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Effect of Temperature on Co-Anaerobic Digestion of Chicken Manure and Empty Fruit Bunch: A Kinetic Parametric Study

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Abstract: The rapid growth of the Malaysian poultry and palm oil industries has led biomass waste generation in abundance specifically chicken manure and empty fruit bunch (EFB). Anaerobic digestion (AD) is a circular economy-based approach which converts chicken manure and EFB into biogas which can be utilized for heating and power generation. Operating temperature is an imperative consideration for AD hence the objective of the study is to evaluate the effect of different temperature profiles namely, psychrophilic (20 °C), mesophilic (35 °C) and thermophilic (50 °C) on AD of chicken manure and EFB. The kinetic parameters are also evaluated using five kinetic models to enable readers to comprehend the kinetic behaviours of the systems. The volume and composition of biogas is measured every five days for a 50-day retention time. The findings observed that mesophilic condition is the most favourable with cumulative methane, CH_4 composition of up to 17.07%, almost two folds that of thermophilic (9.12%) and five folds that of psychrophilic (3.49%). The CH_4 generation rate, R_b based on the modified Gompertz model which is deemed the best fit further supports these findings as the R_b under mesophilic condition is significantly higher (0.330 mL/g_{vs} day) compared to psychrophilic (0.088 mL/g_{vs} day) and thermophilic (0.120 mL/g_{vs} day) conditions.

Keywords: anaerobic digestion; chicken manure; empty fruit bunch; psychrophilic; mesophilic; thermophilic; first order kinetic model; Monod model; Cone model; modified Gompertz model; Logistic function model

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Citation: Manogaran, M.D.; Hakimi, M.; Basheer Ahmad, M.H.N.; Shamsuddin, R.; Lim, J.W.; M Hassan, M.A.; Sahrin, N.T. Effect of Temperature on Co-Anaerobic Digestion of Chicken Manure and Empty Fruit Bunch: A Kinetic Parametric Study. *Sustainability* **2023**, *15*, 5813. https://doi.org/10.3390/su15075813

Academic Editors: Ester Scotto di Perta and Stefano Papirio

Received: 30 January 2023
Revised: 15 March 2023
Accepted: 17 March 2023
Published: 27 March 2023

1. Introduction

The popularity of chicken meat amongst Malaysians has increased as of lately until the extend that it is the second most popular food item after rice [1]. Consequently, the poultry industry has grown significantly such that there is an abundance of chicken manure being produced [2]. It has been estimated that a chicken produces 0.08 to 0.1 kg of manure daily, corresponding to 3 to 4% of its body weight [3]. Similar to other livestock droppings, chicken manure is a nutrient rich organic waste that contains substantial amounts of nitrogen, phosphorus and potassium and is often utilized as an organic fertilizer in agricultural fields [4]. However, utilizing raw chicken manure as fertilizer leads to environmental pollution concerns such as enhanced greenhouse gas emissions, accumulation of harmful trace metals and eutrophication in water bodies. Such circumstances are due to norms which do not abide to the Environmental Quality Act (EQA) 1974 specifically on leachate characterization in which parameters such as the biological oxygen demand, pH and suspended solids are of utmost importance [5]. Apart from that, the odour concern triggered by raw chicken manure also attracts flies, pest and rodents which in addition to propagation of pathogens, posing a significant biohazard [6].

