Modeling of the methane production and pH value during the anaerobic co-digestion of dairy manure and spent mushroom substrate

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HIGHLIGHTS

- ADM1 was used to predict anaerobic co-digestion of DM and SMS under different HRT.
- SMS was divided into inert part as well as biodegradation parts of SHF and RHF.
- The model assesses combined effects of HRT and DM–SMS ratio on the methane and pH.

ARTICLE INFO

Article history:

Received 1 September 2013

Received in revised form 22 January 2014

Accepted 2 February 2014

Available online 8 February 2014

Keywords:

Anaerobic co-digestion

Spent mushroom substrate

Dairy manure

Anaerobic Digestion Model No. 1 (ADM1)

Hydraulic retention time (HRT)

ABSTRACT

A dynamic mathematical model, based on the IWA Anaerobic Digestion Model No. 1 (ADM1), was used to predict the methane production and pH value during anaerobic co-digestion of dairy manure (DM) and spent mushroom substrate (SMS) under different hydraulic retention times (HRT). In this model the degradation of DM was modeled according to classical ADM1, while SMS was divided into inert part as well as biodegradation parts of slowly hydrolysable fraction (SHF) and readily hydrolysable fraction (RHF). The data from lab-scale experiment was used to calibrate and validate this model. The results showed that the model was able to predict reasonably well the steady-state results of methane production and pH value at HRT of 12, 20 and 28 d. The results also indicated that the model suitability to assess the combined effects of HRT and substrate ratio on the methane production and pH value.

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1. Introduction

Mushroom, cultivated on a variety of agro-residues such as straw, saw dust and cotton seed hull, is the biggest solid-state-fermentation industry in China. According to Food and Agriculture Organization [1], there could be more than 8 million tons of spent mushroom substrate (SMS) produced in China each year. SMS is being used as soil amendment because it could improve soil structure [2], provide some nutrients [3] and biodegrade of pollutant [4]. In China, mushroom cultivation and dairy feed are usually kept in one farm due to the favorable economic benefits. The dairy manure (DM) is always used as fertilizer or feedstock for biogas production, while SMS is usually disposed anywhere.

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Anaerobic digestion of organic matter has been considered as a suitable technology for organic wastes treatment and energy production in the form of biogas. Recently, more and more researchers pay attention to anaerobic co-digestion due to the fact that co-digestion could increase biogas production, buffer the capacity, provide a better nutrient balance, manage mixed wastes easily, and improve fertilizer value of digested residues [5,6]. However, anaerobic co-digestion includes a series of interrelated reactions, and experimental assessment the impacts of all involved variables on the process efficiency is time consuming and hardly possible. Therefore, a mathematical model is definitely useful to predict the behavior of anaerobic co-digestion, optimize the production and prevent process failure.

Anaerobic Digestion Model No. 1 (ADM1), developed by the International Water Association (IWA) Task Group for Mathematical Modeling of Anaerobic Digestion Processes [7], has been widely used both for lab- and full-scale anaerobic reactors. ADM1 or its modified version has been implemented in anaerobic co-digestion of various

substrates. For example, the original ADM1 was used to model the thermophilic anaerobic co-digestion of olive mill wastewater with olive mill solid waste [8,9]. The results indicated that ADM1 was able to predict the results of gas flows, methane contents and pH values with different influent concentrations at various hydraulic retention times (HRT). A modified ADM1 was also used to simulate the methane production profiles for anaerobic co-digestion of pig manure and wastewater of glycerine in a batch test [10]. Zaher et al. [11] developed ADM1 to optimize the ratio of different wastes and HRT for maximizing the biogas production in the anaerobic co-digestion of diluted dairy manure and kitchen wastes. Furthermore, ADM1 was used to model the anaerobic co-digestion of municipal solid wastes and activated sludge in a 2000 m³ anaerobic digester, operating at an average HRT of 26.9 d with an average organic loading rate of 1.01 kg TVS/m³ d, at a temperature of 37 °C with an average gas production rate of 0.296 m³/m³ d [12]. The above models were all used the classical disintegration process proposed by ADM1. In order to describe the dynamic behavior exactly, Esposito et al. [13] proposed a modified ADM1 for the anaerobic co-digestion of organic fraction of municipal solid waste and sewage sludge. In their model, the sewage sludge degradation was followed the ADM1 while a surface based kinetics was used to simulate the organic fraction of municipal solid waste disintegration process.

