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Research Article

Solid-state anaerobic digestion of sweet corn waste: The effect of mixing and recirculation interval

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Abstract. The mixing and sludge recirculation interval is one of the key successes of the solid-state anaerobic digestion process, a promising technology for converting high-solid agro-industrial wastes to renewable energy. This study employed a pilot-scale completely stirred tank reactor to examine biogas production from sweet corn waste, including corn cobs, husks, and seeds. The reactor was operated as solid-state anaerobic digestion at an ambient temperature. The mixing and recirculating intervals were set to non-mixing and mixing for 10 minutes every 3, 6, and 12 hours. The initial total solid of the feedstock was 25%, while the hydraulic retention time was 30 days. The results showed that during the mixing and recirculation every three hours, the highest chemical oxygen demand, total solid, and volatile solid (VS) removal efficiencies were 85.42%, 62.92%, and 64.59%, respectively. The ratio between volatile fatty acid and alkalinity ranged between 0.20 and 0.30 without any sign of system failure. The highest specific methane yield of 766 L/kg VS_{added} was obtained in the experiment with mixing and recirculating intervals every 3 hours. It was found that the modified Gompertz model could effectively fit the methane yields with an R^2 of 0.9667. The modeled methane production potential and the maximum methane production rate were 867.40 NL/kg VS_{added} and 132.01 NL/kg VS_{added}-d, respectively. Additionally, the levelized cost of the biogas produced from the solid-state anaerobic digestion of the sweet corn waste was calculated to be 0.61 USD/kg. The findings of this study can serve as a guide for the design and operation of the SS-AD system, which aims to transform various types of lignocellulosic waste into environmentally friendly energy.

Keywords: biogas, methane, solid-state anaerobic digestion, lignocellulosic biomass, agricultural residue

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1. Introduction

Presently, northern Thailand faces severe air pollution caused by agricultural waste (AW) from farmers and forest fires. Over time, the air quality of this area has deteriorated to a level that could harm people by causing respiratory and cardiovascular diseases. Thus, this area has become one of the world's most polluted cities (Hantrakool *et al.*, 2024). Agricultural residues are typically abundant and promising second-generation feedstock for producing a broad spectrum of biofuels. In Thailand, more than 170 million tons of this biomass are generated annually (Jusakulvijit *et al.,* 2021). In addition, corn was one of Thailand's significant crops, taking over more than 30% of the national upland farmlands in 2017 (Supasri *et al.*, 2020). As a result, the search for an appropriate AW management method has attracted the interest of many researchers. Anaerobic digestion (AD), a multi-stage biochemical process that generates energy-rich biogas without oxygen, is a promising technology for mitigating AW issues. The generated biogas could be used as an environmentally friendly biofuel to generate electricity and heat. Excess sludge obtained from an anaerobic digester can be used as an organic fertilizer and soil condiment with inactivated pathogens (Sindibu *et al.*, 2018). Therefore, the utilization of AD for converting organic waste into biogas has the potential to address environmental issues effectively. It could facilitate the development of environmentally friendly cities and communities. Furthermore, the utilization of biogas derived from AD as a renewable energy source has the potential to alleviate the impacts of climate change by substituting fossil fuels (Piadeh *et al.*, 2024; Matin and Hadiyanto, 2018). Solid-state anaerobic digestion (SS-AD) with an initial total solid of the substrate > 20% is appropriate for treating AW, which typically has a total solid (TS) content of 20–40% (Saipa *et al.*, 2024). This strategy requires a small digester, little dilution water, and low operating and maintenance costs (Pan-In & Sukasem, 2017). In addition, co-digestion of AW, a carbon-rich substrate, and a high-nutrient substrate (such as animal manure) might increase biogas yield (Chen *et al.*, 2015; Hussien *et al.*, 2020). Appropriate mixing patterns and intensity are one of the key successes affecting the performance of the SS-AD. It could enhance the interaction between microorganisms and substrate while minimizing the negative impact of toxicity (Wang *et al.*, 2020). Similarly, sludge recirculation is also a crucial operation of SS-AD microorganisms in the digester (Pezzolla *et al.*, 2017). Many researchers have presented the effect of mixing and recirculation intervals on the performance of SS-AD of many organic wastes in lab-scale experiments. For example, the appropriate and sufficient mixing could enhance the biogas production during SS-AD of corn straw slurry (Liu *et al.*, 2019), cow manure (Kaparaju *et al.*, 2008), and corn stover (Tian *et al.*, 2015). Wang *et al.* (2020) also presented the significant effect of mixing mode on the group of the involved microorganisms during the SS-AD of animal manure, cucumber residue, and corn stover. The inappropriate recirculation interval could

