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Co-anaerobic digestion of sawdust and chicken manure with plant herbs: Biogas generation and kinetic study

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ABSTRACT

Plant herbs specifically *serai wangi* (SW) and peppermint (PPM) are selected for its insect repellent properties as the use of chicken manure (CM) in anaerobic digestion (AD) potentially attract flies due to the digestate produced. Hence, the addition of SW and PPM in the AD system of CM could deter flies' infestation while producing biogas. Previous work has shown that AD of sawdust (SD) and CM with these plant herbs were able to produce biogas and reduce the flies attraction towards the digestate. However, the combination of SW and PPM for AD of CM has yet to be investigated. This work describes the effect of mixing SW and PPM on the co-AD of SDCM with respect to biogas production, methane yield and kinetic analysis. The mixture of SW and PPM was varied at different concentrations. The composition of methane in biogas was characterized every 10 days by using gas chromatography (GC) equipped with a thermal conductivity detector (TCD). The results suggest that co-AD of 10SW10PPM exhibited the highest biogas production (52.28 mL/g_{vs}) and methane yield (30.89 mL/g_{vs}), which the purity of methane increased by 18.52% as compared to SDCM. However, increasing the concentration of SW and PPM does not significantly improve the overall process. High R^2 (0.927–0.999), low *RMSE* (0.08–0.61) and low prediction error (<10.00%) were displayed by the modified Gompertz, logistic and Cone models. In contrast, Monod and Fitzhugh model is not preferred for the co-AD of SDCM with a mixture of SW and PM, as a high prediction error is obtained throughout the study. Increasing the dosage of PPM decreases the maximum cumulative methane yield, ranging from 31.76 to 7.01 mL/g_{vs} for modified Gompertz and 89.56 to 19.31 mL/g_{vs} for logistic model. The Modified Gompertz obtained a lag phase of 10.01–28.28 days while the logistic model obtained a lag phase of 37.29–52.48 days.

1. Introduction

The forestry and logging industries are one of the significant drivers of GDP growth, as Malaysia's GDP increased by 3.1% (RM1,386.7 billion) in 2021 compared to the previous year (RM1,345.1 billion) [1]. Malaysia is a major exporter and producer of tropical timber, including sawn timber and panel products [2]. Consequently, according to Ref. [3], it generates 3.4 million m^3 of wood waste each year, including sawdust, wood chips and other raw materials. A sustainable way to produce bioenergy is to convert this

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waste into biogas or biofuel instead of incinerating or dumping it in a landfill. Anaerobic digestion is a biological activity sequence that decomposes organic materials without oxygen to produce biogas. Biogas is a sustainable and clean energy source that may be used to generate electricity, power generators, and cooking [4].

The performance of anaerobic digestion (AD) is mainly determined by the temperature, pH and as well as the types of substrates used for AD [5]. Lignocellulosic biomass, such as sawdust (SD), has received significant attention because of its abundant availability [7]. However, its C/N ratio is undesirable for undergoing digestion on its own. A high C/N ratio indicates insufficient nitrogen for cell function, inhibiting microbial growth and, consequently, reducing biogas generation [6]. It is commonly reported that the C/N ratio of 20–30 is ideal for AD [7–9].

To achieve an optimum C/N ratio, the co-AD method is preferred. Co-AD is a method of treating a mixture of two or more substrates simultaneously, which may increase the process' overall efficiency by enhancing its stability and sustaining microbial activity [10]. In addition, co-anaerobic digestion has been proven beneficial for its economic feasibility due to its higher methane yield for existing AD plants compared to mono-digestion [11]. The complications associated to mono-digestion, such as nutritional imbalance and presence of hazardous materials, have made co-anaerobic digestion a crucial research area in developing enhanced AD systems [12,13].

Thus, a nitrogen additive, such as chicken manure (CM), must be mixed with SD to balance the high C/N ratio. Integrating both wastes is essential as CM may provide the nutrients needed for the AD process, which is necessary for microbial growth [14], simultaneously able to enhance the biogas production and methane generation. Mono-digestion of CM also produced insignificant biogas production and methane generation as high nitrogen content and low C/N ratio of CM cause ammonia inhibition. Undigested protein and uric acid will be converted into ammonia during the AD process. Excess ammonia could hinder microbial activity as ammonia has a strong inhibitory effect towards methanogens [15,16]. A study from Ref. [9] showed that the mono-digestion of CM only produced 20.5% of methane yield. This could be due to ammonia inhibition caused by a high nitrogen concentration, averaging 68.30%. Throughout the study, the highest methane production was obtained from a C/N ratio of 30 (65.9%), implying the optimum C/N ratio for the co-AD process [9].

The use of CM as a part of the feedstock of AD may pose flies attraction as it contains high protein and carbohydrates, which act as a food source for flies [17,18]. Plant herbs contain various volatile chemicals that possess insecticidal, larvicidal, and reproduction-inhibiting properties [19]. In Malaysia, lemongrass or known as *serai wangi* (SW) and peppermint (PPM) herbs are utilized for a variety of uses, including aromatherapy, medicine, and natural insect repellent. Incorporating these plants for co-AD of SD and CM could generate biogas while addressing the flies issue. However, its effectiveness as a fly deterrent agent with respect to digestate utilization is yet unknown, although the AD of PPM and SW alone is able to produce biogas, according to prior studies [20–22].

