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A study of an optimal condition for solid-state anaerobic digestion biogas production from broiler litter

Ninlawan Chaitanoo[1*], Janyawat Vuthijumnonk[1], Duangporn sisai[2], Anan Naila[2]

[1]Research and Development Unit for Agricultural Materials and Bio-Energy Properties, Rajamangala University of Technology Lanna, Chiang Mai

[2]Department of Mechanical Engineering, Rajamangala University of Technology Lanna, Chiang Mai

*Corresponding author: Tel: +66-6-1958-9781, E-mail: ninlawan_ch@hotmail.co.th

Abstract

The purpose of this research is to determine the best conditions for producing biogas from bedding material utilizing batch solid-state anaerobic digestion (SS-AD), which will then be employed in a new waste management technique in broiler farms. Total solid (TS) concentration (20% and 23%), fermentation method (continual mixing versus non-mixing), and $CaCO_3$-pretreatment prior SS-AD were all investigated. The most suitable experimental setting for methane production and methane content were 20% TS with $CaCO_3$-pretreatment with continual mixing (test 1) at 77.1±2.7 NmL/gVSadded and 73.2±2.2%, respectively. The optimal condition generated 2.5 times more methane than the condition without $CaCO_3$-pretreatment and continuous mixing (test 3), and therefore 8.9 times more than the condition with a greater percentage of total solid (23% TS with $CaCO_3$-pretreatment and continual mixing in test 5). In this study, continual mixing showed inconclusive result on biogas output which require further study. Alkaline pretreatment is suitable for broiler litter since it can weaken lignocellulose structure. In order to increase total solid concentration in SS-AD system, further studies on pretreatment methods are required.

Keywords: Biomethane Potential, Broiler litter, and Solid-state anaerobic digestion

1 Introduction

Thailand's primary industries are agriculture and livestock. The country is rated fifth in terms of poultry meat and processed poultry exports. (USDA, 2022). As a result, poultry farm business has increased. Data obtained in 2021 revealed a total of 3 million broilers from 32,000 poultry farms throughout Thailand (DLD, 2021). Therefore, broiler litter (chicken manure and bedding materials (rice husk)) is an unavoidable occurrence (Figure 1). A survey conducted in a broiler farm in Northern Thailand discovered that broiler litter produced ranged from 4,000 to 10,000 kg/house depending on farm size or an average at 1 kg waste/bird harvested which was similar to the previous finding (Coufal et. al., 2006) which produced significant issues for the environment and farm owners. Composting and incinerating are being utilized to alleviate this problem. However, they have no economic benefit and may cause additional issues such as air pollution (Janczak et. al., 2019)

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Figure 1 Characteristics of broiler farm and broiler litter in Yakhampor Farm, Mueang, Lamphun, Thailand

For a number of reasons, eliminating waste from chicken farms through biogas production is of interest. Not only would the farm waste be abolished, but the production process would also produce high-quality biogas and compost (AL-Masalha et. al., 2017 and Bayrakdar et. al., 2017). The technique known as solid-state anaerobic digestion (SS-AD), which operates with a high total solids (TS) content (>15%), is appropriate for the lignocellulose-heavy waste from poultry farms. The system has the benefit of requiring minimal space and water (Ge et. al., 2016). To our knowledge, a study on high nitrogen content-lignocellulose material in biogas production using SS-AD system is rare. Moreover, a pretreatment stage is one of the most important steps in utilizing cellulose and hemicellulose-containing substrates, therefore a study for an optimal pretreatment condition and process is of interest.

Broiler litter consists of rice husk (56.8%), a lignocellulose material, therefore, it is challenging for anaerobic bacteria in the biogas production system to breakdown cellulose and hemicellulose (Amin et. al., 2017). Pre-treatment of the raw materials is therefore required to weaken the structure and facilitate microorganisms to ingest it. Additionally, solid overload in the SS-AD system could lead to a decrease of biogas production efficiency. As a result, continual mixing is required to facilitate mass movement, which in turn promotes better digestion and the creation of biogas.

In line with prior research, the goal of this study is to investigate how parameters such as pre-treatment with $CaCO_3$, continuous mixing, and percentage of total solid effect biogas production from broiler litter utilizing a batch SS-AD system. The findings of this study could be used to better management of broiler litter as resources while simultaneously adding value to a broiler farm by-product.

2 Materials and Methods

2.1 Feedstock and inoculum

Broiler litter used in this study was collected from Yakhampor Farm, Mueang Lamphun, Lamphun, Thailand. Physical and chemical properties of broiler litter are presented in Table 1.

Inoculum was obtained from a mesophilic-channeled digester of Energy Research and Development Institute-Nakornping, Chiang Mai University (ERDI-CMU). The feedstock and the inoculum were refrigerated at 4°C prior to the start of the experiment.

