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OPTIMIZATION OF BIOGAS PRODUCTION FROM CO-DIGESTION OF WASTE ACTIVATED SLUDGE AND MODIFIED TAPIOCA STARCH SLUDGE

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ABSTRACT: Waste activated sludge (WAS) obtained from a modified tapioca starch wastewater treatment plant has potential for use as feedstock for biogas production. However, it has a very low C/N ratio of 4.3, leading to a low methane yield. Co-digestion of WAS with starch sludge (SS) can potentially provide balanced nutrients and can enhance biogas production. The results from a biochemical methane potential (BMP) test showed that using WAS as a single feed stock provided a low biogas production at 80 L/kg TVS_{added}. In co-digestion, the addition of 30% and 50% SS increase the biogas yields by as much as 150 and 209 L/kg TVS_{added}, respectively. However, the addition of 70% SS reduces the biogas yield to as low as 117 L/kg TVS_{added}. The result also showed that the optimum condition for biogas production is achieved at 2% TVS_{added} of mixed WAS and SS (1:1) with a desired C/N ratio of 23.56. The increase in % TVS_{added} of the mixed feedstock resulted in a reduction of the biogas yield. The co-digestion of WAS and SS (1:1) also improved the rate of digestion and enhanced the system stability. TVS removal efficiency of the mixed WAS and SS was 41.44% higher than the efficiency when using WAS alone. Moreover, the result of continuous stirred tank reactor (CSTR) confirmed that the co-digestion ratio of WAS:SS (1:1) can enhance biogas yield and methane yield at 301 and 142 L/kg TVS_{added}, respectively at retention time of 11 days.

Keywords: Waste activated sludge, Starch sludge, Co-digestion, Biogas yield

1. INTRODUCTION

Modified tapioca starch is a value-added product. Thailand is the world's largest exporter of modified tapioca starch, it exported approximately 1.01 million tons with a value of 649 million dollars in 2017 [1]. The modified starch is produced from native tapioca starch that has been changed in its properties to provide the characteristics needed for specific uses. Two major sources of solid waste generation from the production process commonly consist of starch sludge (SS) from a primary sedimentation tank and excess waste activated sludge (WAS) from a secondary sedimentation tank. The reaction and drying starch processes are expressed as mostly a loss of SS. Generally, the tapioca starch loss rate discharges as large quantities, with wastewater comprising approximately 1 percent of raw starch [2]. SS was dewatered and sold at a low price of approximately 73-97 dollars per ton [3] to produce animal feeds that were not economically valuable.

Due to the large quantities and nutrients of WAS, many researchers have studied the biogas production potential from various sources of WAS. For example, Wang et al.[4] reported that the methane production from WAS of an oil refinery plant was 228 L/kg COD_{added}. Karlsson et al.[5] found that the WAS of six Swedish pulp and paper plants could produce methane in the range of 100-200 L/kg TVS_{added}, and Bolzonella et al. [6] found that WAS from four Italian wastewater treatment plants could produce methane between 500-900 L/kg TVS_{added}. WAS is a substrate with high potential for biogas generation. However, WAS has a very low C/N ratio that typically ranges from 6 to 9, thereby possibly limiting the efficiency of biogas production [7]. An excessive amount of nitrogen in the WAS can lead to an overabundance in ammonia accumulation and result in a subsequent inhibition to methanogenesis. [8].

The co-digestion with a rich carbon substrate may be an effective option for improving nutrient balances and biogas production. According to the co-digestion of 95% sewage sludge with 5% glycerol that is rich in carbon content, the biogas yield may be increased by almost 67.4% compared to the digestion of sewage sludge alone [9]. Moreover, co-digestions may offer several advantages such as an improved buffer capacity, an increased biodegradation of feedstock as well as dilutions of toxic substances, which will lead to increases in biogas yields [10].

Thus, it is more appropriate to use SS as a co-substrate with WAS. Meanwhile, this approach helps to tackle the limitation of the pH drop at the beginning of single SS digestion. Because WAS, consisting of 95 percent of bacterial cells [11], has a slower digestion rate than SS consisting of mostly carbohydrates.

This research aims to study the biogas production potential, system performance and TVS removal efficiency of different co-digestion ratios between WAS and SS using the biochemical methane potential method (BMP) for experimentation and the response surface methodology (RSM) for analysis.