Conducting a kinetic analysis is crucial due to its ability to forecast and define the response of the digestion process and establish correlations with kinetic properties [23]. The determination of several parameters, such as maximum methane production rate (*Rb*), lag phase (λ), methane production potential (*B*) and hydrolysis rate (*k*), are crucial in understanding the behaviour of the AD process. A wide range of models, including, modified Gompertz [5,24,25], logistic [26], Cone [27,28], Fitzhugh [29] and Monod model [30] have been used in numerous kinetic analysis that have been done which is associated with anaerobic digestion.

The digestate produced from AD of CM normally draws the flies attention due to the remaining undigested protein. At first, the addition of certain plant herbs with insect-repellent properties, such as SW and PPM may aid in deterring flies' infestation concerns while producing biogas. Prior study has shown that AD of SD and CM with these plant herbs generated biogas and minimized the attraction of flies to the digestate [31]. On the other hand, to the authors' best knowledge, the combination of SW and PPM has not been investigated yet, hence, this work aims to study the effect of the mixture of SW and PPM at different dosages on the co-AD of SDCM with respect to the biogas production and methane yield. The substrate consisted of sawdust with chicken manure (SDCM) and a mixture of SW and PPM at different concentrations. Then, the study was enhanced by applying kinetic analysis on methane yield using modified Gompertz, logistic, Cone, Monod and Fitzhugh models to estimate the kinetic parameters of the co-AD of SDCM with the mixture of SW and PPM.

2. Methodology

2.1. Materials

Saw dust (SD), chicken manure (CM) and cow dung (CD) was collected at a local sawmill, chicken and cow farm in Perak, Malaysia. Chicken manure is used as a nitrogen additive to adjust the feedstock's carbon-to-nitrogen (C/N) ratio, and cow dung is used as an

Table 1
Characteristics of SD and CM [31].

Parameter	CM	SD
*w_C (wt%)	36.20	48.43
*w_N (wt%)	4.41	0.59
C/N ratio	8.21	82.08
*w_{TS} (wt%)	48.54	66.46
*w_{VS} (wt% of TS)	54.27	74.80

* w is mass fraction.

inoculum. A local grocery store provided the *serai wangi* (SW) and peppermint (PPM).

2.2. Methods

2.2.1. Analytical methods

Total solids (TS) and volatile solids (VS) were analyzed according to standard methods [32] as described in our previous work [31]. The carbon and nitrogen of the raw materials were determined by Carbon Hydrogen Nitrogen Sulphur (CHNS) analyzer. The characterization results of the raw materials have been reported from previous work [31] which can be seen in Table 1.

The volume of biogas for each digester was determined every five days using the water displacement method, which is shown in Fig. 1. Gas chromatography thermal conductivity detector (GC-TCD) was used to analyze biogas composition in duplicates every ten days. The purity of methane can be calculated through Equation (1).

$$\text{Purity }(\%) = \frac{\text{Methane}\left(\frac{\text{mL}}{g_{vs}}\right)}{\text{Biogas}\left(\frac{\text{mL}}{g_{vs}}\right)} \text{x}100\% \tag{1}$$

2.2.2. Anaerobic digester setup

SD and CM was blended at an optimal C/N ratio of 30:1 [33]. The substrate-to-inoculum ratio was set to 70:30 by weight (g) [34]. CD is chosen as inoculum due to its shorter retention time to produce biogas and higher biogas production [35]. The substrate (SD, CM and CD) to water ratio was 1:3 by weight (g) [36], as previous studies showed that this ratio produced the highest biogas production on AD of CD. SW and PPM were mixed and added at 10 parts per hundred of the substrates (pph_s), 20pph_s, and 30pph_s, respectively. The concentration of SW and PPM were calculated by using Equation (2).

$$10pph_s = \frac{10}{100} \text{x dry substrates (SD, CM, CD) (g)} \tag{2}$$

In order to guarantee consistent levels of performance, the pH level of each sample was brought down to a range of 7.00–7.50 using 0.1 M sulphuric acid (H_2SO_4) [37] and survivability of the microbes in the digesters. Before loading the samples into the digesters, the pH value of each digester was measured again, and the composition of each digester is shown in Table 2. Note that the control results are obtained from our previous work [31] and used to compare with the present work.