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negatively affect the methane yield of the AD of various organic substrates, i.e., animal manure (Degueurce *et al*., 2016), food waste (Ratanatamskul & Saleart, 2016), palm oil mill effluent (chsan et al, 2014)and dairy manure (Rico *et al*., 2011). Typically, the mixing during AD was either by mechanical mixing using an impeller in a completed stirred tank reactor or slurry recirculation in a leach bed reactor (Singh *et al*., 2019). However, to the best of the authors' knowledge, there is a limitation of the research using the pilot-scale digester integrating mechanical mixing and sludge recirculation for mixing the digester contents and controlling the amount of microorganisms in the digester. In addition, most of the previous research was conducted in the temperature-controlled condition. However, this research was performed at an ambient temperature, which is the actual condition of sweet corn processing industries in tropical countries like Thailand. Additionally, the levelized cost of the produced biogas was also calculated. Thus, this study's technical and economic information could be used to design and operate the appropriate full-scale SS-AD system treating lignocellulosic biomasses. The objective of this study is to investigate the effect of the mixing and sludge recirculating rate on the performance of a pilot-scale solid-state anaerobic digester for AW management.

2. Materials and Methods

2.1 Feedstock and inoculum

The substrate in this study, as presented in Fig. 1., was sweet corn waste (SCW), the mixture of corn cobs (CC), corn husks (CH), and corn seeds (CS) in a ratio of 54:44:2 by weight. The SCW was collected from Sun Sweet Co., Ltd., Chiang Mai, Thailand, and shredded with an agricultural cutting machine to approximately 5-10 mm in length. Afterward, it was pre-acidification at ambient temperature for 72 hours to enhance the hydrolysis and the acidogenesis stage (Tian *et al*., 2015). The liquid and solid phases of the pretreatment have been analyzed for pH, Total Solid (TS), volatile solids (VS), and the carbon-to-nitrogen (C/N) ratio following the standard methods (APHA, 2005; Eaton & Franson, 2005). The inoculum was the mixture of anaerobic sludge (AS) withdrawn from the anaerobic filter digester fed with wastewater from Sun Sweet Public Co., Ltd., and the sludge from the anaerobic digester of pig manure (PM) from the small-scale pig farm in the ratio of 1:2 by volume (Hussien *et al*., 2020). Later, the pH, moisture content, TS, VS, and C/N ratio of the inoculum were determined (Chanathaworn et al., 2018; Pan-In & Sukasem, 2017).

2.2 Solid-state anaerobic digester

As Figure 2 shows, the solid-state anaerobic digester used in this study consists of three main parts: the main reactor, the mixing and recirculating sludge system, and the biogas storage tank.

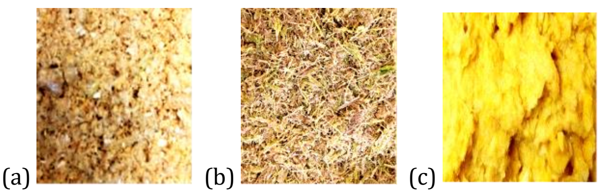
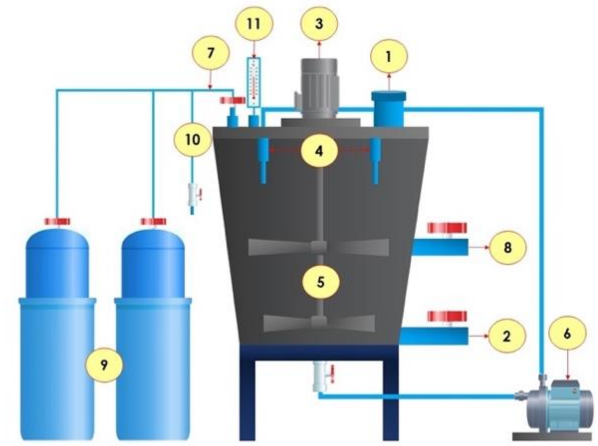


Fig. 1 Sweet corn waste (a) corn cobs (b) corn husks and (c) corn seeds



(1) Inlet port (2) Outlet port (3) Motor
(4) Spray (5) Mixer (6) Pump
(7) Gas outlet (8) Effluent sampling port
(9) Biogas storage tank (10) Biogas sampling port
(11) Thermometer

Fig. 2 The 1000-L solid-state anaerobic digester

2.2.1 The main reactor

The main reactor, made of fiberglass, was designed in a cylindrical shape with a round bottom. The total and effective volumes of the reactor were 1,000 and 600 L, respectively.