2. MATERIALS AND METHODS

2.1 Feedstock and inoculum preparation

The The WAS and SS were sampled from a primary sedimentation tank and a secondary sedimentation tank of an activated sludge wastewater treatment process of the modified tapioca starch factory in Rayong province, Thailand. The feedstocks were analysed for moisture, pH, total solids (TS), total volatile solids (TVS) and the carbon to nitrogen (C/N) ratio. Then, the WAS and SS were stored at 4°C before the experiment.

The feedstock was prepared at different ratios of WAS and SS. The %TVS of each substrate in the feedstock were calculated using the following Eq. (1):

$$TVS_1W_1 = TVS_2W_2 \quad (1)$$

Where:
TVS_1 = TVS of the feed substrate (% by wet weight);
W_1 = Weight of substrate (g);
TVS_2 = TVS of feedstock (% by wet weight); and
W_2 = Weight of feedstock (g).

The seed sludge from the up flow anaerobic sludge blanket (UASB) tank of the beverage factory in Pathum Thani province, Thailand was used as an inoculum in this experiment. The TVS of inoculum was prepared at 2.5%.

2.2 Experimental design

The co-digestion ratios of WAS with SS were established using Design Expert Software version 10 based on a central composite design (CCD) with an alpha value of 1.414. The TVS of each substrate was specified within the range of 0-2% in which the codes and scales of the variables are shown in Table 1. This experiment consisted of 13 runs, and each run was conducted in triplicate using BMP method.

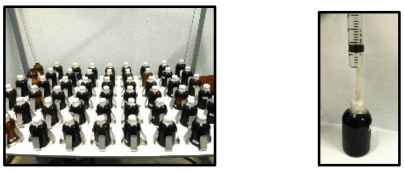
The experimental design of the variables was 13 runs with the biogas yield as the response value (Table 3). The proportions of each substrate were varied at 0, 30, 50, 70 and 100 percent while the C/N ratios were in the range from 6.06 to 56.44, which covered the optimum C/N ratio ranging between 20 and 30.

Table 1 The codes and scales of variables

Independent variable	Unit	Coded level				
		-1.414	-1	0	+1	+1.414
WAS concentrations	% TVS	0	0	1	2	2.414
SS concentrations	% TVS	0	0	1	2	2.414

2.3 Biochemical methane potential (BMP) test

A biochemical methane potential (BMP) test was applied to assess the biogas production efficiency of the AD system based on the earlier suggestion of Owen et al. [12]. The ratio of feedstock to active inoculum of 60:40 (by volume) was added to 125 ml serum bottles with working volumes of 80 ml. The pH was initially adjusted using a digital pH meter in the range of 6.8-7.2 by adding sodium bicarbonate ($NaHCO_3$). The headspace of the prepared serum bottles was purged with nitrogen gas before being sealed with airtight rubber stoppers and covered by an aluminium cap. Then, they were incubated on a rotary shaker at a room temperature of 25-30°C with a speed of 140 rpm for 45 days. The volume of biogas was monitored daily using a syringe. The produced biogas was measured by reading the scale on the syringe (Fig. 1).



(A) (B)

Fig. 1 BMP test (A) BMP bottle incubated on the shaker and (B) biogas measurement

2.3 Continuous stirred tank reactor (CSTR) test

The optimum co-digestion ratio of WAS:SS obtained from the BMP test was used for further batch CSTR test. The ratio of inoculum to feedstock was 40:60 by volume. The CSTR working volume was 5 L and mixed with a speed of 70 rpm. The entire pH of the mixture between 6.8 and 7.2 by adding sodium bicarbonate ($NaHCO_3$). The biogas volume was measured by a gas counter based on a water-gas displacement system connected to a sensor counter (Fig. 2). The CH_4 content in biogas was analysed by GC (Model Shimadzu GC-2014, Shimadzu Corp., Japan).

Fig.2 CSTR reactor and gas counter

2.4 Calculations and statistical analysis

The biogas yield (L/kg TVS_{added}) after 45 days of incubation was calculated using the following Eq. (2):

$$\text{Biogas yield} = BV/TVS_{added} \quad (2)$$

Where:
BV = Cumulative biogas volume (L); and
TVS_{added} = Weight of TVS of feedstock added to the bottle (kg).