The anaerobic digestion in a lab-scale bio-digester made from a 1.5 L black-painted soda bottle is shown in Fig. 2. The digester was

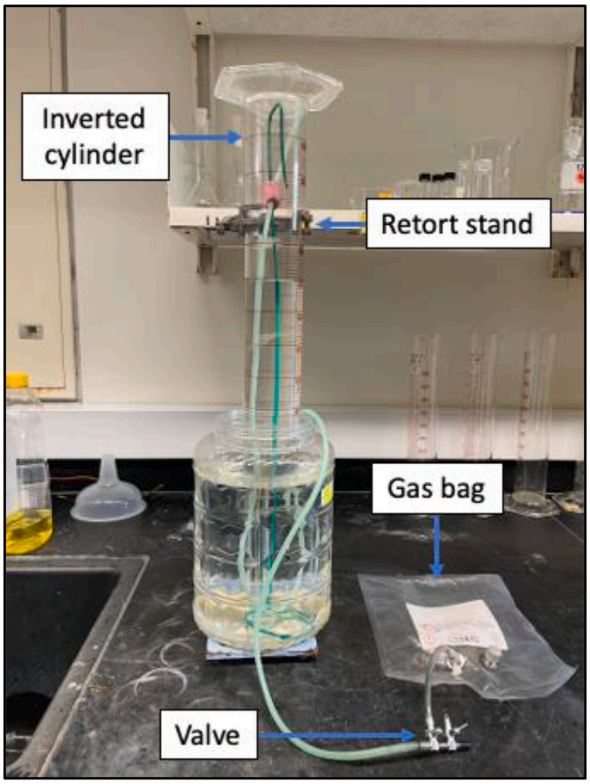

Fig. 1. Water displacement method.

equipped with a two-holed cap. One of the holes was used as a sample collection point, and the other was covered with a stopper. Soap water was used to conduct a leak test on the digesters to detect any potential leaks. The substrates and water that were mixed during the feedstock preparation are transferred to the digesters. The digestion temperature and retention time were conducted at 35 °C for 60 days. Anaerobic conditions were achieved for the digesters by utilizing a compressor.

2.3. Kinetic analysis

Kinetic analysis of AD of SDCM with different concentrations of SW and PPM was carried out using five models, namely, modified Gompertz, logistic, Cone, Monod and Fitzhugh models as shown in Equations (3)–(7). The predictions of the kinetic parameters were made by using Polymath 6.1, and the equation of each model is presented in Table 3. The models were evaluated using statistical tools such as the determination of coefficient (R^2) and root mean square error (*RMSE*). R^2 is used to measure the fitness of the data to the model, while *RMSE* is used to measure the accuracy between the actual (experimental) and predicted values generated by the model. The R^2 and *RMSE* can be calculated by using the following equation:

$$R^2 = \frac{\sum_{k=1}^{n_s}\left(B_{exp,i} - B_{mod,i}\right)^2}{\sum_{k=1}^{n_s}\left(B_{exp,i} - B_{AVG}\right)^2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(B_{exp,i} - B_{mod,i}\right)^2}{N}}$$

where $B_{exp,I}$ is the experimental methane yield, $B_{mod,I}$ is the predicted methane yield, and N is the number of data points. R^2 value approaching one and a lower value of *RMSE* indicates a more appropriate model [38].

3. Results and discussion

3.1. Biogas and methane production

The co-AD process of SDCM was conducted with the mixture of SW and PPM at 10pph$_s$, 20pph$_s$ and 30pph$_s$. It is performed to see the potential synergistic effect among the substrates used. The mix of substrates in the co-AD process may produce synergistic or antagonistic effects. The synergistic effect in the AD process can be defined as the contribution of an additional substrate in terms of nutrient balance, enzymes and any other changes that the substrate itself may lack and may increase the biodegradability of the substrate and, therefore, the methane yield [40]. In contrast, lower methane yield produced from mixed substrate of co-AD is known as an antagonistic effect.

Daily biogas production of co-AD of SDCM with SW and PPM at different dosages is shown in Fig. 3, which can be depicted by the peaks on specific days. The control started to produce its biogas on day 10 of AD. After day 15, biogas production of the control began to increase gradually until it reached a second peak on day 40 at 14.62 mL/g$_{vs}$. For co-AD of SDCM with SW and PPM, almost all feedstock formulations were observed to record significant peaks on day 5 prior to a lag phase from day 10. These early biogas spikes correspond to high CO_2 content at 60.65%–81.89%, which can be seen in the inset of Fig. 3. The highest daily biogas production was recorded with A, corresponding to 11.07 mL/g$_{VS}$. Other co-AD blends either gave their highest biogas generation between day 25 to day 35 (5.19–7.87 mL/g$_{VS}$) or resulted in consistently poor biogas generation (<2.50 mL/g$_{VS}$). The possible cause of different biogas production from different digesters will be discussed throughout this section.

The four stages of the AD process can be seen from the co-AD of SDCM as depicted in Fig. 4, which shows the daily and cumulative biogas production and methane yield. The first peak produced from the digesters was probably due to high CO_2 content (60.65–81.89%), indicating that all digesters are in the acidogenesis step of the AD process as acidogenic bacteria convert soluble monomers to organic acids such as VFAs and carbon dioxide (CO_2) [41]. A gradual decrease in biogas production after day 10 could be due to the adaptation of microbes for the next step of the AD process, which was acetogenesis, where the microbes need to convert a longer chain of volatile fatty acids (VFAs) into acetate and hydrogen [42].