Anaerobic digestion (AD) is a circular economy-based approach which converts biomass waste like chicken manure into biogas and biofertilizer which can further be upgraded into value added outputs that offer societal, environmental and economic benefits. Like any other intricate process, to execute the AD process well, a few variables need to be taken into account such as the pH, carbon-to-nitrogen (C/N) ratio and most importantly the temperature of the system. The downside of utilizing chicken manure as feedstock for AD is its rich nitrogenous content hence leading to inadequate C/N ratio for the process [7]. Accordingly, many past studies opt to execute AD of chicken manure with carbon rich co-substrates such as corn stover [8], sawdust [9] and food waste [10] such that the C/N ratio is balanced hence developing a co-anaerobic digestion (co-AD) system. Another domain of carbon rich biomass waste that has shown much potential to be exploited are energy crop residues such as sugarcane bagasse as well as oil palm frond and empty fruit bunch (EFB) which are abundant as the nation is the second largest palm oil contributor worldwide after Indonesia [11]. Cahyono, et al. [12] conducted a fundamental study to evaluate the feasibility of EFB as a co-substate in a co-AD system however did not delve into the effects of key parameters on the process. As such, operating temperature is an imperative factor to be taken into consideration when discussing about the AD process as it could exhibit major repercussions on the system including ammonia toxicity which retards the process [7]. Temperature considerations for AD fall under three domains namely psychrophilic anaerobic digestion (PAD), mesophilic anaerobic digestion (MAD) and thermophilic anaerobic digestion (TAD). The purpose of this study is to observe the effect of different temperature profiles on co-AD of chicken manure and EFB. This study is distinct compared to it's precursors as it evaluates a co-AD system whereby chicken manure and EFB act as co-substrates instead of being the sole feedstock. Additionally, this study also employs five kinetic models namely the first order kinetic model, Monod model, Cone model, modified Gompertz model and Logistic function model to evaluate the co-AD system with respect to several kinetic parameters which are the maximum methane, CH_4 generation potential, hydrolysis rate constant, maximum CH_4 generation rate and lag phase duration. This insight is fruitful as it enables ease in foreseeing the behaviour of an AD system and to comprehend correlations with kinetic characteristics aiding in enhanced CH_4 generation. In fact, these findings are especially crucial should there be measures to upscale the system for mass power generation [13].

Temperature constraints are especially essential to scrutinize as past studies stresses on its implications on the microbial community, process kinetics as well as stability and CH_4 yield. PAD has caused decline in microbial growth, adversely affecting substrate utilization rates and deterring biogas generation [14]. TAD on the other hand observes decline in biogas quality due to presence of impurities such as ammonia which is not apt for methanogens [15]. In the case of AD of chicken manure and EFB as sole substrates, the findings have been fairly favourable for MAD [16,17] hence, the hypothesis of this study would be that in a single system, MAD yields enhanced biogas quality as compared to PAD and TAD. Accordingly, the study was conducted by adjusting the C/N ratio of the feedstock to 25 as this ratio is optimum for the AD process [18]. An optimum C/N ratio results in prolonged protein solubilization rate inducing low total ammonium concentration in the system. As such, the risk of ammonia inhibition can be deterred by adjusting the feedstock of the anaerobic biodigester to meet the optimal C/N ratio [19]. Feedstock with too high of a C/N ratio causes the system to be low on elemental nitrogen. Such circumstances pose a hurdle to maintain cell biomass resulting in rapid nitrogen decomposition by microbials leading to deterioration of biogas quality [20]. On the other hand, too low of a C/N ratio makes the system susceptible to ammonia inhibition due to insufficient carbon content [21]. The pH of the system is adjusted to 7.0 ± 0.1 as the optimum pH range for the AD process is 6.8 to 7.2 [22] while the solid-to-liquid ratio is set at 1:3 [12].

2. Materials and Methods

2.1. Preparation of Feedstock Materials

The raw materials utilized in this study are chicken manure, EFB and cow dung. The chicken manure is obtained from Dindings Poultry Development Center (DPDC) Sdn Bhd whereas EFB is acquired from FELCRA Nasaruddin Palm Oil Mill. The inoculum material utilized during the study is cow dung obtained from a Sikh settlement in Tanjung Tualang, Perak. The feedstock materials are acquired at most a week before the experimental setup and stored at 4 °C to sustain its freshness. The addition of the inoculum to the system enhances the process stability and efficiency of the AD process [12]. The EFB is shredded into loose fibrous form and dried at the temperature of 105 °C overnight in a BINDER drying oven (manufactured in Darmstadt, Germany). The dried EFB is then further refined (0.25 mm) using a RETCSH Cutting Mill SM 100 biomass grinder (manufactured in Germany). As for the chicken manure, it is crushed into powder-like form using a mortar and pastel.

Chicken manure, EFB and cow dung are characterized for its carbon (C), nitrogen (N) and moisture content. The elemental compositions and moisture content of the raw materials are measured using the Perkin Elmer EA Series II CHNS/O 2400 Analyzer (manufactured in Shelton, CT, USA) and Mettler Toledo HX-240 Moisture Analyzer (manufactured in Greifensee, Switzerland) respectively. The C/N ratio of the feedstock is computed using Equation (1) as shown below:

$$R = \frac{\sum Q_n[C_n \times (100 - M_n)]}{\sum Q_n[N_n \times (100 - M_n)]} \quad (1)$$

where R is the C/N ratio, Q is the mass of material, C is the carbon content (%), N is the nitrogen content (%), M is the moisture content (%) and n is the number of samples.