An R squared (R^2) analysis was applied to evaluate the RSM model's appropriateness. The optimum co-digestion ratios can be obtained by considering a three-dimensional RSM plot of biogas yields, the system performance and the TVS removal efficiency.

The pH, volatile fatty acids (VFA), alkalinity (ALK) and TVS of the effluent were analysed. All analytical methods were performed by following the American Public Health Association (2017) standard method for the examination of water and wastewater.

3. RESULTS AND DISCUSSION

3.1 The characteristics of the feedstock

The characteristics of the feedstock and inoculum are presented in Table 2. The WAS collected from the secondary sedimentation tank contained a low total solids content at 7.56% by wet weight. Since the major composition is an aerobic bacterial cell, it has a high TVS/TS ratio at 0.78 that was suitable for an anaerobic digestion (AD) system. The pH of WAS was 6.5, and the C/N ratio was 4.3, which can lead to a low biogas yield. Therefore, the digestion of WAS alone may not suitable for biogas production. Thus, such waste may have a substantial advantage on the nutrient balance when co-digested with SS.

The SS from the primary sedimentation tank consisted of the residual starch in the acidic slurry, at a low pH of 4.48. Generally, tapioca starch contains a large amount of amylopectin at up to 83%, which is easy to digest [13]. Additionally, the high C/N ratio of 242 may lead to VFA accumulation and an important drop in pH. Both its pH property and VFA accumulation have a similar adverse effect on the system pH drop, which consequently inhibits methanogenic activity. Concern about this limitation was an important reason for why the AD of SS alone was not appropriate. The useful application of SS was co-substrate with WAS that may help to solve the prior problem by balancing the nutrients and enhancing the biogas yield higher than using WAS alone.

Table 2 Characteristics of co-digestion feedstock and inoculum

Parameter	WAS	SS	Inoculum
Moisture (%)	92.44±1.01	39.09±0.62	93.05±0.14
pH	6.50±0.03	4.48±0.01	-
TS (% by wet weight)	7.56±1.01	61.00±0.45	6.95±0.14
TVS (% by wet weight)	5.92±0.04	31.26±0.03	6.73±0.03
C/N ratio	4.3	242	8.51
TVS/TS	0.78	0.51	0.97

Note: n = 3

3.2 BMP test

3.2.1 Effect of the initial feedstock concentration on the digestion time

Fig. 3 showed the cumulative biogas yield from the WAS and SS feedstocks at various concentrations of TVS_{added}. The digestion time was affected by source of feedstock for both WAS and SS (as a single digestion or co-digestion system). When using WAS as a single substrate, the biogas yield was highest at a reaction time of 38 days, while when using SS as a single substrate the reaction time was 45 days at 1% TVS. Various co-digestions of WAS and SS may reduce the digestion time to less than 30 days. The co-digestion of WAS:SS at a ratio of 1:1 and 2% TVS_{added} achieved the shortest digestion time of 25 days. At this condition, the biogas yield was 209 L/kg TVS_{added}. We emphasize that SS has high potential for co-digestion with WAS.

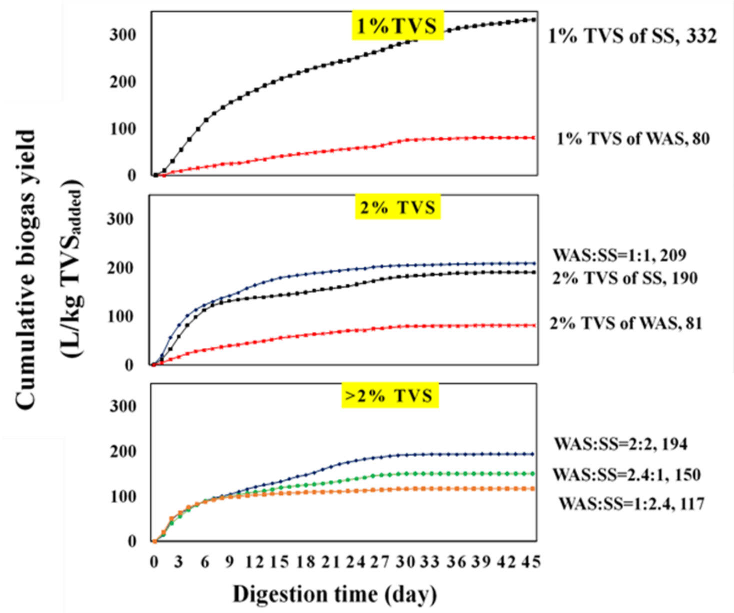


Fig. 3 The cumulative biogas yields from different feedstock and TVS concentrations