The fluctuation in biogas production could be due to the change in the metabolism of the microbes, which is affected by the

Table 2
Composition of digesters for co-AD of SDCM with different concentrations of SW and PPM.

Setup	SW	PPM	pH
Control [31]	–	–	7.35
A	10pph$_s$	10pph$_s$	7.16
B	10pph$_s$	20pph$_s$	7.45
C	10pph$_s$	30pph$_s$	7.25
D	20pph$_s$	10pph$_s$	7.21
E	30pph$_s$	10pph$_s$	7.11

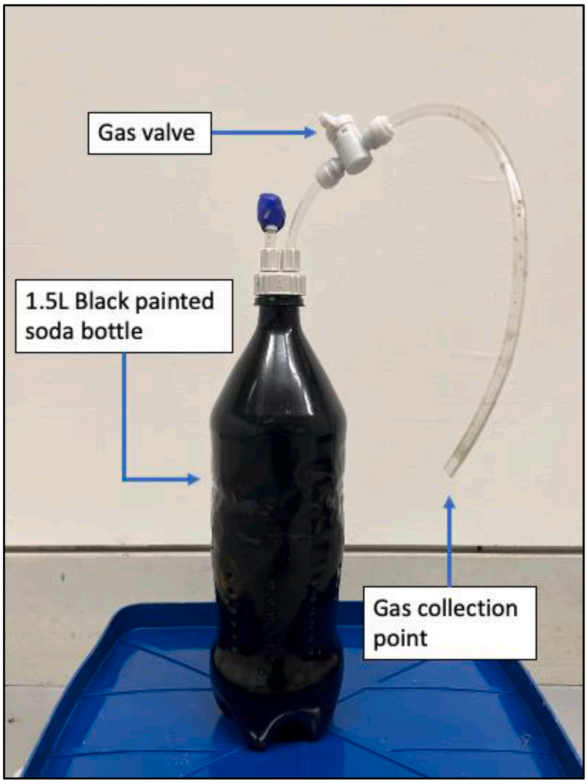

Fig. 2. Digester setup.

Table 3
Kinetic models used in this study.

Model	Equation	
Modified Gompertz [25]	$B_t = B \exp\left[-\exp\left[\frac{R_b \text{ x } e}{B}(\lambda - t) + 1\right]\right]$	(3)
Logistic [25]	$B_t = \frac{B}{1 + \exp\left(4.\frac{R_b(\lambda - t)}{B} + 2\right)}$	(4)
Cone [39]	$B_t = \frac{B}{[1 + (kt)^{-n}]}$	(5)
Monod [30]	$B_t = B\frac{kt}{[1 + kt]}$	(6)
Fitzhugh [29]	$B_t = B[1 - \exp\,(kt)^n]$	(7)

fluctuation of pH in the digestate [43]. As the process proceeds to the methanogenesis step from day 30, the biogas volume increases with increasing methane content. After day 45, the biogas production from most co-AD blends dropped progressively until day 60. This trend could be seen in a previous study as well on AD of CM with lemongrass which observed the fluctuation of biogas throughout the 30-day retention period [43]. The continuous decrease in substrate concentration in the digesters due to microbial degradation of the substrate could be the cause of the progressive drop shown by most co-AD blends. This is common in the AD process, which is typically substrate-limited [44].

The overall biogas production and methane yield from co-AD of SDCM with the mixture of SW and PPM at different concentrations is shown in Fig. 5A and B. It was revealed that the control produced the highest biogas production (62.42 mL/g_{vs}) and methane yield (31.12 mL/g_{vs}), followed by A (52.28 mL/g_{vs}, 30.89 mL/g_{vs}). At the same time, other formulations gave their highest biogas production between 39.842 mL/g_{vs} to 12.75 mL/g_{vs} and methane yield at 18.02 mL/g_{vs} to 17.71 mL/g_{vs}. Previous work has shown that CM10SW and CM10PPM only produced 22.33 mL/g_{vs} and 15.422 mL/g_{vs} of methane yield [31]. Surprisingly, the methane yield from A in this work increases to 30.89 mL/g_{vs} compared to the previous work. The combination of SW and PPM at a dosage of 10pph_s produced a synergistic effect. Due to a lack of work regarding the AD of SDCM with SW and PPM, the cause of this effect is undetermined, as more work needs to be done in the future. A synergistic effect also could be seen through the work from Ref. [24], where AD of CM with pre-treated corn stover increased the cumulative methane yield between 6.54% and 24.65%.

The increasing dosage of SW in the system shows an antagonistic effect as the methane yield decreases with increasing dosage of the

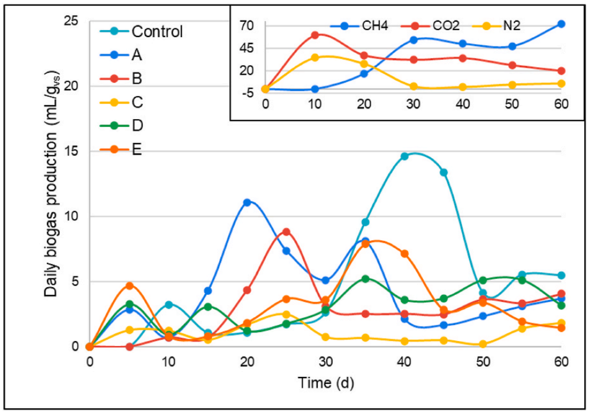

Fig. 3. Daily biogas production of co-AD of SDCM with mixture of SW and PPM at different concentrations (Inset picture: gas composition produced from Control).