2.2.2 The mixing and recirculating sludge system

2.2.2.1 The mixing system

The SS-AD's effectiveness strongly depends on the mixing system with respect to the high solid contents in the digester. The appropriate mixing interval could enhance the performance of SS-AD (Sekine *et al*., 2022). The mixing system in this study was determined using the velocity gradient (G) of the stirring impeller in Equation 1. The mixing system includes a motor to ensure homogeneity with a four-blade axial-flow impeller (45° pitched blade impeller) operated at 60 rpm to prevent the accumulation of organic acids in the digester, which may result in reactor failure.

$$G = (P/\mu V)^{1/2} \qquad (1)$$

Where G is the Velocity gradient, s^{-1}; P is Power imparted to the feedstock; V is the volume of the feedstock in the reactor, m^3; and μ is the Absolute viscosity of the feedstock, N-s/m^2. Therefore, the motor power capacity should be more than 1,900 watts or 2.5 hp. However, the motor must have more power than the calculated power to be a safety factor. Thus, the installed motor could serve feedstock loading with a more than 20% TS content.

2.2.2.2 The sludge recirculating system

The purpose of sludge recirculation is to maintain the concentration of the microflora in the digester, which could strongly affect SS-AD performance (Ratanatamskul & Saleart, 2016). The sludge recirculating system in this study was designed using a pump performance curve (Lowara, 2015). Thus, the present study used a centrifugal pump operated at 100

L/min (Model. COF305/03) with the pump's efficiency, power, and head of 40%, 0.3 kW, and 6.8 meters, respectively. Additionally, the recirculating sludge from the bottom was sprayed on the top of the reactor to maintain effective microorganisms.

2.2.3 The biogas storage tank

The biogas storage tanks comprised two high-density polyethylene tanks with a total volume of 500 L. The main reactor still spaced for the biogas holder was 400 L. Generally, the space for the biogas holder should be more than 20% of the total volume and the biogas production collected with the water replacement method. The method is a widely used principle for measuring the amount of biogas production (Meegoda *et al.*, 2018).

2.3 Experimental procedure

The SS-AD was operated at an ambient temperature. The mixing and recirculating intervals were set to non-mixing and mixing for 10 minutes every 3, 6, and 12 hours based on information from other published manuscripts (Ratanatamskul & Saleart, 2016; Sekine *et al.,* 2022). The working period of the system was between 6.00 am and 6.00 pm to simulate the actual working hours of the factory. The substrate and inoculum (SI ratio) ratio was 1:1 (g Volatile Solid (VS) Substrate/g VS Inoculum) to shorten the start-up period, and the initial TS of the feedstock was 25%. The operating parameters (i.e., pH, Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), TS, VS, Volatile Fatty Acid (VFA), and Alkalinity) were analyzed initially and during the experiment following the Standard Methods (APHA, 2005). The ratio between Total Organic Carbon (TOC) and TKN was used to represent the C/N ratio of the substrate. TOC of the substrate was analyzed following the method presented by Walkley and Black (1934). The produced biogas was quantified by the water replacement method, and the biogas composition was analyzed using a portable gas check (Biogas 5000 Portable Analyser, Geotech, USA). The experiment was performed for 30 days.

3. Results and Discussion

3.1 Characteristics of the Feedstock and the Inoculum

Table 1 presents the characteristics of SCW and inoculum. The SCW contained high VS, representing organic matter that was 26.94% of the total weight. Further, the VS/TS ratios of SCW and inoculum, indicators for evaluating biodigestibility, were high at 0.87 and 0.83, respectively. Typically, a substrate with a VS/TS ratio of over 0.80 is considered a potential anaerobic digestion feedstock (Hassan *et al.*, 2017). The C/N ratio, which indicates a proper amount of macronutrients to facilitate microbial growth, is one of the important operating parameters for AD. Table 1 shows that the C/N ratios of SCW and inoculum were 32.55 and 9.13, respectively, which falls in the recommended range of 9-35 for the AD process (Dixon *et al.*, 2019).