Thermogravimetry analysis (TGA) on the feedstock is also executed using Perkin Elmer STA6000 Thermogravimetry Analyzer (manufactured in Shelton, USA) to evaluate the total volatile solid content. The system is set in the temperature range of 26 °C to 800 °C under nitrogen condition at a heating rate of 10 °C/min.

2.2. Batch Digester Setup and Experimental Design

The study is conducted in makeshift batch reactors developed using 1.5 L plastic bottles which acts as the main digester body as depicted in Figure 1. These makeshift digesters are made airtight and painted in black to prevent any form algae growth in the presence of sunlight which hinders the development of anaerobic condition. Bubble leak test (ASTM F2096) is performed as well to make sure there are no leakages throughout the tubes, fittings and connectors.

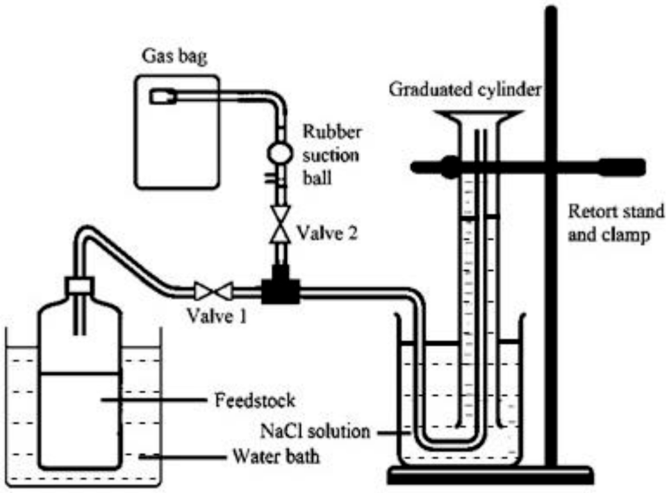

Figure 1. Diagram of experimental setup, published by Cahyono, et al. [12].

Chicken manure, EFB and inoculum are mixed following Equation (1) such that the C/N ratio is 25. The solid-to-liquid ratio is 3:1. The pH is modified to 7.0 ± 0.1 using phosphoric acid. The PAD (20 °C) setup is placed on the table bench whereas the MAD (35 °C) and TAD (50 °C) setups are placed in separate Grant GLS Aqua 18 Plus water baths (manufactured in Cambridgeshire, England) for temperature regulation.

2.3. Biogas Volume and Composition Analysis

The experimental setup is observed over a 50-day hydraulic retention time (HRT). The volume of biogas is recorded every 5 days via the water displacement technique using an inverted measuring cylinder as depicted in Figure 1. The generated biogas is then drawn out of the air space of the inverted measuring cylinder using a rubber suction ball and stored in a gasbag. Accordingly, the biogas composition is evaluated using the Shimadzu GC-8A Gas Chromatography (manufactured in Kyoto, Japan) with Thermal Conductivity Detector which uses a molecular sieve 5A (MS-5A) column. The carrier gas used is purified argon. The temperature of the column, injector and detector on the other hand are fixed at 100 °C with a pressure of 100 kPa [23]. The peak area of the chromatography is then mapped onto the calibration curve with coefficient of regression, R^2 of 0.9996 constructed using pure CH_4 injections from 0.5 up to 5.0 mL with 0.5 mL increments.