3.2.2 Effect of the co-digestion ratio on biogas yields

A three-dimensional plot (Fig. 4) was developed by relating the WAS and SS concentrations to the biogas yields by using RSM analysis. The determination coefficient (R^2) was 0.9561, which indicated that the model is highly capable of explaining up to 95.61% of the experimental condition. The result showed that the major factors impacting biogas yield were the ratios of WAS and SS and the initial concentrations of TVS_{added}. The biogas yield increase with the SS ratio is shown in Fig. 4. At 1% TVS_{added}, the highest predicted biogas yield may be achieved at 301 L/kg TVS_{added} by using SS alone, while the lowest predicted biogas yield occurred at 80 L/kg TVS_{added} by using WAS alone (Table 3). Many studies reviewed that the methane yield from WAS varied in the range of 100-900 L/kg TVS_{added} depending on the source of feedstock, such as: 100-200 L/kg TVS_{added} from pulp and paper plants [5], 500-900 L/kg TVS_{added} from a municipal wastewater treatment plant in Italy [6], 183-200 L/kg TVS_{added} from a municipal wastewater treatment plant in China [14] and 190 L/kg TVS_{added} a municipal wastewater treatment plant in France [15].

The co-digestion of WAS: SS at ratio 1:1 is able to achieve the highest predicted biogas yield at 210 L/kg TVS_{added}. The co-digestion of WAS and SS (1:1) enhanced the biogas yield by 159% compared to the WAS alone (2:0). Meanwhile, the biogas yield from using SS as a single feedstock at 2%TVS_{added} (0:2) was 10% lower than using a mixed feedstock (1:1). Thus, the co-digestion of the WAS:SS at a ratio of 1:1 is suitable for usage at 2% TVS_{added}.

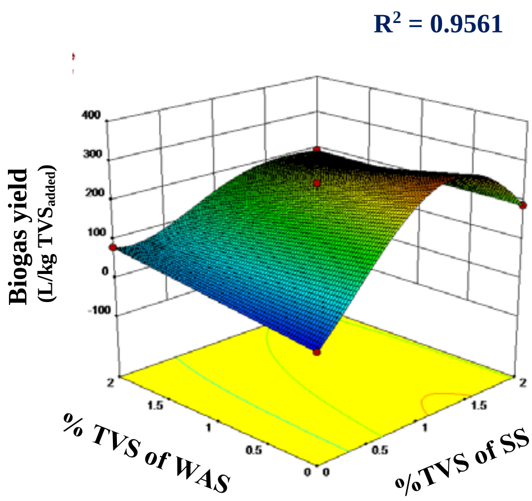


Fig. 4 The RSM pot of the influences of WAS and SS concentrations on the predicted biogas yields

3.2.3 Effect of the C/N ratio on biogas yields

Table 3 showed the C/N ratios of biogas feedstock and biogas yields in each CCD experimental run. The result showed that the C/N ratio of the initial feedstock influenced the biogas yield. The optimum C/N ratio was in the range of 20-30 [16]. The results showed that the optimum biogas yield depended on the ratio of WAS and SS that resulted in a suitable C/N ratio for methanogens. The addition of the SS to WAS feedstock resulted in the increase of the C/N ratio, which may thus increase the biogas yield. For example, the mixed feedstock of WAS and SS at a ratio of 1:1 and the C/N ratio of 23.56 and 29.30 (2%

and 4% TVS, respectively) may achieve a biogas yield as high as 209 and 194 L/kg TVS_{added}, respectively. However, the addition of SS to WAS at a higher ratio than 1:2.4 would reduce the biogas yield since the C/N ratio was 43.57, which exceeds the optimum range.