Table 1
Characteristics of the feedstock

Properties	Sweet corn waste	Inoculum
pH	3.76	7.72
Moisture Content	69.11%	90.23%
Total Solids	308.91 g/kg	97.68 g/L
Volatile Solids	269.42 g/kg	81.43 g/L
VS/TS Ratio	0.87	0.83
C/N Ratio	32.55	9.13

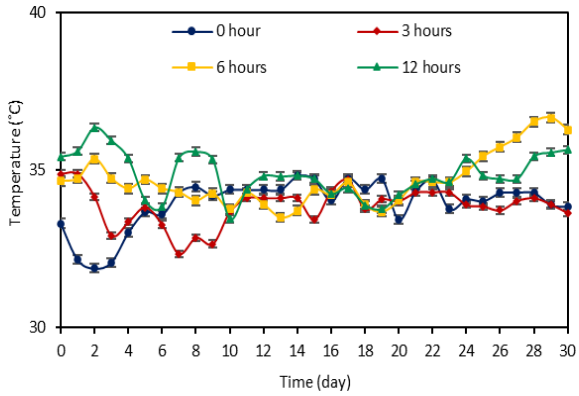


Fig. 3 Temperature of the digester contents of solid-state anaerobic digestion system

3.2 Temperature in the solid-state anaerobic digestion system

Most studies have been performed at constant operational temperatures at laboratory scales. However, some authors have published results that attest to the impact of differing temperatures between 20 and 40 ˚C (Artsupho *et al.*, 2016; Duan *et al.*, 2018). There are two main temperature regimes for anaerobic digestion: mesophilic (35 ˚C) and thermophilic (55 ˚C). As mesophilic digestion operates at a lower temperature, it leads to slower reaction and less biogas yield; however, mesophilic digesters remain attractive because of their lower heater energy costs compared to thermophilic digesters (Azman *et al.*, 2019; Guo *et al.*, 2018). Figure 3 shows that the average temperatures of the digester contents during the experimental period of 30 days in the condition of mixing and recirculating intervals, which were set to non-mixing and mixing every 3, 6, and 12 hours, were 32.9, 32.9, 33.8, and 34.1 ˚C, respectively. These temperatures were appropriate for mesophilic bacteria, which prefer temperatures between 25 and 40 ˚C for growth (Hassan *et al.*, 2016; Patinvoh *et al.*, 2017). The ambient temperature in Chiang Mai province, Thailand, varies between 25 and 40 ˚C. Thus, this does not necessitate any controlling device for maintaining the temperature (Sawatdeenarunat *et al.*, 2023).

3.3 pH in the solid-state anaerobic digestion system

The process of AD for generating methane was susceptible to acidic conditions, and their growth stopped in the said conditions. For proper growth of anaerobic sludge optimum, pH was 6.5-7.5 (Kakuk *et al.*, 2017; Majd *et al.*, 2017). The average pH values over 30 days of SS-AD in the condition of mixing and recirculating intervals, which were set to non-mixing and mixing every 3, 6, and 12 hours, were 6.97, 7.02, 7.09, and 7.27, respectively, as presented in Fig. 4. The pH value decreased on day 3. This phenomenon could result from the feedstock's highly biodegradable portion getting hydrolyzed and acidogenesis during the initial setup period, as well as the adaptation of methanogen (Meegoda *et al.*, 2018). The pH value increased from day four and became stable during the experimental period. It was indicated that the pH value highly

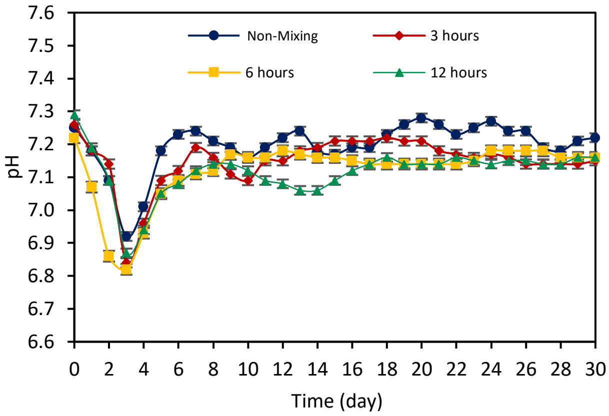


Fig. 4 pH in the solid-state anaerobic digestion system

affects the performance of the anaerobic digestion process and the maximum amount of biogas production (Saipa *et al.*, 2024).

3.4 Volatile fatty acid (VFA) and alkalinity of solid-state anaerobic digestion system

The concentration of VFA and Alkalinity is an important factor to control during AD. A drop in the pH value through VFA accumulation during the acidogenesis stage can inhibit the VFA utilization of methanogens. Figure 5 presents the VFA and Alkalinity concentrations in the SS-AD during an average period of 30 days. The results indicate that the average VFA concentration during 30 days in the condition of mixing and recirculating intervals, which were set to non-mixing and mixing every 3, 6, and 12 hours, were 2,416.02, 1,838.27, 1,911.43, and 2,282.38 mg/L as CH_3COOH, respectively. The VFA concentration sharply increased until day three and remained stable during the experimental period. Generally, the VFA concentration in anaerobic digestion should not exceed 2,000 mg/L as CH_3COOH (Huang *et al.*, 2016). The average alkalinity concentration over 30 days was 5,761.44, 5,779.83, 5,250.30, and 5,510.52 mg/L as $CaCO_3$. The alkalinity inside the reactor was stable during the experimental period, and the system's high alkalinity might have helped maintain its performance (Rodriguez-Campos *et al.*, 2012; Yesil *et al.*, 2020). The optimum alkalinity should be between 1,000 and 5,000 mg/L as $CaCO_3$ for anaerobic digestion (Chanathaworn *et al.*, 2018).