In addition, the formation of volatile fatty acid (VFA) for anaerobic digestion of lignocelluloses followed the characteristics that easily digestible portions had a relatively faster initial fermentation, followed by a slower fermentation, where the more refractory portions are consumed [14,15]. Zhao et al. [16] used ADM1 to model the anaerobic digestion of cattail, a lignocellulosic substrate, and found that the lignocellulosic substrate could be divided into slowly hydrolysable fraction (SHF), readily hydrolysable fraction (RHF) and inert part. However, this approach has not been applied in the model of anaerobic co-digestion. Furthermore, only a limited number of studies have been carried out to evaluate the effects of HRT on methane production and pH value in anaerobic co-digestion, indicating that HRT was an important operating parameter for methane production [11]. However, little information about the model of anaerobic co-digestion of lignocellulosic wastes and solid waste can be found in literatures. So taking into account the advantages of ADM1 implementations in modeling anaerobic co-digestion of more complex lignocellulosic wastes, the major objective of this study was to approach a model with an emphasis on anaerobic hydrolysis of lignocellulosic wastes, and used the modified ADM1 to describe the kinetics of anaerobic co-digestion. The model was then calibrated and validated by the results of biogas production and pH value during the anaerobic co-digestion of DM and SMS. In addition, the optimization of HRT and substrate ratio on biogas production and pH value were also explored.

2. Materials and methods

2.1. Experimental setup

The SMS and DM used in the experiment were obtained from the same dairy farm in Gansu Province of China. Both the substrates were ground in a blender and stored at 4 °C before further use. The characteristics of SMS and DM are shown in Table 1. Anaerobically digested manure slurry was filtered and used as the inoculum, which was collected from an 800 m³ size of biogas plant (Qingdao, China) operating at 32 °C with a 25 d retention time. The total solid (TS) and volatile solid (VS) contents of the slurry are 21.50% and 63.93%TS, respectively. The experiments were carried out in the semi-continuous continuous stirred-tank reactors (CSTR) fabricated from 10 mm polymethylmethacrylate sheets with a temperature-controlled water bath at 35 °C. The

Table 1

Characteristics of dairy manure and spent mushroom substrate.

Substrate	Components	Unit	Value	Reference
Dairy Manure	Soluble monosaccharides	kgCOD/m ³	5	[17]
	Total soluble valerate	kgCOD/m ³	1.21	[18]
	Total soluble butyrate	kgCOD/m ³	0.77	[18]
	Total soluble propionate	kgCOD/m ³	1.3	[18]
	Total soluble acetate	kgCOD/m ³	2.16	[18]
	Particulate carbohydrates	kgCOD/m ³	18	[19]
	Particulate proteins	kgCOD/m ³	31	[17]
	Particulate lipids	kgCOD/m ³	1.7	[17]
	Particulate inert	kgCOD/m ³	35.3	[19]
Spent Mushroom Substrate	Cellulose	%TS	32.0	Calculated
	Hemicellulose	%TS	15.7	Calculated
	Lignin	%TS	12.2	Calculated
	Ash	%TS	13.1	Calculated
	Readily hydrolysable fraction	kgCOD/m ³	101.52	Calculated
	Slowly hydrolysable fraction	kgCOD/m ³	179.35	Calculated
	Inert fraction	kgCOD/m ³	95.13	Calculated

Fig. 1. Schematic of bioconversion pathways in the model.

CSTR, with the working volume of 2.0 L, was connected to a wet-type gas flow meter and gas sampling ports using silicone tubes. At the beginning, all digesters were inoculated and set in batch mode until the start up of biogas production. Then each digester was fed with a TS concentration of 6.0% at the HRT of 12, 20 and 28 d, respectively. The ratio of DM and SMS in the mixed substrates was fixed to 3:1 (m/m).

2.2. Analytical methods

The daily biogas production was recorded by the gas flow meter. Samples from the digester were daily collected for measurement of pH value and biogas components. The biogas components were analyzed by a gas chromatograph (SP 6890, Shandong Lunan Inc., China), equipped with Porapak Q stainless steel column (180 cm long, 3 mm outer diameter) and a thermal conductivity detector. The temperatures of the injector, detector and oven were 120 °C, 150 °C and 50 °C, respectively. Total lipid was determined by Soxhlet extraction with a hexane/isopropanol (60/40) mixture as a solvent. After evaporation of the solvent, the percentage of hexane extractable materials (HEM) in TS was determined by gravimetry [20]. Proteins content was based on the organic nitrogen content. The content of cellulose, hemicellulose, and lignin was estimated according to Goering and Van Soest [21]. The TS, VS, total Kjeldhal nitrogen (TKN), total ammonia nitrogen (TAN), pH and COD were determined according to the standard methods [22]. The equations for the fraction of proteins, lipid and carbohydrates in total COD were as follows.