2.2 Alkaline Pretreatment

Broiler litter was thoroughly mixed with 1% (w/v) calcium carbonate ($CaCO_3$) solution at 90 and 120 ml for 20%TS and 23%TS, respectively. A quantity of $CaCO_3$ solution used was calculated based on broiler litter weight. The mixtures were left at ambient temperature for 24 hours to ensure a decomposition of lignocellulose in bedding material.

Table 1 Physical and chemical properties of broiler litter samples. (The presented data was mean ± SD of three broiler litter samples).

Parameters	Broiler litter
Total solids (TS), %	83.8±0.4
Volatile solids (VS), %	80.6±0.2
Rice husk, %db	56.8
Carbon to Nitrogen (C/N) ratio	18.7
Total organic carbon (TOC), %db	34.9 ± 0.7
Total nitrogen (TN), %db	1.9 ± 0.1
Total Kjeldahl nitrogen (TKN), mg/kg	13,908.0 ± 2,115.7
Ammonia nitrogen (NH_3-N), mg/kg	2,475.0 ± 176.0
Cellulose, %db	25.0 ± 0.8
Hemicellulose, %db	10.6 ± 0.4
Lignin, %db	19.5 ± 1.0

2.3 Batch solid-state anaerobic digestion test

The experiments were conducted in 1000 ml airtight bottles. Deionized water (300 mL) was added to the mixtures. A feedstock to inoculum (F/I) ratio was maintained at 6.0 (based on VS) in all experimental group. Volatile solid and Volatile Suspended Solids (VSS) in the inoculum were 37,337.04±2,407 mg/L and 14,935±804 mg/L, respectively. All experimental containers were flushed with nitrogen gas for 5 min to ensure an anaerobic environment prior tight closure then placed in a temperature-controlled room at 30 ± 2°C. All experiments were carried out in triplicates. The produced biogas was measured daily using a water displacement set as shown in Figure 2.

The biogas compositions were determined by relative gas volume over 300 ml collected in a cylinder of a water displacement set using a portable gas analyzer (Geotech Biogas500, UK). The amount of biogas production was reported based on a standard temperature and pressure (STP) condition. Biogas product was monitored until end of the reaction where the amount of daily biogas produced was less than 1% of the cumulative biogas production (Filer et. al., 2019). When the effect of continual mixing was studied, the experimental bottles were horizontally shaken at 100 rpm. The shaking cycle was set at one hour on and one hour off.

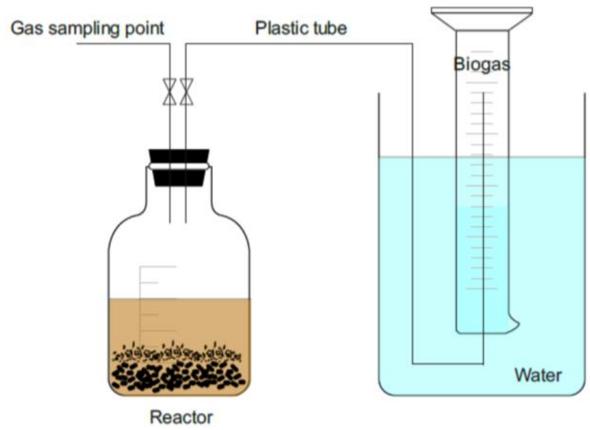

Figure 2 Schematic diagram of series laboratory of a batch SS-AD

2.4 Analytical methods

The broiler litter and inoculum were analyzed for parameters including TS, VS, VSS, total organic carbon (TOC), total nitrogen (TN), and ammonia nitrogen (NH_3-N) according to the standard methods (APHA/AWWA/WEF, 2012). Chemical compositions, including cellulose, hemicellulose, and lignin, of the samples were determined according to the detergent methods (Van Soest, 1967) at Animal Nutrition Laboratory, Department of Animal and Aquatic Sciences, Faculty of Agricultural, Chiang Mai University, Thailand. The pH value of each sample was collected both before and after AD process by pH meter (Mettler-Toledo, China)

2.5 Statistical analysis

All experiments and analyses were conducted in triplicates. The statistical differences were determined by a one-way analysis of variance (ANOVA) followed by a Tukey's test at a 95% confidence level. The values reported are mean values with standard deviation and the resulting statistical analyses with difference/same are presented with superscript letters.