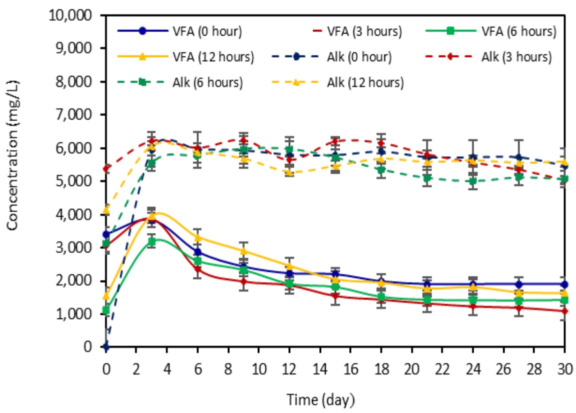


Fig. 5 Concentrations of volatile fatty acid and alkalinity during solid-state anaerobic digestion

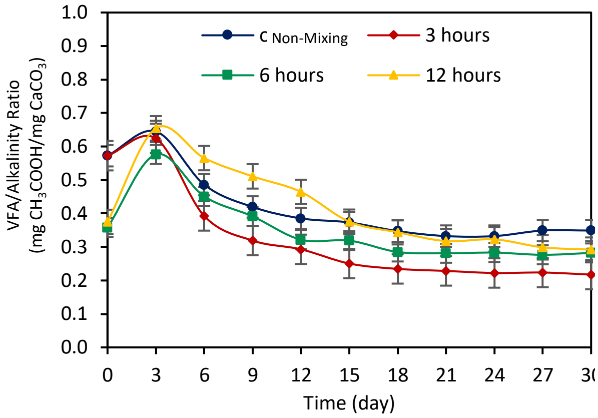


Fig. 6 VFA/Alkalinity ratio of solid-state anaerobic digestion system

The average VFA/Alkalinity ratio was found to be 0.42, 0.33, 0.35, and 0.41, respectively. Moreover, the increase of VFA on day three resulted in the VFA/Alkalinity ratio rising to 0.65, 0.62, 0.58, and 0.65, respectively, which is more than the recommended VFA/Alkalinity ratio of 0.4 (Demirbas *et al.*, 2016; Kuruti *et al.*, 2017). Further, the VFA/Alkalinity ratio was maintained between 0.20 and 0.30, lower than the recommended value of 0.4. The reactor showed no failure signs during the 30 days, as presented in Figure 6.

3.5 Removal efficiency

Figure 7 presents the critical operating parameters such as COD, TS, and VS removal efficiencies, which could indicate the SS-AD reactor performance. Typically, the VS and COD represented organic compounds derived from the solid and liquid components of the substrate, respectively.

The highest COD, TS, and VS removal efficiencies were obtained at the mixing and recirculating intervals every three hours at 85.42%, 62.92%, and 64.59%, respectively. The biogas production from AW, with appropriate mixing and recirculating intervals, may cause the highest removal efficiencies of over 70% (Ratanatamskul & Saleart, 2016). Indeed, the SS-AD with mixing and recirculation sludge could enhance organic waste and solid reduction efficiencies better than the digester without mixing and recirculation because of the more contact between the substrate and the involved microorganisms (Pezzolla *et al.*, 2017).