Table 2
Process matrix for COD conservation in the model.

Component Process	S_{su}	S_{aa}	S_{va}	S_{bu}	S_{pro}	S_{ac}	S_{h2}	S_{c14}	S_{ic}	X_{sms}	X_{dm}	X_{sf}	X_{ch}	X_{pr}	X_{sms}	X_{su}	X_{aa}	X_{c4}	X_{pro}	X_{ac}	X_{h2}	X_i	Rate
1. Disintegration of SMS										-1	f_{sic}	f_{chxc}											$k_{dis,sms}X_{sms}$
2. Disintegration of DM										-1													$k_{dis,dm}X_{dm}$
3. Hydrolysis of SHF											-1	f_{sf}											$k_{hyd,sf} \frac{X_{sf}}{K_{hyd,sf} + X_{sf}} X_{sms}$
4. Hydrolysis of RHF												-1											$k_{hyd,rf} \frac{X_{rf}}{K_{hyd,rf} + X_{rf}} X_{sms}$
5. Hydrolysis of carbohydrates													-1										$k_{hyd,cr}X_{ch}$
6. Hydrolysis of protein														-1									$k_{hyd,pr}X_{pr}$
7. Uptake of sugar																							$k_{m,su} \frac{S_{su}}{K_{m,su} + S_{su}} X_{su}$
8. Uptake of amino acids																							$k_{m,aa} \frac{S_{aa}}{K_{m,aa} + S_{aa}} X_{aa}$
9. Uptake of valerate																							$k_{m,c4} \frac{S_{c4}}{K_{m,c4} + S_{c4}} X_{c4} \frac{1}{1 + S_{su}/S_{su}}$
10. Uptake of butyrate																							$k_{m,c4} \frac{S_{c4}}{K_{m,c4} + S_{c4}} X_{c4} \frac{1}{1 + S_{su}/S_{su}}$
11. Uptake of propionate																							$k_{m,pro} \frac{S_{pro}}{K_{m,pro} + S_{pro}} X_{pro}$
12. Uptake of acetate																							$k_{m,ac} \frac{S_{ac}}{K_{m,ac} + S_{ac}} X_{ac}$
13. Uptake of hydrogen																							$k_{m,h2} \frac{S_{h2}}{K_{m,h2} + S_{h2}} X_{h2}$
14. Decay of X_{sms}																							$k_{dec,sms}X_{sms}$
15. Decay of X_{su}																							$k_{dec,su}X_{su}$
16. Decay of X_{aa}																							$k_{dec,aa}X_{aa}$
17. Decay of X_{c4}																							$k_{dec,c4}X_{c4}$
18. Decay of X_{pro}																							$k_{dec,pro}X_{pro}$
19. Decay of X_{ac}																							$k_{dec,ac}X_{ac}$
20. Decay of X_{h2}																							$k_{dec,h2}X_{h2}$

Proteins (%COD) = 100

$$\times \frac{6.25 \text{ g}_{\text{protein}}/\text{g}_{\text{organicN}} \times (\text{TKN}-\text{TAN}) \times 1.42 \text{ g}_{\text{COD}}/\text{g}_{\text{protein}}}{\text{TCOD}} \quad (1)$$

$$\text{Lipid (\%COD)} = 100 \times \frac{2.86 \text{ g}_{\text{COD}}/\text{g}_{\text{lipid}} \times \text{HEM}}{\text{TCOD}} \quad (2)$$

$$\text{Carbohydrates (\%COD)} = 100 - \text{proteins} - \text{lipid} \quad (3)$$

2.3. Assumption and implementation of the model

In this model, the influent was considered as two separated substrates, DM and SMS. The degradation of DM was based on the proposal of ADM1. The fraction of lipid in DM was slight, so this fraction was ignored for simplification. And SMS was divided into SHF, RHF and inert fraction. The cellulose and hemicellulose, considered together as a single substrate, were defined as SHF. The carbohydrates in cell contents were regarded as RHF and the others in SMS were considered as inert solid fraction. The fractions of both crude proteins and fat in SMS were small and thus were not taken into account. The SHF was hypothetically hydrolyzed into the RHF and the inert solid by SMS-degraders. Then the RHF hydrolyzed and generated the soluble sugars and soluble inert fraction by SMS-degraders. Hence, the biochemical conversion pathway and matrix of the model equations for this model were shown in Fig. 1 and Table 2, respectively. The ADM1 was implemented using Aquasim 2.0 [23] and values for initial conditions of ADM1 were listed in Table 3.