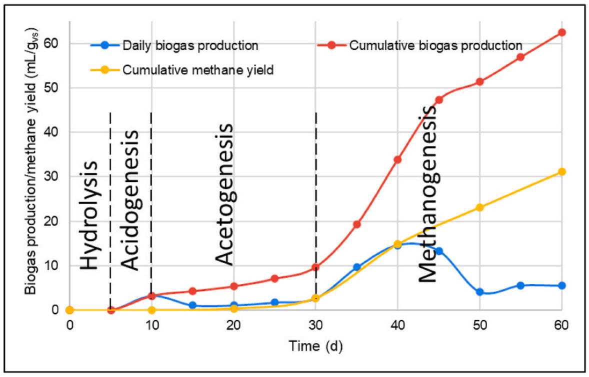

Fig. 4. Daily and cumulative biogas production and methane yield from co-AD of SDCM.

SW. This could be due to the increasing concentration of lignin in the system, which will affect the performance of the overall AD process. SW contains a high percentage of lignin content which is 28.5%. Lignocellulosic biomass such as SW contains lignin which forms a lignin sheath that surrounds and protects cellulose and hemicellulose from degradation by cellulase and hemicellulase [45]. Lignocellulosic biomass's complex composition increases the resistance to degradation, known as the biomass recalcitrance [46]. In the AD process, hydrolysis of lignocellulosic biomass is considered a rate-limiting step as the process is often very slow and incomplete [47]. The higher the composition of lignin, the slower the production of biogas as the resistance to degradation increases, which can be seen throughout this work.

Furthermore, the increasing dosage of PPM in the system also shows an antagonistic effect towards the AD process as the methane yield decreases from 30.89 mL/g_{vs} to 17.71 mL/g_{vs} and 6.58 mL/g_{vs}. PPM mostly consists of menthol (38.45%) and menthone (21.8%) [48]. The menthol's antibacterial properties may impact the entire AD process [49]. However, a study on peppermint's effectiveness in feeding in terms of digestibility and ruminal fermentation demonstrated that peppermint did not exhibit any adverse impacts on these processes [50]. The presence of limonene, whose level is roughly 1.58%, is one factor that could explain the drop in methane yield as the concentration of PPM increases [48]. Limonene is a chemical compound known for its antimicrobial properties which can inhibit the AD process [21].

Table 4 shows the purity of methane from control and A. Based on Table 4, although the control produced the highest biogas production and methane yield, the highest purity of methane was obtained from A, which increased by approximately 18.52% from the control. Similar findings were observed in a study associated to AD of CM with lemongrass whereby the methane concentration in the biogas increased from 45.71% to 66.20%, indicating that lemongrass could be a good co-substrate for AD with CM [44]. The combination of 10pphs of SW and PPM substrates could provide a nutrient balance that may enhance biodegradability and methane yield, subsequently improving the overall performance of AD. Another study related to co-AD of CM with banana pseudo-stem and sugarcane bagasse has shown that the substrates' nutrient balance (sugar, fibre and nitrogen) exhibits significant implications on the microbial activity that strategically enhances methane production and process stability [13].