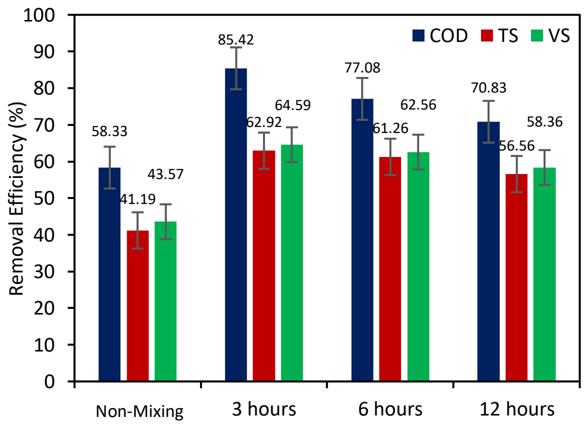


Fig. 7 Removal Efficiency of solid-state anaerobic digestion system

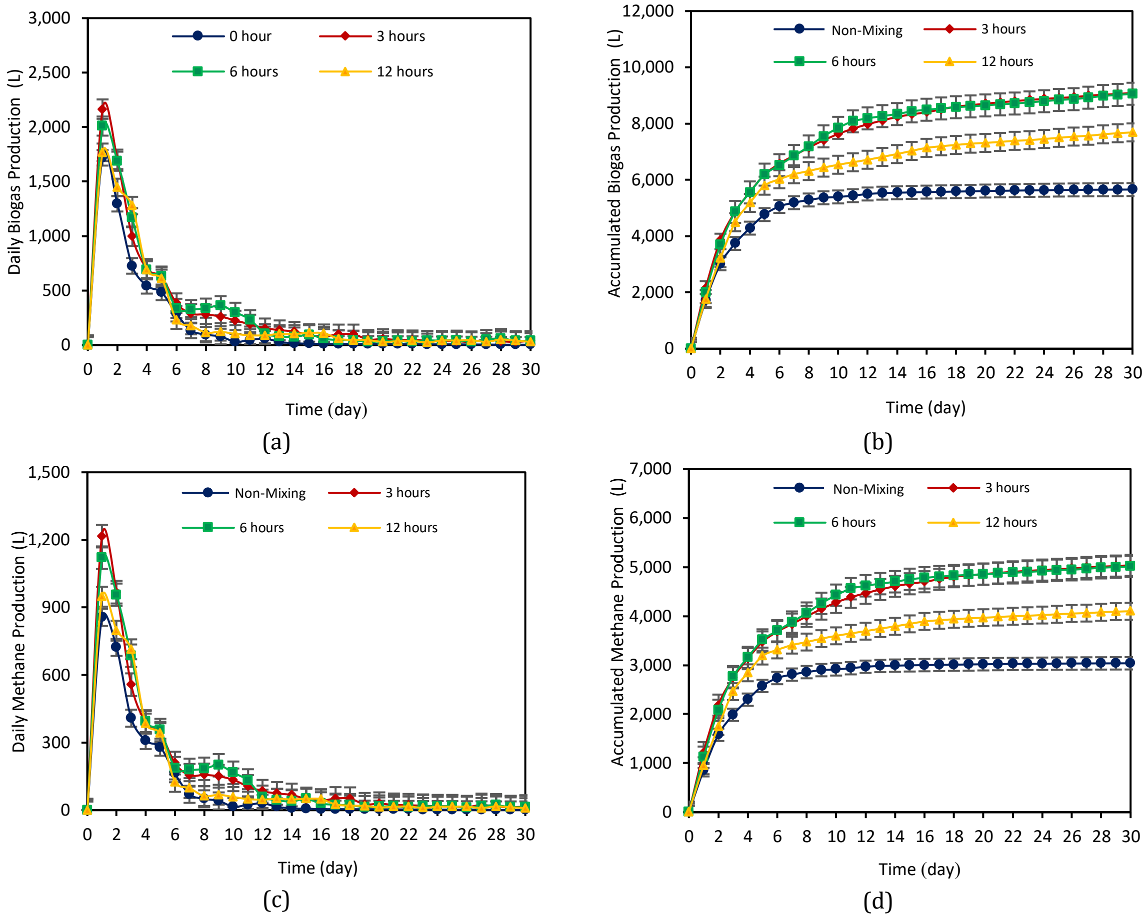


Fig. 8 Biogas and methane volume in the solid-state anaerobic digestion system

3.6 Daily and accumulated gas production

Figure 8 presents the daily and accumulated methane production. Figure 8a shows the daily biogas production of SS-AD in the condition of mixing and recirculating intervals set to non-mixing and mixing every 3, 6, and 12 hours of 188.6, 303.1, 302.0, and 256.3 L/day, respectively. In the same trend, the maximum daily biogas productions on day two were 1,718.4, 2,165.1, 2,009.3, and 1,768.5 L/day, respectively. Significant daily biogas production peak values of most treatments appeared in the early stage of digestion (i.e., the first 13 days). The microorganisms started and kept growing from the first day after seeding. Most treatments reached their peak values in two to four days when the process went into hydrolytic acidification. After 13 days of fermentation, daily biogas production of all treatments was significantly dropped to less than 40 L/day.