2.4. Sensitivity analysis

The sensitivity analysis was carried out according to the manual of Aquasim 2.0, which was presented in the following equation [23].

$$\delta_{y,p}^{a,r} = p \frac{\partial y}{\partial p} \quad (4)$$

where y is an arbitrary variable calculated by Aquasim 2.0 and p is a model parameter represented by a constant variable or by a real list variable. This function measures the absolute change in y for a 100% change in p .

3. Results and discussion

3.1. Model calibration

Experimental results of anaerobic co-digestion of SMS and DM (m/m = 1:3) at HRT of 20 d were used for model calibration. In order to fit the model to the experimental results, the simulation was undertaken to fit the outputs to the experimental data by changing the most sensitive parameters until finding the best values. Other parameters, with low sensitivity on the model outputs, were applied without any modification. The sensitivity analysis (data not shown) indicated that the hydrolysis rate constant $k_{dis,sms}$ and $k_{dis,dm}$ was the most sensitive for both methane production and pH value. And $k_{hyd,pr}$ and $k_{m,ac}$ were also more sensitivity than the other parameters. This result suggested that hydrolysis was the rate-limiting step in the anaerobic co-digestion of DM and SMS, which was in agreement with the previous reports on the digestion of particulate substrates [26,27]. Based on the results of sensitivity analysis, the changed values that better fit the experimental results are given in Table 4. The experimental and modeled values of daily methane production and pH value after model calibration are shown in Fig. 2. From Fig. 2, the daily methane production was predicted with good accuracy at HRT of 20 d. The model could also describe the pH value very well since the 8th d. At the beginning of the operation, a transient state with strongly nonlinear operating behavior may be dom-

inated in the digester. The essential biochemical processes in ADM1 could probably describe the steady state [28], which caused the simulated results did not show a good fit.

3.2. Model validation

To assess the accuracy and applicability of the calibrated parameters in the anaerobic co-digestion of DM and SMS at different conditions, the model verification was undertaken basing on a comparison between the experimental results and the calibrated model predictions with the previous calibrated parameters. The model was validated with the experimental results at HRT of 12 and 28 d, respectively. As shown in Fig. 3, the simulated daily methane production and pH value were reasonably match the tem-

poral trends of the experimental results at HRT of 12 and 28 d. Such an agreement validated the modeling approach as well as the model parameters used in this study.

3.3. Effect of HRT and substrate ratio on methane production and pH value

The calibrated model was used to investigate the effect of HRT and substrate ratio on methane yield and pH value in the digester with a working volume of 2 L, a TS concentration of 6% and the characteristics of the influent DM and SMS reported in Table 1. Fig. 4 shows the simulations of different ratio of DM and SMS in the range 0.1–5 (m/m), assuming a semi-continuous addition of the co-substrate with a HRT range of 18–28 d. From Fig. 4(A), a gradually in-

Table 3

Values of parameters used in the initial state of ADM1.