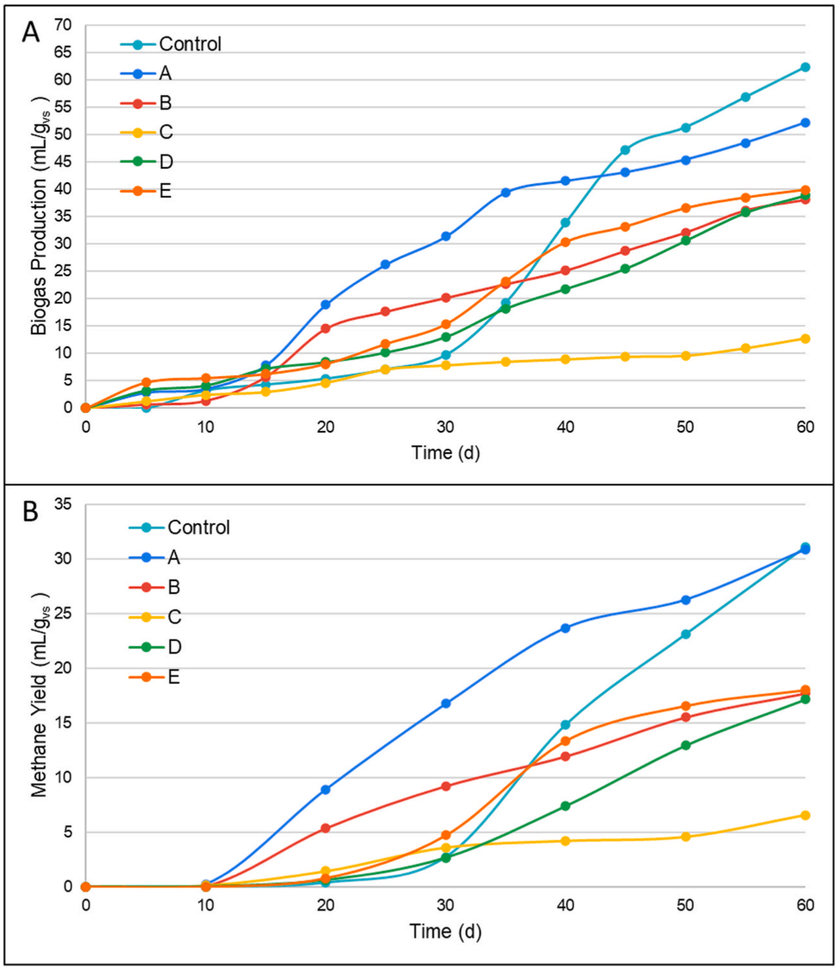

Fig. 5. A) Biogas production and B) methane yield for co-AD of SDCM with mixture of SW and PPM at different concentrations.

Table 4
Purity of methane from Control and A.

Sample	Control [31]	A
Biogas (mL/g_{vs})	62.42	52.28
Methane (mL/g_{vs})	31.12	30.89
Purity (%)	49.85	59.09

3.2. Kinetic analysis

To assess the effectiveness of the AD of SDCM with SW and PPM, five kinetic models—modified Gompertz, logistic, Cone, Fitzhugh, and Monod—were evaluated. The estimated parameters, such as the lag phase (time taken for the microbes to adapt in the system), maximum methane production rate, and maximum cumulative methane yield, can be obtained through a modified Gompertz and logistic model. The Cone, Fitzhugh, and Monod models can be used to determine the hydrolysis rate constant. Fig. 6A–E illustrates the comparison between the experimental and predicted methane yield with respect to each model. The estimated kinetic parameters from each model are displayed in Tables 5 and 6.

The modified Gompertz, logistic and Cone models effectively represented the experimental methane yield throughout this study. This was supported by the excellent coefficient determination (R^2) values obtained from these models. The modified Gompertz model obtained R^2 of 0.947–0.997, the logistic model obtained R^2 of 0.927–0.999, and the Cone model obtained R^2 of 0.953–1.00. This shows that these models offer a more reliable estimation because they could account for over 99% of the variations in the data. The current study's finding is consistent with [39], who obtained R^2 of 0.993–0.997 for modified Gompertz and 0.9997 to 0.9999 for the Cone model for co-AD of durian shell with chicken, dairy and pig manure. Another study reported by Ref. [25] has demonstrated that the modified Gompertz and logistic model fits well for the co-AD of sugarcane bagasse and poultry waste. In terms of *RMSE* values, these