The accumulation of biogas volume of SS-AD in the condition of mixing and recirculating intervals, which were set to non-mixing and mixing every 3, 6, and 12 hours, were 5,657.5, 9,094.3, 9,060.9 and 7,688.1 L, respectively, as presented in Fig. 8(b). Additionally, the methane percentage was determined, and the results demonstrated that the average methane percentages during the experimental period were 43.2%, 50.9%, 49.8%, and 44.9%, respectively. Moreover, the advantage was that this SS-AD produced a similar methane concentration (more than 50%) from corn waste to other researchers (Chanathaworn *et al*., 2018; Pérez-Rodríguez *et al*., 2017). The average methane productions of SS-AD in mixing and recirculating intervals, which were set to non-mixing and mixing every 3, 6, and 12 hours, were 94.9, 157.5, 156.8, and 128.5 L/day, respectively. In the same trend, the maximum daily biogas production on day two was 855.8, 1,216.8, 1,121.2, and 947.9 L/day, respectively, as presented in Figure 8c. As Figure 8d shows, the accumulation methane volumes in the condition of mixing and recirculating intervals, which were set to non-mixing and mixing every 3, 6, and 12 hours, were 3,037.4, 5,037.4, 5,012.8, and 4,099.5 L, respectively.

3.7 Methane yield

As presented in Figure 9, the average methane yield in the condition of mixing and recirculating intervals, which was set to non-mixing and mixing every 3, 6, and 12 hours, were 0.415, 0.766, 0.692, and 0.580 $LCH_4/g\ VS_{added}$, respectively. The maximum methane yield was observed for the same conditions on day one of 3.797, 5.235, 4.837, and 4.192 L/gVS_{added}. Notably, a significant rise in methane yield was observed at the beginning stage (i.e., days one to four), gradually decreasing from day six onward and reaching the minimum methane yield and percentage at the end of the experiment. Reducing the supply of substrate might have had a significant impact on this phenomenon (Pezzolla *et al*., 2017; Wang *et al*., 2018).

The results from this study presented a higher maximum methane yield and average methane content (0.766 L CH_4/g VS_{added} and 50.9%) compared to the previous study that used the lignocellulosic biomass as the substrate i.e., the mixture of 36% corn stover, 24% dairy manure, and 40% tomato residues in a 250-m^3 SS-AD as digester, and mixing by leachate recirculation

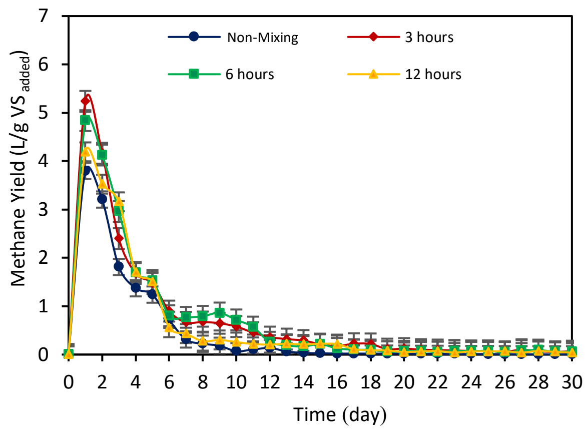


Fig. 9 Methane yield of solid-state anaerobic digestion system

rates at 400 m^3/h (0.379 L CH_4/g VS_{added}, 40%) (Li *et al.*, 2018). Additionally, the methane production of 0.141 L CH_4/g VS_{added} during the SS-AD of the mixure of chicken manure and corn stover was reported by Guo et al. (2022). The impact of mixing on the performance of the SS-AD system is evident. However, the effectiveness of SS-AD could also be influenced by the type of mixing, SIR, and the characteristics of the substrate.

3.8 Kinetic modeling

The modified Gompertz equation, as presented in Equation 2, was applied to fit the experimental data (i.e., cumulative methane yield) because the lag phase term, the acclimatization period of the microorganisms, is included in the model (Córdoba *et al.*, 2018; Hadiyanto *et al,* 2023).

$$Y = Mexp\left\{-exp\left[\frac{Rme}{M}(\lambda - t) + 1\right]\right\} \qquad (2)$$

Where Y is the accumulated methane volume (mL/g VS_{added}); t is an experimental period (d); M is methane production potential (mL/g VS_{added}); R_m is the maximum methane production rate (mL/g VS_{added}/d); λ is the lag phase time (d); and e is an Euler's number of 2.718.