In the case of using SS alone at 1% TVS_{added}, the highest biogas yield was achieved 332 L/kg TVS_{added}. This is because during the preparation of feedstock, seed was added to the SS feedstock (40:60) before the BMP test. Thus, the C/N ratio of using SS alone was 35.2. Meanwhile, the C/N ratio of 2% TVS of SS alone was 56.44.

Table 3 C/N ratio of the biogas feedstock and biogas yield in each CCD experimental run.

Run	TVS concentrations (% by wet weight)		Proportion (%)		C/N ratio	Biogas yield (L/kg TVS_{added})	
	WAS	SS	WAS	SS		Actual value	Predicted value
1	0	0	0	0	8.51	0	0
2	1	0	100	0	6.79	80±0.42	80
3	2	0	100	0	6.06	81±16.62	81
4	2.41	1	70	30	16.86	150±5.56	119.43
5-9	1	1	50	50	23.56	209±25.55	210.42
10	2	2	50	50	29.30	194±8.42	193.92
11	1	2.41	30	70	43.57	117±3.23	116.8
12	0	1	0	100	35.21	332±3.57	301.41
13	0	2	0	100	56.44	190±13.08	189.88

3.2.4 Performance of AD

Fig. 5C showed the pH and the ratios of VFA and ALK of each experimental run after 45 days of operation. At the beginning of the experiment, all reactors were adjusted so that the pH of the reactor was in range in 6.8-7.2 with $NaHCO_3$. The reactors using WAS alone and the co-digestion of the WAS:SS ratio were 2.4:1 and 1:1 (run 2-9), while the final pH values were in the range of 7.01-7.27 (Fig. 5B). VFA/ALK ratios of these reactors were in the range of 0.09-0.23. These values may be an indicator that the reactors were working within the optimum interval for methane formation, which should be lower than 0.4 [17]. This may be because WAS had the low concentrations of readily available organic carbon [14]. Typically, it is not quickly degraded to VFA by the hydrolysis, acidogenesis and acetogenesis stages. Therefore, the VFA produced in the co-digestion ratios of 2.4:1 and 1:1 can be converted into biogas through the methanogenesis stage with a suitable conversion rate that resulted in no excess VFA accumulation occurring. This result was confirmed by the neutral pH value and the lower VFA/ALK ratio in this digestion system.

For reactors using SS alone and the co-digestion of the WAS:SS ratio of 1:2.41 (run 11-13), the pH values were in the range of 4.16-6.86, while VFA/ALK ratios were in the range of 2.55-15.8. The co-digestion that added the high ratio of SS had the low biogas yields. The SS is too much starch content, causing the speed of the VFA production in the early stage to be faster than the speed of VFA consumption by methanogenic bacteria, which resulted in a high VFA accumulation. This dynamic may inhibit the methanogenesis process [18]. These results are in line with those obtained by Cuzin et al. [19], who reported that the AD of cassava peels consists of a major biodegradable starch that usually results in excess acid production, which affects the pH drop and is highly toxic to methanogens. Anunputtikul and Rodtong [20] showed that there was the decrease in pH in the initial fermentation of rich starch cassava tubers.

Meanwhile, the co-digestion of WAS:SS at the ratio of 1:1 may give the highest biogas yield compared with other co-digestion ratios. Additionally, it can enhance the performance and system stability with a lower VFA/ALK ratio of 0.23 and a neutral pH of 7.01 compared to the digestion of SS alone. Thus, selecting the optimum co-digestion ratio should also consider the biogas yield, the system stability and the TVS removal efficiency.