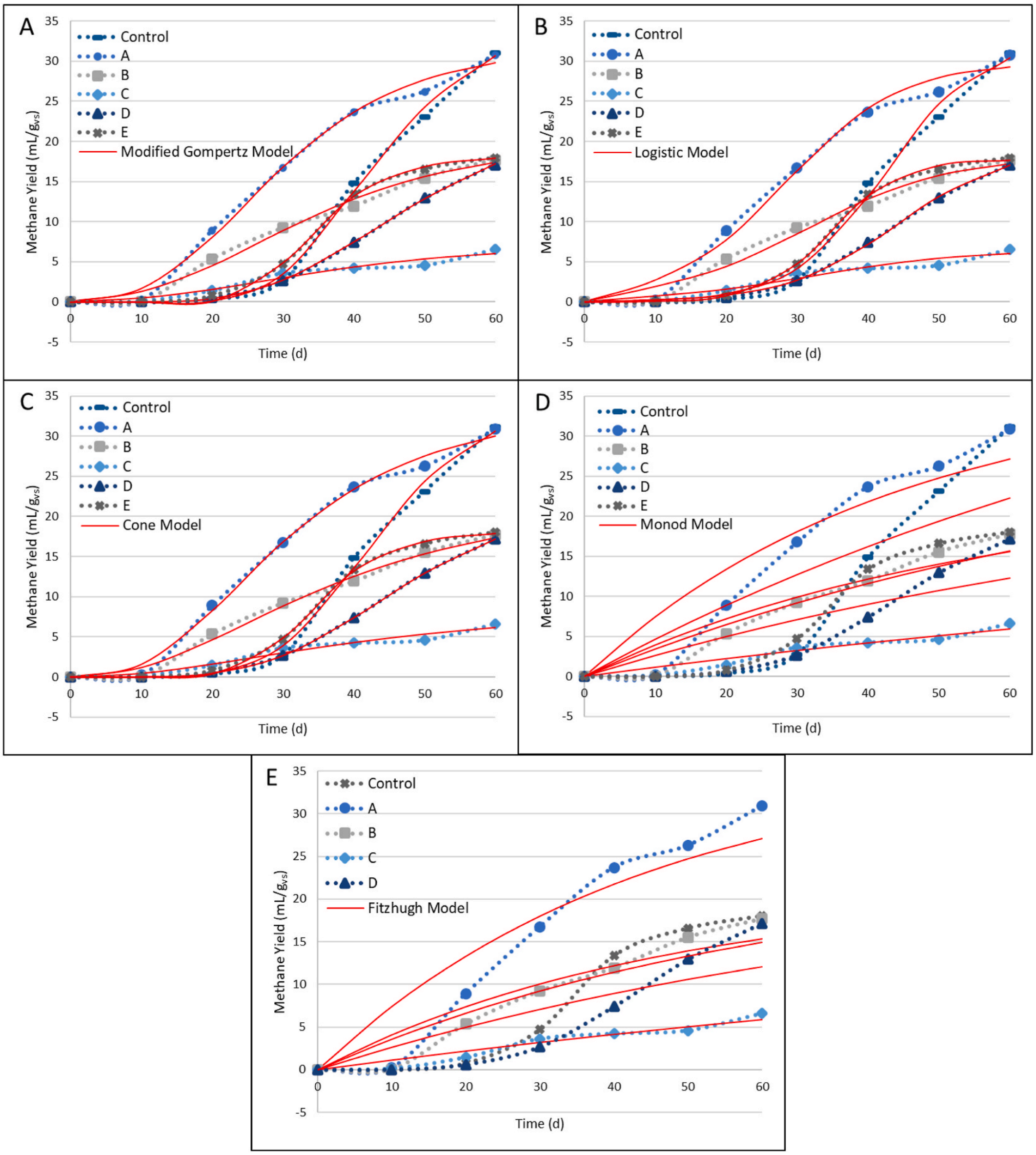

Fig. 6. Comparison of co-AD of SDCM with mixture of SW and PPM at different concentrations between the actual and predicted methane yield (A) Modified Gompertz model (B) Logistic model (C) Cone model (D) Monod model (E) Fitzhugh model.

models obtained low *RMSE* values, ranging from 0.21 to 0.41 for modified Gompertz, 0.08 to 0.61 for logistic and 0.02 to 0.36 for Cone models. These models accurately described the methane yield data obtained throughout this study, as indicated by their high R^2 and low overall *RMSE* values. Furthermore, modified Gompertz, logistic, and Cone models showed a good prediction of methane values with less than 10% error, comparable with previous findings [28].

As for Monod and Fitzhugh model, the R^2 values were moderately low, ranging from 0.709 to 0.933 for both models. Both models showed high overall *RMSE* values, ranging from 0.22 to 2.42. The low R^2 and high overall *RMSE* values indicate that Monod and Fitzhugh models might not be appropriate to simulate the co-AD of SDCM with SW and PPM. This could be supported by the high prediction error between the experimental and simulated methane yield from both models, ranging from 11.65 to 39.51% for Monod and 11.72–41.78% for the Fitzhugh model. Modified Gompertz, logistic, and cone models are widely used to determine the biological characteristics of AD because they exhibit typical "S" shape curves. These models can accurately and successfully depict the three stages of fermentation, including the lag phase, exponential phase, and stationary phase [24].

The modified Gompertz and logistic model can determine the maximum production rate of methane (*Rb*). From Table 4, the Rb values differ from both models, ranging from 0.15 to 1.49 for modified Gompertz and 0.45 to 3.75 for the logistic model. Although these models showed different values of *Rb*, both models have shown that increasing the dosage of PPM decreases the value of Rb.

Table 5
Kinetic parameters of co-AD of SDCM with SW and PPM-Modified Gompertz and logistic model.

Setup	λ (day)	*Rb*	*B* (mL/g_{vs})	R^2	*RMSE*	Measured methane yield (mL/g_{vs}) – 60 d	Predicted methane yield (mL/g_{vs}) – 60 d	Percentage difference (%)
Modified Gompertz Model								
Control [31]	28.28	1.18	36.16	0.997	0.26	31.12	30.64	1.56
A	11.15	0.90	31.76	0.991	0.41	30.89	29.80	3.66
B	10.16	0.45	19.69	0.985	0.30	17.71	17.36	2.06
C	10.01	0.15	7.01	0.947	0.20	6.58	6.04	9.00
D	10.16	0.45	19.69	0.985	0.30	17.17	17.22	0.25
E	26.81	1.49	17.90	0.993	0.21	18.02	17.90	0.69
Logistic Model								
Control	49.66	3.75	97.39	0.990	0.48	31.12	30.40	0.72
A	37.29	2.80	89.56	0.980	0.61	30.89	29.28	5.50
B	42.26	1.38	54.56	0.972	0.41	17.71	17.23	2.80
C	44.01	0.45	19.31	0.928	0.23	6.58	5.99	9.86
D	52.48	1.87	57.67	0.999	0.08	17.17	17.08	0.54
E	40.17	2.75	53.33	0.999	0.10	18.02	17.68	1.92

Table 6
Kinetic parameters of co-AD of SDCM with SW and PPM-Cone, Monod and Fitzhugh model.