2.4. Kinetic Modelling and Statistical Indicators

The behaviour of a system going through AD process is evaluated via multiple parameters such as lag phase, hydrolysis rate constant, maximum CH_4 generation potential and maximum CH_4 production rate. These parameters are imperative to comprehend better the limitations of the system and interactions between the co-substrates in a co-AD system. For this study, first order kinetic, Cone, Monod, modified Gompertz and Logistics function models are applied as depicted in Equations (2)–(6).

$$B_t = B_o \times [1 - exp(-kt)] \tag{2}$$

$$B_t = \frac{B_o}{\left[1 + (kt)^{-n}\right]} \tag{3}$$

$$B_t = B_o \times \left(\frac{kt}{1 + kt}\right) \tag{4}$$

$$B_t = B_o \times exp\left\{-exp\left[\frac{R_b \times e}{B_o}(\lambda - t) + 1\right]\right\} \tag{5}$$

$$B_t = \frac{B_o}{1 + exp\left[\frac{4 \times R_b \times (\lambda - t)}{B_o} + 2\right]} \tag{6}$$

where B_t stands for the simulated CH_4 generated (mL/g_{vs}), B_o depicts the maximum CH_4 generation potential (mL/g_{vs}), k stands for the hydrolysis rate constant (1/day), t is the retention time (days), n is a dimensionless shape factor, R_b is the maximum CH_4 generation rate (mL/g_{vs} day), λ states the lag phase duration (days) and e is the Euler's function equal to 2.71828.

A nonlinear least-square regression analysis is executed using Polymath version 6.0 to determine the B_t, B_o, k, n, R_b and λ. The R^2 and root mean square error (*RMSE*) are computed for each model to compare the accuracy of the studied models. R^2 is determined from the Polymath version 6.0 software whereby a higher R^2 indicates a better fit. *RMSE* on the other hand is inferred as the standard deviation between the predicted and measured values as depicted in Equation (7) with a lower *RMSE* being favourable.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(\left[B_{t\ (exp,\ i)} - B_{t\ (mod,\ i)}\right]\right)^2}{n}} \tag{7}$$

where $B_{t\ (exp,\ i)}$ is the CH_4 generated in the experiment, $B_{t\ (mod,\ i)}$ is the forecast CH_4 generated obtained from the model and n is the number of data points.

3. Results

3.1. Biogas and Methane Generation

The cumulative biogas and CH_4 generation over the 50-day HRT are depicted in Figure 2A,B respectively. Generally, biogas yield is directly proportional to the retention time until it achieves the point of nutrient exhaustion or depletion [24].

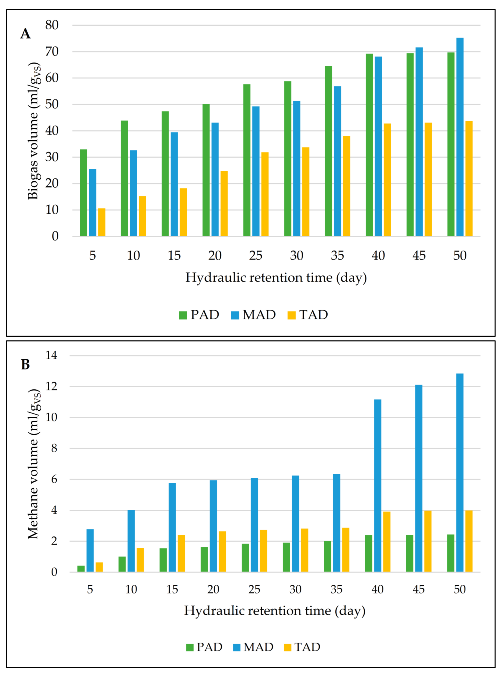

Figure 2. (**A**) Biogas generation and (**B**) Methane generation over 50-day hydraulic retention time.

Figure 2A observes biogas production under all three temperature parameters increasing steadily for the first 40 days. On the contrary, in the remaining 10 days, biogas production for PAD and TAD plateaued, peaking at 69.69 and 43.71 mL/g_{vs} respectively. Biogas volume for MAD on the other hand continues to rise up to 75.23 mL/g_{vs} at the end of the 50-day HRT. Despite recording high biogas production for PAD in the first 40 days, a notable small quantity of CH_4 is generated in comparison to MAD and TAD in the 50-day HRT as depicted in Figure 2B. MAD produced the most CH_4, 12.85 mL/g_{vs} cumulatively, although the pattern of CH_4 production appeared to plateau from day 15 up to day 35 before it depicted steady increment up to day 50. The CH_4 yield for PAD and TAD shows little to no significant increment from day 15 up to day 35 and from day 40 up to day 50 with the cumulative CH_4 production at 2.43 and 3.99 mL/g_{vs} respectively.