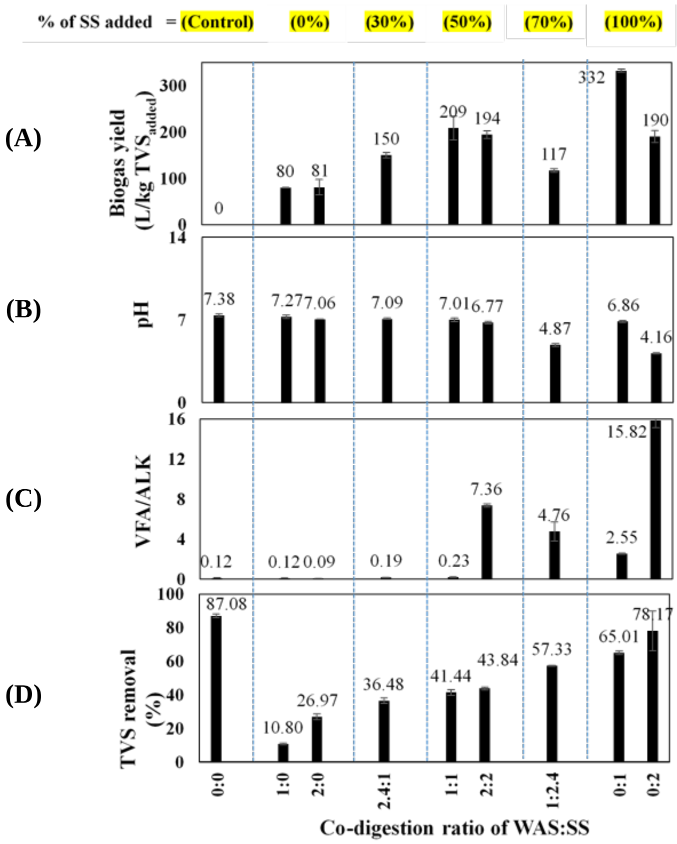


Fig. 5 The performance and system stability in the co-digestion of WAS:SS
(A) Biogas yield, (B) pH, (C) VFA/ALK ratio and (D) TVS removal

3.2.5 TVS removal efficiency

Increasing the ratios of the added SS (at the co-digestion of WAS:SS ratios of 1:0, 1:1 and 1:2.4) resulted in significant increases in the TVS removal efficiency of 10.80%, 41.44% and 57.33%, respectively (Fig. 5D). Since WAS consists of a combination of microorganisms, approximately 95% of bacteria and 5 percent of higher organisms [11], it is more difficult to digest than SS [14]. Thus, increasing the TVS removal efficiencies depends mostly on the SS, which is easy to digest. Specifically, at the co-digestion ratio of 1:1 (WAS:SS), the TVS removal efficiency was 41.44% higher than it was when using WAS alone, which achieved an efficiency of 10.80%. Thus, this result verified that the co-digestion ratio of 1:1 may be a promising and practical option for the use of WAS and SS as feedstock in the anaerobic digestion process due to improved TVS removal efficiency, high biogas yield and proper system stability.

3.3 CSTR test

Fig.6 showed that the biogas yield at the co-digestion of WAS and SS (1:1) in the CSTR was 301 L/kg TVS_{added} at retention time of 11 days. Since the CSTR digestion was carried out with complete mixing, so the biogas yield was higher than those obtained from BMP test. Moreover the reaction time was also faster than BMP test. Considering the methane (CH_4) yield and content equal to 142 L/kg TVS_{added} and 47%, respectively. The final pH and VFA/Alk ratio was equal to 7.04 and 0.36, respectively. It was emphasis that the system has good performance.

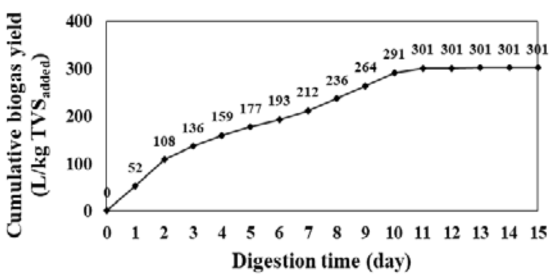


Fig. 6 The biogas yield in the CSTR

4. CONCLUSIONS

WAS and SS may be used as feedstocks for biogas generation. The optimum condition for biogas production was the co-digestion of WAS:SS at the ratio 1:1 at 2% TVS_{added}. At this condition, biogas yields may be achieved at 209 L/kg TVS_{added}. Result from CSTR batch experiment of such condition showed that biogas yield and methane yield were high as 301 and 142 L/kg TVS_{added}, respectively. After operation for 11 days, the pH and VFA/ALK ratio was7.04 and 0.36, respectively. The biogas obtained in this anaerobic digestion can be used as an alternative fuel in a hot air generator for the starch drying process. Moreover, there are cost-saving for WAS sent to landfills and environmental advantages in reducing the greenhouse gas emissions from landfills.

5. ACKNOWLEDGMENTS

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