Symbol	Description	Unit	Value	Source
$f_{sf,sms}$	Fraction of SHF in substrate	kgCOD/kgCOD	0.477	Calculated
$f_{rf,sms}$	Fraction of RHF in substrate	kgCOD/kgCOD	0.27	Calculated
$f_{i,sms}$	Fraction of inertia in substrate	kgCOD/kgCOD	0.253	Calculated
$f_{ch,dm}$	Fraction of sugar in substrate	kgCOD/kgCOD	0.138	[18]
$f_{pr,dm}$	Fraction of protein in substrate	kgCOD/kgCOD	0.591	[17]
$f_{i,dm}$	Fraction of inertia in substrate	kgCOD/kgCOD	0.271	[18]
$f_{rf,sf}$	Fraction of RHF from SHF hydrolysis	kgCOD/kgCOD	0.7	Calculated
$f_{i,sf}$	Fraction of inertia from SHF hydrolysis	kgCOD/kgCOD	0.3	Calculated
$f_{su,rf}$	Fraction of sugar from RHF hydrolysis	kgCOD/kgCOD	0.95	Calculated
$f_{i,rf}$	Fraction of inertia from RHF hydrolysis	kgCOD/kgCOD	0.05	Calculated
$f_{bu,su}$	Fraction of butyrate from sugar degradation	kgCOD/kgCOD	0.13	Recommend
$f_{pro,su}$	Fraction of propionate from sugar degradation	kgCOD/kgCOD	0.27	Recommend
$f_{ac,su}$	Fraction of acetate from sugar degradation	kgCOD/kgCOD	0.41	Recommend
$f_{h2,su}$	Fraction of hydrogen from sugar degradation	kgCOD/kgCOD	0.19	Recommend
$f_{va,aa}$	Fraction of valerate from amino acid degradation	kgCOD/kgCOD	0.23	Recommend
$f_{bu,aa}$	Fraction of butyrate from amino acid degradation	kgCOD/kgCOD	0.26	Recommend
$f_{pro,aa}$	Fraction of propionate from amino acid degradation	kgCOD/kgCOD	0.05	Recommend
$f_{ac,aa}$	Fraction of acetate from amino acid degradation	kgCOD/kgCOD	0.4	Recommend
$f_{h2,aa}$	Fraction of hydrogen from amino acid degradation	kgCOD/kgCOD	0.06	Recommend
$k_{dis,sms}$	Disintegration rate coefficient of SMS	d ⁻¹	0.4	[16]
$k_{dis,dm}$	Disintegration rate coefficient of DM	d ⁻¹	0.5	Estimated
$k_{hyd,ch}$	Hydrolysis rate constant for carbohydrate	d ⁻¹	10	Recommend
$k_{hyd,pr}$	Hydrolysis rate constant for protein	d ⁻¹	10	Recommend
$k_{hyd,sf}$	Hydrolysis rate constant for SHF	d ⁻¹	2.41	[16]
$k_{hyd,rf}$	Hydrolysis rate constant for RHF	d ⁻¹	9.68	[16]
$k_{dec,x}$	Decay rate of degraders	d ⁻¹	0.02	Recommend
Y_{su}	Sugar degraders yield	kgCOD/kgCOD	0.10	Recommend
Y_{aa}	Amino acid degraders yield	kgCOD/kgCOD	0.08	Recommend
Y_{c4}	C4 degraders yield	kgCOD/kgCOD	0.06	Recommend
Y_{pro}	Propionate degraders yield	kgCOD/kgCOD	0.04	Recommend
Y_{ac}	Acetate degraders yield	kgCOD/kgCOD	0.05	Recommend
Y_{h2}	Hydrogen degraders yield	kgCOD/kgCOD	0.06	Recommend
$k_{m,su}$	Maximum specific uptake rate for sugar	COD/COD·d	30	Recommend
$k_{m,aa}$	Maximum specific uptake rate for amino acid	COD/COD·d	50	Recommend
$k_{m,c4}$	Maximum specific uptake rate for c4	COD/COD·d	20	Recommend
$k_{m,pro}$	Maximum specific uptake rate for propionate	COD/COD·d	13	Recommend
$k_{m,ac}$	Maximum specific uptake rate for acetate	COD/COD·d	8	Recommend
$k_{m,h2}$	Maximum specific uptake rate for hydrogen	COD/COD·d	35	Recommend
$K_{hyd,sf}$	Hydrolysis saturation constant for SHF	kgCOD/m ³	0.05	[16]
$K_{hyd,rf}$	Hydrolysis saturation constant for RHF	kgCOD/m ³	0.05	[16]
$K_{s,su}$	Half-saturation coefficient for sugar	kgCOD/m ³	0.5	Recommend
$K_{s,aa}$	Half-saturation coefficient for amino acid	kgCOD/m ³	0.3	Recommend
$K_{s,va}$	Half-saturation coefficient for valerate	kgCOD/m ³	0.2	Recommend
$K_{s,bu}$	Half-saturation coefficient for butyrate	kgCOD/m ³	0.2	Recommend
$K_{s,pro}$	Half-saturation coefficient for propionate	kgCOD/m ³	0.1	Recommend
$K_{s,ac}$	Half-saturation coefficient for acetate	kgCOD/m ³	0.15	Recommend
$K_{s,h2}$	Half-saturation coefficient for hydrogen	kgCOD/m ³	7×10^{-6}	Recommend
X_{su}	Sugar degraders	kgCOD/m ³	0.05	[24]
X_{aa}	Amino-acid degraders	kgCOD/m ³	0.05	[24]
X_{c4}	Valerate and butyrate degraders	kgCOD/m ³	0.05	[24]
X_{pro}	Propionate degraders	kgCOD/m ³	0.05	[24]
X_{ac}	Acetate degraders	kgCOD/m ³	0.01	[25]
X_{h2}	Hydrogen degraders	kgCOD/m ³	0.01	[25]
X_{sms}	SMS degraders	kgCOD/m ³	0.01	[16]
S_{IC}	Inorganic carbon	kmol/m ³	0.04	[25]
S_{IN}	Inorganic nitrogen	kmol/m ³	0.01	[25]