The CH_4 production at 20 °C is notably unfavourable due to the nature of PAD that has been inferred to be instable [25]. The inclusion of EFB to improve the C/N ratio also proves to be a challenge for PAD as the composition of cellulose, hemicellulose and lignin is high in EFB and they are naturally recalcitrant to microbial degradation [26]. Essentially, AD consist of four stages which are hydrolysis, acidogenesis, acetogenesis and methanogenesis.

In the case of PAD, the hydrolysis stage is established as the rate-limiting step which justifies the pattern of CH_4 generation, observing no apparent increment from day 15 onwards. Additionally, Rajagopal, et al. [27] also recommended to extend the retention time for PAD to improve CH_4 production. Instead, CH_4 production with respect to MAD and TAD have been studied exhaustively. Bayrakdar, et al. [28] pointed out that TAD better accommodates hydrolysis thus the limitation caused by the hydrolysis rate limit can be overcome. However, Yin, et al. [29] debunked that statement by observing that the rate limits for all four steps in AD of chicken manure is lower under MAD in comparison to TAD. Bi, et al. [16] also stood behind this finding by stating that MAD is more favourable in comparison to TAD. This is because chicken manure is an organic biomass waste with significant nitrogen content and in the case of TAD, high levels of total ammonium nitrogen have been observed [30]. Free ammonia nitrogen content, which makes a significant portion of total ammonium nitrogen rises as the temperature increases thus effectively, TAD is more prone to be jeopardized by ammonia inhibition in comparison to MAD [31]. In the case of EFB as the sole feedstock for AD, Lee, et al. [17] noted that despite the fact TAD observed CH_4 production at an enhanced rate because of the shorter lag phase, the yield was lower compared to MAD. Furthermore, the higher dissociation constant of volatile organic acids during TAD also makes the system more vulnerable to inhibition as well [32]. Nonetheless, although EFB is known to have a low degradability rate due to its high lignin content, the CH_4 enhanced favourably over time in the case of MAD and TAD. This is mainly due the composition of EFB which is rich with cellulose. The high cellulose content (23.7–65%) in the EFB leads to higher glucose formation through the hydrolysis process, in which it could be further converted to CH_4 during methanogenesis [12,33].

The current study instead emphasizes on a co-AD system thus both chicken manure and EFB are responsible for the rate of CH_4 production. As such, it can be inferred that ammonia inhibition is greater an issue to manage under TAD causing there to be an extended lag phase from day 15 onwards compared to MAD which plateaued from day 15 up to day 35, after which the CH_4 production flourished. Overall, it can be deduced that in the case of optimized C/N ratio, co-AD of chicken manure and EFB under MAD is most favourable as it observed the most biogas generation with a significantly abundant CH_4 content in comparison to PAD and TAD which can be converted into energy. These findings are also especially favourable with respect to the Malaysian climate should there be further initiatives for mass energy generation which could see the nation adopt multiple Sustainable Development Goals (SDGs) promoted by the United Nations, most notably SDG 7: Affordable and Clean Energy [34]. Additionally, such measures are also in line with the 11th Malaysia Plan observing a transformation into a carbon-neutral nation [35].

The results obtained are comparable to that of Chen, et al. [36] who evaluated pilot-scale AD of thermal hydrolysed sludge at thermophilic and mesophilic conditions with the latter observing significantly favourable results. Essentially, in their study, the effectiveness of the process is measured by the HRT required to achieve maximum biogas production in which MAD required 15 days, half of which demanded by TAD (30 days). In another study by Wu, et al. [37], although TAD observed higher biogas production, it was only under strict and stable conditions with much emphasis on low-solids feedstock to prevent ammonia inhibition which results in a more tedious and laborious effort.

3.2. Kinetic Analysis

A kinetic study is especially fruitful as it provides insight on the AD process such as the maximum CH_4 generation potential, B_o as well as its constraints including the lag phase, λ which is a challenge to deduce without the aid of a systematic, mathematical approach. Figure 3A–E are the kinetic plots for first order kinetic, Cone, Monod, modified Gompertz and Logistics function models respectively while Table 1 portrays the computed kinetic parameters relevant to each model.