Batch SS-AD test was adapted from Biochemical Methane Potential (BMP) test. It was tested for a substrate anaerobic biodegradability which presented as Methane yield according to equation 1. Moreover, the yield can also be compared and confirmed with the system's organic digestion efficacy (Equation 2) (Kafle et. al., 2015)

Methane Yield Accumulation

$$= \frac{\textbf{Methane Accumulation}}{\textbf{Volatile solid of feedstock}} \;;\; \frac{NmL}{gVS_{added}} \qquad (1)$$

Where; Methane accumulation is accumulated biogas times methane content in each collected biogas sample.

$$\%VS_{removal} = \frac{VS_{added} - VS_{final}}{VS_{added}} \times 100\% \qquad (2)$$

Kinetic modeling is widely used in predicting methane yields, establishing key parameters for reactor design and optimizing the performance of AD process. The modified Gompertz model (Eq. (3)) was used to develop kinetic model in this study (Wang et. al., 2020).

$$P_{CH_4}(t) = P_{max} \times exp\left\{-exp\left[\frac{R_m \times e}{P_{max}} \times (\lambda - t) + 1\right]\right\} \qquad (3)$$

Where; $P_{CH4}(t)$ is the cumulative methane production at a certain incubation time (t) (NmL/gVS$_{added}$), P_{max} is the methane production potential (NmL/gVS$_{added}$), R_m is the maximum methane production rate (NmL/gVS$_{added}$), λ is the lag phase duration (days), and e is the exp (1) = 2.71828. The parameters (P_{max}, R_m, and λ) were estimated by non-linear regression using Solver function in Microsoft Excel version 16.0 (Microsoft, Inc.). The daily methane increase rate over time was determined to find the point time of maximum daily methane increase rate (t_{max}) (Lemmer et. al., 2017).

3 Results and Discussion

Methane production potential of broiler litter using batch SS-AD experiment was determined within 60 consecutive days experimental period. Three parameters which were percentage of total solid, pre-treatment with $CaCO_3$ and continual mixing, were examined in this study.

From table 2, the findings revealed that the highest biogas and methane production was found in test 1 (20%TS, $CaCO_3$-pretreatment, continual mixing) at 105.4±3.6 and 77.1±2.7 NmL/gVS$_{added}$, respectively. The gas content correlated well with organic degradation value (VS removal) which was found at 23.9%. Continual mixing showed no significant influence on biogas production in all tests except test 1 and test 2. $CaCO_3$-pretreatment produced a significant effect on all tests with 20%TS (test 1-4). The pre-treatment tests gave higher biogas yield thus the methane contents in the pre-treated groups were approximately 10% higher compared to their non-treated counterparts. These accounted for 175.4% and 88.4% improvements with respect to their individual controls (Table 2). An increment demonstrated greater methanogenesis stability in the system with $CaCO_3$-pretreatment. $CaCO_3$ assisted in destroying lignin structure and hemi-cellulose degradation in the litter resulted in small single molecules leading to a suitable environment for anaerobic microorganisms (Kim et. al., 2016).

However, $CaCO_3$-pretreatment for AD indicated an opposing trend in all experimental groups when higher total solid (23%) was used. Broiler litter is a high-ammonia lignocellulose material (13,908.0±2,115.7 mg/kg TKN), and when more than 20% of the organic material was used in the system, it resulted in increased ammonium toxicity and pH that is unsuitable for anaerobic microorganisms (Vikrant et. al., 2015; Kim et. al., 2016). The pHs of untreated and $CaCO_3$-treated groups were 8.4±0.3 and 9.8±0.2, respectively, indicating that the untreated tests, tests 7 and 8, produced more biogas than the treated tests, tests 5 and 6. Despite higher biogas generation, the methane percentage among these four experimental groups was not statistically different, owing to the fact that the fermentation conditions were not suitable for anaerobic microorganisms, as previously stated.

Moreover, the kinetic model indicated accurate prediction of the methane generation from broiler litter using the modified Gompertz model with the coefficient of determination (R^2) ranging from 0.934 to 0.998 (Table 3). Figure 3 represents cumulative methane production from the batch SS-AD of broiler litter material each test set and their predicted cumulative methane values from the modified Gompertz model. Table 3 shows estimated kinetic parameters derived from the modified Gompertz model for batch SS-AD at various conditions. The improvements of microbial kinetic parameters including methane production potential (P_{max}), maximum methane production rate (R_m), the lag phase duration (λ) and time of maximum daily methane increase rate (t_{max}) clearly suggested that the use of SS-AD as a promising broiler farm waste management technology. As a result, all of these factors might be used as starting points for constructing a large-scale biogas production system.