Table 4

Initial and optimized values for parameters obtained in the model.

Parameter	Description	Unit	Initial value	Optimized value
$k_{dis, dm}$	Disintegration rate coefficient of SMS	d^{-1}	0.4	0.362
$k_{dis, sms}$	Disintegration rate coefficient of DM	d^{-1}	0.5	0.365
$k_{hyd, pr}$	Hydrolysis rate constant for protein	d^{-1}	10	18.23
$k_{m, ac}$	Maximum specific uptake rate for acetate	COD/COD-d	8	16.34

Fig. 2. Simulated values (line) and experimental values (dot) after model calibration: (A) daily methane production and (B) pH values.

crease of the ratio of DM and SMS resulted in the increase of the methane yield. For example, the methane yield at HRT of 22 d increased from 6.46 mL/g VS to 64.41 mL/g VS with the ratio of DM and SMS increasing from 0.1 to 5. The methane yield decreased with the increase of HRT when the ratio of DM and SMS was higher than 1.9. For the ratio of DM and SMS lower than 1.9, the methane yield at HRT of 20 d was higher than that of the other HRT. From Fig. 4(B), the pH decrease sharply with the ratio of DM and SMS increasing, completely contrary with the trend of methane yield. The pH value increased slightly with the increasing of HRT when the ratio of DM and SMS was higher than 0.5. The highest pH value (7.18) for HRT of 20 d appeared at the lowest ratio of DM and SMS, which was lower than that of the other HRT. It was meaning that the pH value for HRT of 20 d was changed most slightly, ranging from 6.96 to 7.18.

Previous researches suggested that HRT is an important parameter in the operation of anaerobic reactors. Biogas yield generally improves with the increasing of HRT. However, the biogas produced per unit of the reactor volume tends to decrease at higher HRT. On

Fig. 3. Simulated values (line) and experimental values (dot) for model identification: (A) HRT = 12 d and (B) HRT = 28 d.

the other hand, short HRT faces the risk of the methanogen population washout and hence may affect the stability of the anaerobic digestion. Zaher et al. [11] optimized the HRT of anaerobic co-digestion of diluted manure and kitchen waste by ADM1. The HRT of 50 d was the optimal HRT using a pre-hydrolysis step of 2 L and a digester volume of 20 L. However, Chelliapan et al. [29] indicated that each anaerobic system should specific investigate the HRT due to the fact that the HRT depended on many factors, such as reactor configuration, feed characteristics, organic loading rate and method for evaluating performance, etc. Hence, the model of this study gives a powerful tool to optimize the HRT and improve the process efficiency of anaerobic co-digestion of lignocellulosic wastes and solid waste.

4. Conclusions

The modified Anaerobic Digestion Model No. 1 (ADM1) was used to simulate the methane production and pH value during

Fig. 4. Combined effect of HRT and ratio of SMS and DM on (A) methane yield and (B) pH value.

the anaerobic co-digestion of DM and SMS. The results showed that it was reasonable to fractioned lignocellulosic substrate into SHF, RHF and inert part. The simulated results of methane production and pH value show an acceptable fit under different HRT. The sensitivity analysis indicated that the hydrolysis rate constant $k_{dis,sms}$ and $k_{dis,dm}$ was most sensitive for both daily methane production and pH value. This model is useful to better understand the behavior of anaerobic co-digestion of solid waste and lignocellulosic wastes.

Acknowledgments

This work is supported by the National Science Foundation of China (No. 51108443) and the Key Research Program of the Chinese Academy of Sciences (Grant No. KGZD-EW-304). The authors acknowledge the support of Taishan Scholar Program of Shandong Province and Youth Innovation Promotion Association, CAS.

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