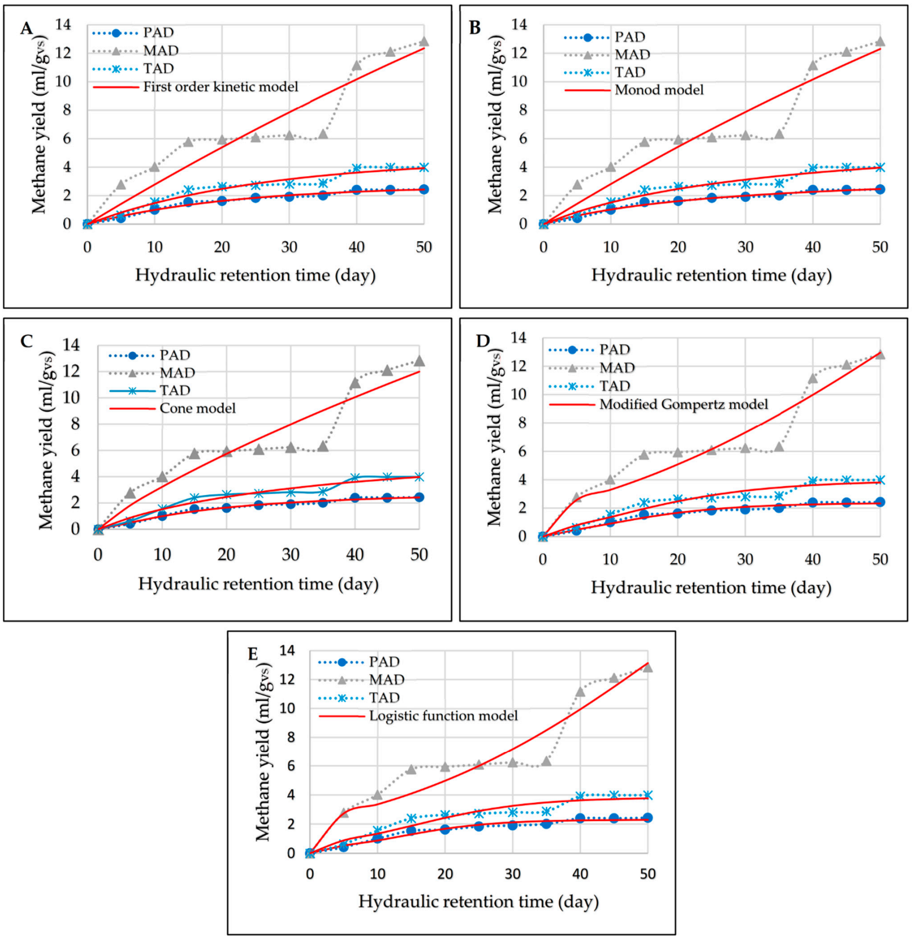

Figure 3. (**A**) First order kinetic, (**B**) Cone, (**C**) Monod, (**D**) modified Gompertz pand (**E**) Logistics function models.

Table 1. Kinetic parameters of first order kinetic, Monod, Cone, modified Gompertz and Logistic function models for co-AD of chicken manure and EFB.

First Order Kinetic Model

Setup	B_o (mL/g_{vs})	k (1/day)	R^2	*RMSE*	Experimental CH_4 Yield at Day 50 (mL/g_{vs})	Computed CH_4 Yield at Day 50 (mL/g_{vs})	Percent Difference (%)
PAD	2.701	0.046	0.984	0.030	2.434	2.431	0.123
MAD	47.277	0.006	0.882	0.391	12.845	12.357	3.799
TAD	4.603	0.039	0.957	0.079	3.988	3.932	1.404

Monod Model

Setup	B_o (mL/g_{vs})	k (1/day)	R^2	*RMSE*	Experimental CH_4 Yield at Day 50 (mL/g_{vs})	Computed CH_4 Yield at Day 50 (mL/g_{vs})	Percent Difference (%)
PAD	3.821	0.036	0.984	0.030	2.434	2.468	1.397
MAD	78.270	0.004	0.882	0.391	12.845	12.309	4.173
TAD	6.659	0.029	0.960	0.076	3.988	3.967	0.527