Table 2 Gas yield and organic matter digestion efficiency

Test	TS content (%)	Pretreatment with $CaCO_3$	Fermentation method	Biogas Yield (NmL/gVS$_{added}$)	CH_4 (%)	Methane Yield (NmL/gVS$_{added}$)	VS removal (%)
1	20	pretreat	shake	105.4±3.6^{a,a,a}	73.2±2.2	77.1±2.7 ^{a,a,a}	23.9
2			non-shake	77.4±4.0^{b,a,a}	73.8±2.3	58.4±2.2 ^{b,a,a}	20.5
3		non-pretreat	shake	46.4±12.1^{a,b,b}	61.9±11.1	28.0±13.1^{a,b,a}	18.0
4			non-shake	49.7±11.5^{a,b,b}	66.2±9.1	31.0±10.8^{a,b,a}	16.2
5	23	pretreat	shake	37.3±3.2^{a,b,b}	25.1±2.3	8.4±2.1^{a,b,b}	11.1
6			non-shake	35.6±5.6^{a,b,b}	23.4±5.3	8.4±2.9^{a,b,b}	6.8
7		non-pretreat	shake	92.2±9.7^{a,a,a}	22.5±7.4	20.8±8.8^{a,a,a}	20.9
8			non-shake	101.6±7.8^{a,a,a}	25.9±9.1	26.4±10.9^{a,b,a}	22.6

Note: The superscript letters correlate statistical analyses of the biogas and methane yields where the first letter compared the effect of mixing, the second letter compared the effect of $CaCO_3$-pretreatment and the third letter compared the effect of total solid content

All analyses are based on n (sample size) = 3.

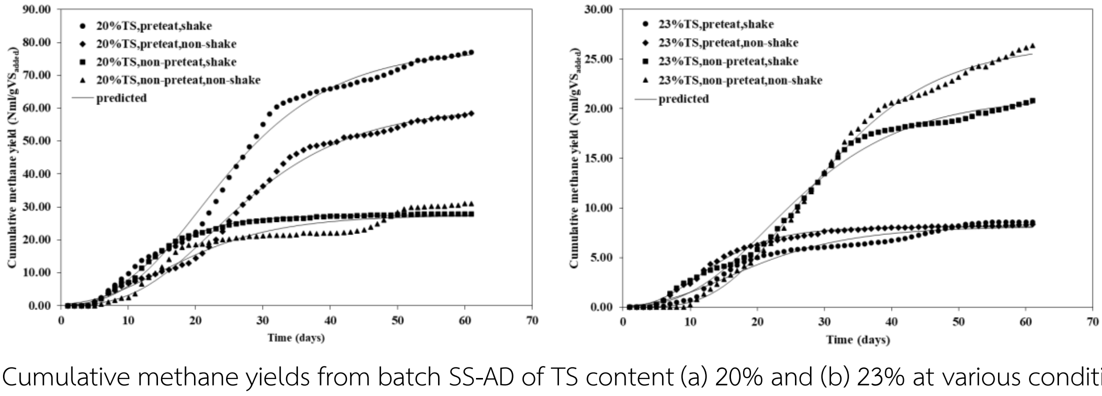

Figure 3 Cumulative methane yields from batch SS-AD of TS content (a) 20% and (b) 23% at various conditions and methane yield prediction from modified Gompertz model.

Table 3 Summary of estimated kinetic parameters derived from the modified Gompertz model for batch SS-AD at various conditions.

Test	R_m (NmL/gVS$_{added}$/day)	λ (day)	t_{max} (day)	P_{max} (NmL/gVS$_{added}$)		R^2
				Predict	Experiment	
1	2.6	8.3	30.2	78.2	77.1	0.991
2	1.9	9.8	34.1	60.5	58.3	0.992
3	1.7	4.3	17.1	27.5	28.0	0.998
4	1.0	3.8	17.5	27.6	31.0	0.934
5	0.3	4.0	17.6	8.2	8.6	0.966
6	0.5	3.5	14.3	8.1	8.4	0.996
7	0.7	8.7	33.5	21.2	21.0	0.990
8	0.9	13.1	36.2	26.7	26.4	0.997

Note: P_{max} is the methane production potential, R_m is the maximum methane production rate, λ is the lag-phase time, and t_{max} is time of maximum daily methane increase rate.

4 Conclusions

Nowadays, production of alternative energy from natural resources is significant. Even though challenges in the production of biogas from broiler litter, a high lignocellulose and ammonium agricultural waste, as raw material, are common, this study have revealed a possibility of using the material in a biogas production system using SS-AD. The technique would benefit broiler farm entrepreneurs in terms of waste management and sustainable energy production.

It was determined that the best experimental condition for methane production was 20% TS with $CaCO_3$-pretreatment and continual mixing. The biogas yield and methane yield were 105.4±3.6 and 77.1±2.7 NmL/gVS$_{added}$, respectively. In this investigation, continual mixing showed inconclusive results and further investigation may be required.

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