Setup	*k* (d^{-1})	*n*	*B* (mL/g_{vs})	R^2	*RMSE*	Measured methane yield (mL/g_{vs}) – 60 d	Predicted methane yield (mL/g_{vs}) – 60 d	Percentage difference (%)
Cone Model								
Control [31]	0.016	1.18	35.78	0.994	0.36	31.12	30.60	1.71
A	0.032	2.71	35.00	0.993	0.36	30.89	30.04	2.84
B	0.026	2.21	23.66	0.988	0.26	17.71	17.38	1.93
C	0.023	2.04	9.23	0.953	0.19	6.58	6.12	7.45
D	0.021	4.41	23.43	1.000	0.02	17.17	17.18	0.05
E	0.029	6.80	23.82	0.999	0.09	18.02	17.86	0.90
Monod Model								
Control	0.009	–	51.50	0.709	2.42	31.12	22.31	39.51
A	0.023	–	36.35	0.900	1.38	30.89	27.17	13.69
B	0.018	–	23.22	0.914	0.73	17.71	15.56	13.81
C	0.006	–	19.18	0.933	0.22	6.58	5.89	11.65
D	0.010	–	26.25	0.731	1.26	17.17	12.25	40.21
E	0.012	–	31.30	0.795	1.28	18.02	15.63	15.27
Fitzhugh model								
Control	0.003	3.07	51.50	0.709	2.42	31.12	22.21	40.14
A	0.005	4.77	36.35	0.901	1.38	30.89	27.06	14.14
B	0.005	4.62	21.20	0.902	0.78	17.71	15.32	15.61
C	0.002	2.47	19.18	0.933	0.22	6.58	5.89	11.72
D	0.003	3.58	24.23	0.723	1.27	17.17	12.11	41.78
E	0.004	4.00	24.23	0.769	1.36	18.02	14.93	20.67

Increasing the dosage of PPM also reduces the maximum cumulative methane yield (*B*), from 31.76 to 7.01 mL/g_{vs} for the modified Gompertz and 89.56 to 19.31 mL/g_{vs} for the logistic model. This could be supported by the previous discussion regarding the existence of limonene in PPM, which could decrease AD's overall performance. In terms of lag phase, the values of lag phase also vary for each model, ranging from 10.01 to 28.28 days for modified Gompertz and 37.29–52.48 days. These results contradict prior literature findings, which suggested a shorter lag phase ranging from 0 to 2.41 days for AD systems with cattle manure with coffee pulp [51], livestock manure [52] and CM with sawdust and *Miscanthus* (silver grass) [5]. This apparent inconsistency can be explained due to the inoculum utilized in previous studies which contained readily active microbes that were either taken from an operating anaerobic digester or a biogas plant. This improves the performance of the overall AD process and shortens the lag phase. According to Ref. [53], the AD start-up time is influenced by the initial pH of the digester, the inoculum activity and the number of degradable substrate components.

In this work, the hydrolysis rate (*k*) obtained from the Cone model varies from 0.016 to 0.032. The difference in the substrate's composition and structure caused a variation in the hydrolysis rate constant among the substrates [38]. Theoretically, a lower hydrolysis rate constant corresponds to lower biodegradability and a longer time taken for the methane yield to reach its maximum value. The lowest *k* was obtained from SDCM (0.016). However, it does not correspond to the lowest methane yield, as SDCM produced the highest predicted methane yield, which corresponds to 30.60 mL/$g_{vs.}$ It is necessary to emphasize that the whole AD process is influenced by more than just the hydrolysis rate constant. Other factors such as C/N ratio, temperature, pH and lignin content also need to be addressed since these factors directly affect the AD process.

4. Conclusion

The highest biogas and methane yield for co-AD of SDCM with the mixture of SW and PPM was found to be at a dosage of 10pph_s, which increased the methane concentration by 18.52% as compared to the previous work. Increasing the dosage of SW and PPM on the other hand does not portray any significant impact on the AD process. The high lignin content in SW and the limonene content in PPM inhibit biogas production and methane yield. A complete kinetic study of co-AD of SDCM with the mixture of SW and PPM was performed. The modified Gompertz, logistic and Cone models were preferred in predicting methane production as high R^2 (0.927–0.999), minimal RMSE (0.08–0.61), and low prediction error (<10.00%) is obtained through kinetic analysis. High prediction error in methane yield were observed from Monod (11.65–39.51%) and Fitzhugh (11.72–41.78%), suggesting that these models are unsuitable for co-AD of SDCM with mixture of SW and PPM. Future work will involve further treatment of the digestate produced to generate compost via aerobic composting. Additionally, fly deterrent test will be conducted for both digestate and compost produced to see the effectiveness of SW and PPM.

Declarations

Author contribution statement

Mohd Hakimi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

M.Devendran Manogaran: Analyzed and interpreted the data.

Rashid Shamsuddin: Conceived and designed the experiments.

Siti Aminah Mohd Johari: Performed the experiments.

Muzamil Abdalla M Hassan, Totok Soehartanto: Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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