Cone Model

Setup	B_o (mL/g_{vs})	k (1/day)	n	R^2	*RMSE*	Experimental CH_4 Yield at Day 50 (mL/g_{vs})	Computed CH_4 Yield at Day 50 (mL/g_{vs})	Percent Difference (%)
PAD	3.070	0.056	1.277	0.975	0.031	2.434	2.422	0.493
MAD	150.259	0.001	0.852	0.840	0.415	12.845	11.996	6.610
TAD	7.078	0.026	0.960	0.933	0.084	3.988	3.979	0.226

Table 1. *Cont.*

Modified Gompertz Model								
Setup	B_o **(mL/g$_{vs}$)**	R_b **(mL/g$_{vs}$ day)**	λ **(Days)**	R^2	*RMSE*	**Experimental CH_4 Dield at Day 50 (mL/g$_{vs}$)**	**Computed CH_4 Dield at Day 50 (mL/g$_{vs}$)**	**Percent Difference (%)**
PAD	2.373	0.088	−0.278	0.970	0.040	2.434	2.334	4.108
MAD	52.569	0.330	11.100	0.897	0.365	12.845	12.962	0.911
TAD	3.968	0.120	−1.435	0.935	0.096	3.988	3.813	4.388
Logistics Function Model								
Setup	B_o **(mL/g$_{vs}$)**	R_b **(mL/g$_{vs}$ day)**	λ **(Days)**	R^2	*RMSE*	**Experimental CH_4 Yield at Day 50 (mL/g$_{vs}$)**	**Computed CH_4 Yield at Day 50 (mL/g$_{vs}$)**	**Percent Difference (%)**
PAD	2.299	0.086	−0.137	0.951	0.051	2.434	2.290	5.916
MAD	29.205	0.336	10.906	0.895	0.369	12.845	13.139	2.289
TAD	3.837	0.112	−1.797	0.913	0.112	3.988	3.771	5.441

The polynomial regression models observe the relationship between cumulative CH_4 generation as a function of co-AD of chicken manure and EFB. All five kinetic models depict a relative satisfactory fit with the experimental data as justified by the overall high R^2 and low *RMSE* values. The modified Gompertz model however stood out as it exhibits the highest overall R^2 (0.897–0.970) and lowest overall *RMSE* (0.040–0.365) in comparison to the other models. This suggests that the modified Gompertz model presents a more robust estimation of up to 97% with respect to the experimental data. This claim is in agreement with past studies associated with AD of kitchen waste [38] and cattle manure [39]; both of which observed the modified Gompertz model to be a more robust model which can be applied for better estimation of CH_4 generation.

The maximum CH_4 generation potential, B_o is depicted by all five models but considering the modified Gompertz model is the best fit, further inference is based on this model. The B_o for MAD is significantly higher (52.569 mL/g$_{vs}$) in comparison to PAD (2.373 mL/g$_{vs}$) and TAD (3.968 mL/g$_{vs}$). This indicates the untapped potential of MAD in the current setup as it has only achieved approximately one fifth of its predicted CH_4 generation potential. The maximum CH_4 generation rate, R_b and lag phase duration, λ is portrayed by the modified Gompertz model as well as the Logistic function model and the values do not deviate significantly. With respect to both models, the R_b for MAD (0.336–0.330 mL/g$_{vs}$ day) is higher by more than two folds and three folds in comparison to TAD (0.112–0.120 mL/g$_{vs}$ day) and PAD (0.086–0.088 mL/g$_{vs}$ day) respectively. The significantly higher B_o and R_b is further testimony that MAD is more apt compared to PAD and TAD in the case of chicken manure and EFB acting as co-substrates in a single system. EFB being rich in cellulose, hemicellulose and lignin strains microbial degradation [23] posing a hurdle for PAD in addition to its instable nature [40]. On the other hand, TAD with chicken manure as the sole feedstock is highly prone to be subjected to ammonia toxicity as reported in a past study by Ao, et al. [41]. In the case of EFB as a single substrate, Lee, et al. [17] noted that although MAD enhances CH_4 generation, TAD depicted higher R_b indicating shorter λ. Nonetheless, findings from the current study suggest that the nitrogen rich chicken manure has a greater effect on the co-digestive system and the effect of ammonia inhibition is too great of a challenge for the microabes hence deteriorating the B_o and R_b.

