogen nutrient for methanogens during AD process. Along with the AD process, AN was constantly consumed and methanogens activity was improved which accelerated the availability of VFA and pH was increased. As a result, methane production was improved. For R1 and R2, higher carbon content resulted in VFA accumulation and much lag time than other treatments. For R4, complex nutrient

TABLE 2. CORRELATION ANALYSIS BETWEEN METHANE YIELD AND PROCESS PARAMETERS IN THE DIGESTERS

		MY	pH	VFA	AN	AL
MY	Pearson Correlation	1	.678**	-.316	.115	.173
	Sig. (2-tailed)		.000	.064	.509	.320
	N	35	35	35	35	35
pH	Pearson Correlation	.678**	1	-.704**	.343*	-.425*
	Sig. (2-tailed)	.000		.000	.043	.011
	N	35	35	35	35	35
VFA	Pearson Correlation	-.316	-.704**	1	-.257	.455**
	Sig. (2-tailed)	.064	.000		.136	.006
	N	35	35	35	35	35
AN	Pearson Correlation	.115	.343*	-.257	1	-.022
	Sig. (2-tailed)	.509	.043	.136		.899
	N	35	35	35	35	35
AL	Pearson Correlation	.173	-.425*	.455**	-.022	
	Sig. (2-tailed)	.320	.011	.006	.899	1
	N	35	35	35	35	35

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
structure improved the stability of AD system.

C. Kinetics Analysis

Two kinetics results obtained from first-order model and Logistic model were shown as in Table 3. It demonstrates a strong fit between AD process in batch tests and the two models with the R^2 ranges of 0.700-0.945 and 0.942-0.997 respectively.

k is representing the hydrolysis rate and high values represent fast degradation and biogas production. As for k values, high swine manure content in co-digestion system showed higher k values and increasing swine manure content caused an increased degradation and biogas production, compared to the lower swine manure content in AD system when swine manure content higher than R2. In addition, in the initial stage (Fig.1a), high degradation efficiency was accelerated by the increase of swine manure,

thus, k of substrate exhibits a rising trend at increasing contribution of swine manure.

Lag phase duration (λ) is a phenomenon inherent to microbial kinetics and is regarded as a delayed response of the microbial population to the environment change. In the present study, compared with the λ values of each treatment, the shortest lag phase (1.70d) was observed at the R5 and the longest lag phase (13.65d) for R1 was observed while others falling between these two values and demonstrating an decreasing along with the increasing of swine manure content. The variation of λ values presented opposite tendency of k. Hence, it could be speculated that higher swine manure content would have a positive effect on the hydrolysis and acidogenesis of organics, thus enhancing the buffer capacity of AD system and causing shorter lag phases.

R values demonstrate the biological reaction rate and describe methanogenic activity, which showed similar tendency with k with the increase of swine manure content. The R values of all treatments ranged from 6.09–25.41mLg^{-1}VSd^{-1}, and the higher R values were achieved at the higher swine manure content. For example, the R value in R5 was 25.41mLg^{-1}VSd^{-1} followed by R4 of 21.98mLg^{-1}VSd^{-1}, 24.4%, 44.3% and 76% higher respectively compared with R3, R2 and R1. Based on the above analysis, the variation of R with different swine manure content could be due to the difference in substrate component and microbial activity and hydrolysis rates during AD process. P_{max} values exert similar tendency with accumulative biogas production.

TABLE 3. RESULTS OF PARAMETERS OBTAINED FROM FIRST-ORDER MODEL AND LOGISTIC MODEL

Items	First-order model		Logistic model			
	k	R^2	P_{max}	R	λ	R^2
R1	0.0519	0.700	139.47	6.09	13.65	0.942
R2	0.0659	0.717	313.15	14.16	12.70	0.994
R3	0.1358	0.899	350.45	19.22	5.76	0.997
R4	0.1513	0.943	437.30	21.98	2.27	0.997
R5	0.1528	0.945	324.64	25.41	1.70	0.993

In addition, the correlation relationship between kinetic parameters obtained from first order model and Logistic model and VS concentration in the total substrate was analyzed and the results were presented in Fig. 2.

As for k, the values decreased quadraticly with VS (Fig. 2a) and P_{max} values showed similar trend with k (Fig. 2b). As to R, it decreased linearly with VS (Fig. 2c), which indicated that high VS concentration would inhibit the digestion process thus influencing the biogas production. For λ value, it increased exponentially with VS. These relationships indicated that high VS concentration would have a major adverse impact on anaerobic co-digestion performance of swine manure and corn straw and may influence biogas production and alter the stabilization of methanogenesis processes. As shown in Fig. 2, with increased VS concentration in the substrate, the lag phase (λ) was prolonged and the biogas potential (P_{max}), R and k were decreased.
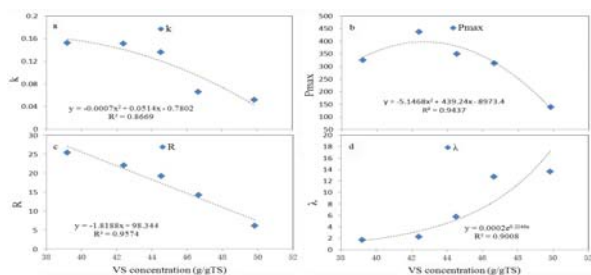
Figure 2 Correlation analysis between VS concentration and parameters obtained from first-order model and Logistic model

IV. CONCLUSIONS

This study studied the process performance and kinetics of mono-digestion and co-digestion of swine manure and corn straw and analyzed the relationship between biogas production and process parameters, effect of swine manure content on kinetic parameters. The results showed that R1 and R2 presented lower organics degradation efficiency, biogas production and hydrolysis rate and longer lag phase duration due to the inhibition of the organics bioconversion cause by rich lignocellulose. Based on the analyzed results obtained in this study, it can be concluded that swine manure content is recommended up 70% in the co-digestion of corn straw causing not only a shorter lag phase duration and AD period, but also higher hydrolysis rate and biogas yield.

ACKNOWLEDRMENTS

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