The results indicated that the modified Gompertz model fit well with the experimental data with R^2 of 0.9667, as presented in Fig. 10. Table 2 presents the kinetic parameters obtained in this study and other previous research using various lignocellulosic biomasses. The result also shows that the methane production potential and the maximum methane production rate of the SS-AD of sweet corn waste obtained in this study were significantly higher than those of the other lignocellulosic biomasses. The acid pretreatment of the SCW before being used as the substrate of the experiments, as mentioned in section 2.2, might play a key role in degrading the complexity of the structure and enhancing the accessibility of the hydrolytic enzymes as well as converting the cellulosic constituents, i.e., hemicellulose, to sugars. Thus, the acidogenic microorganisms could rapidly utilize this soluble organic substrate to produce VFA (Tian *et al.*, 2016). In addition, the pre-acidify process could also shorten the lag phase by accelerating hydrolysis, which is the bottleneck stage of the AD of the complex-structure substrate like lignocellulosic biomass (Shrestha *et al.*, 2017).

3.9 The levelized cost of biogas produced from the solid-state anaerobic digestion system

The levelized cost of biogas produced from SS-AD of SCW was determined based on information from the existing SS-AD system (the capital cost is excluded). The evaluation of the optimal condition of the highest accumulated biogas volume and the average daily biogas production for 30 days with mixing and recirculating intervals every three hours were 9,094.3 L and 303.1 L/day, respectively. Table 3 presents the calculation of the levelized cost of biogas produced from the SS-AD of the sweet corn waste.

Based on the data presented in Table 2, the levelized cost of biogas produced from the SS-AD of the SCW was 0.61 USD/kg in the appropriate operating condition i.e., mixing and recirculating intervals every three hours.

4. Conclusion

This study used a pilot-scale reactor to examine the biogas production from SCW (i.e., CC, CH, and CS). The reactor was operated as solid-state anaerobic digestion at an ambient temperature. The mixing and recirculating intervals were set to non-mixing and mixing for 10 minutes every 3, 6, and 12 hours, and the TS of the feedstock was 25%. The results presented that during the mixing and recirculation every three hours, the highest removal efficiencies of COD, TS, and VS were 85.4%, 62.9%, and 64.6%, respectively.

Further, the reactor mixing and recirculating every 3 hours presented the highest specific methane yield of 0.766 L CH_4/g VS_{added}. The modified Gompertz equation could effectively fit the experimental data with an R^2 of 0.9667. It was also found that the levelized cost of biogas produced from the solid-state anaerobic digestion of the SCW was 0.61 USD/kg. The developed technology could strongly support the United Nations Sustainable Development Goals (UNSDGs), especially SDG 7 and SDG 13. Moreover, this system has the potential to convert agro-industrial waste into renewable energy, thereby improving national energy security and supporting the development of a low-carbon society through the utilization of non-fossil fuel sources.

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Table 2
Kinetic modeling parameters of various lignocellulosic biomasses

Substrate	M (N L/kg VS $_{added}$)	Rm (N L/kg VS $_{added}$-d)	λ (d)	R^2	Reference
Sweet corn waste	828	132.01	0.00	0.9667	This study
Sugar beet leaves silage	485	83.27	0.00	0.9702	Undiandeye *et al.* (2022)
Green corn stover	347	38.17	0.22	0.9974	Li *et al.* (2016)
Elephant dung	293	7.18	1.64	0.9873	Sawatdeenarunat *et al.* (2023)
Maize stover	237	16.92	1.56	0.9986	Cui *et al.* (2021)
Corn straw silage	197	20.38	4.05	0.9984	Ma *et al.* (2021)

Table 3
Data analysis for the levelized cost of produced biogas

Data		Value	Unit
Project Lifetime		10.00	Year
Working time		300.00	day/year
Discount rate[a]		6.87	%
Expense	Maintenance cost	328.95	USD/year
	Administrative cost		
	Electricity cost[b]	986.84	USD/year
	Total cost		
		256.36	USD/year
		1,572.15	USD/year
Income	Bio-fertilizer[c]	29,605.26	USD/year
	LPG replacing[d]	2,928.33	kg LPG/year
		2,311.84	USD/year
	Total income	31,917.11	USD/year
Net income		30,344.96	USD/year
Levelized cost of the produced biogas[e]		0.61	USD/kg

Note: a is discount rate from Bank of Thailand (2024)
b is electricity unit cost from the Provincial Electricity Authority (PEA) in Thailand (Muangjai *et al.*, 2020)
c is the price of bio-fertilizer (National Statistical Office of Thailand, 2023)
d is biogas can replace liquefied petroleum gas at 0.46 kg LPG/m^3 at a methane concentration of 60% (Damrongsak et al., 2017), HHV of 100% CH_4 was 39.96 MJ/m^3 (Nam *et al.*, 2023) and price of liquefied petroleum gas was 0.79 USD/kg LPG (Energy Policy and Planning Office (EPPO), Ministry of Energy, 2024)
e is calculated following Khan *et al.* (2014)

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