A downside for MAD is its λ which is 10.906–11.100 days based on the modified Gompertz model and Logistic function model, longer than PAD and TAD however objectively speaking the B_o and R_b makes up for this. The negative λ suggests that the CH_4 generation started from day one which is also an indication of desirable condition for growth of microbes [42]. Pečar and Goršek [43] observed that MAD of chicken manure with sawdust and miscanthus exhibited a relatively short λ, at most 0.22 days but it is imperative to note that the lignocellulosic content of said carbon additives are relatively low compared to EFB. Li, et al. [44] on the other hand explored MAD of chicken manure solely and with kitchen waste and corn stover. Similar to the findings of the current study, although the λ is extended with the addition of kitchen waste and corn stover, the B_o is significantly enhanced indicating the untapped potential for abundant CH_4 generation in said system. In another study by Lahboubi, et al. [45] using EFB as the single substrate for MAD, the λ was not more than 3.3 h however it is imperative to note that in said study the inoculum was put through an activation phase of 17 days before loaded with EFB so it is not realistic to compare both systems. Nonetheless, there are alternatives to reduce the λ such as maintaining the volatile fatty acid to alkalinity ratio below 0.4. Another option is to regulate the feed to microorganism ratio within 0.4 to 0.6 [46]. The λ is also associated to another variable which is the hydrolysis rate constant, k that is evaluated with respect to the first order kinetic model, Monod model and Cone model. The values do not deviate much but it is crucial to note that the R^2 for the first order kinetic model and Monod model is relatively higher, 0.882–0.984 as compared to the Cone model, 0.840–0.975. Based on the first order kinetic model and Monod model, the k value for MAD is significantly lower, 0.004–0.006 day^{-1} compared to PAD (0.036–0.046 day^{-1}) and TAD (0.029–0.039 day^{-1}). However, in contrary with claims by Pramanik, et al. [47] suggesting that higher k values lead to improved biogas production rates, findings from the current study suggest otherwise with respect to B_o and R_b with the exception of the extended λs.

4. Conclusions

The study comprehensively evaluated biogas and CH_4 generation under different temperature profiles with respect to five different kinetic models. The CH_4 yield, computed with respect to the cumulative biogas generation for PAD, MAD and TAD are 3.49%, 17.07% and 9.12% respectively; indicating that MAD is favourable in comparison to the other two. Although the CH_4 content plateaued from day 15 to 35, a significant increment is observed from day 40 onwards depicting the untapped potential of MAD. This is further justified by the B_o, observed from the best fit modified Gompertz model whereby the B_o for MAD is significantly higher, 52.569 mL/g_{vs} as compared to PAD (2.373 mL/g_{vs}) and TAD (3.968 mL/g_{vs}). Poor CH_4 yield for PAD is attributed to its instable nature in addition to high lignocellulosic content of EFB which posed an even greater challenge for microbial degradation. Microbes under TAD on the other hand is in jeopardy of ammonia inhibition due to the nitrogen rich chicken manure as well as the nature of elevated temperature conditions which encourage enhanced free ammonia concentrations. However, it is advantageous that TAD observes poor CH_4 yield as there is no need for additional heating of the AD system which results in higher operating cost should the system be upscaled.

Author Contributions: Conceptualization, M.D.M. and R.S.; methodology, M.D.M. and M.H.; software, M.D.M. and M.H.; validation, M.H., R.S. and J.W.L.; formal analysis, M.D.M., M.A.M.H. and N.T.S.; investigation, M.D.M. and M.H.N.B.A.; data curation, M.D.M. and M.H.N.B.A.; writing—original draft preparation, M.D.M. and M.H.N.B.A.; writing—review and editing, M.D.M., M.H., R.S., J.W.L., M.A.M.H. and N.T.S.; visualization, M.D.M.; supervision, R.S. and J.W.L.; project administration, M.D.M. and R.S.; funding acquisition, M.D.M. and R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Malaysian Ministry of Higher Education (MOHE) through Prototype Research Grant Scheme, PRGS/1/2022/TK09/UTP/02/2.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study is available on request from the corresponding author. The data are not publicly available as it is confidential.

Acknowledgments: The authors recognize the support from the Malaysian Ministry of Higher Education (MOHE) through HICoE Grant to Centre for Biofuel and Biochemical Research (CBBR).

Conflicts of Interest: The authors declare no conflict of interest. Author Rashid Shamsuddin received research grant from the Malaysian Ministry of Higher Education (MOHE). The funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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