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Excel Solver Aided Biogas Kinetics Computation for Varied Ratio Co-digestion of Cassava Peels with Chicken Manure

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ABSTRACT

Existing biogas kinetic models require computational expertise. This study presents an Excel Solver-based approach to improve accessibility and accuracy. The co-digestion of cassava peels (CP) and chicken manure (CM) represents a sustainable approach to biogas production; however, optimizing process conditions and kinetic modeling remain crucial for efficiency. The study employed Excel Solver to estimate kinetic parameters in the modified Gompertz and Cone models for three different CP:CM ratios (1:1, 1:3, and 3:1) under mesophilic conditions (ambient temperature) and a retention time of 40 days. Anaerobic digestion (AD) was conducted in 4-L batch digesters with a working volume of 2 L. Results showed that the 1:3 CP:CM ratio produced the highest cumulative biogas yield (0.25 m^3) from the experiment, outperforming the other ratios (1:1 = 0.2384 m^3 & 3:1 = 0.1576 m^3). At the optimal ratio, the modified-Gompertz model exhibited a superior fit (R^2 = 0.9684) compared to the Cone model (R^2 = 0.7586), with lower SSE values (2.157 vs. 16.503, respectively), confirming its reliability in capturing microbial adaptation and substrate degradation dynamics. The estimated parameters—biogas production potential (BP = 0.2076 m^3), maximum production rate (k = 0.0226 m^3/day), and lag phase (λ = 3.4 days)—highlighted the significance of nitrogen balance in optimizing biogas yield. The kinetic study is essential for predicting biogas production trends, optimizing digester performance, and designing efficient biogas systems. The Excel Solver, provided, is a user-friendly tool for nonlinear regression, eliminating the need for specialized statistical software.

1. INTRODUCTION

Cassava peels (CPs) and chicken manure (CM) are rich in essential nutrients, making them highly suitable for biogas production through anaerobic digestion (AD). CPs contain a high concentration of carbohydrates (primarily starch and fiber), lignocellulosic materials, and moderate protein content, which serve as an excellent source of fermentable organic matter for microbial degradation [1]. The high carbon content in CPs provides an abundant energy source for methanogenic bacteria, enhancing methane yield. Additionally, the presence of cellulose and hemicellulose contributes to sustained biogas production; however, pretreatment may be necessary to improve biodegradability. Onokwai et al. [2] reported that significant CP waste during Garri processing in Nigeria, as well as cassava bagasse from tuber starch production [3], is suitable for biogas production. On the other hand, CM is a nitrogen-rich substrate with a high protein and ammonia content [4], which helps balance the carbon-to-nitrogen (C/N) ratio investigated by Al-Zoubi et al. [5], when co-digested with CPs. It also contains essential trace elements such as phosphorus, potassium, sulfur, and micronutrients (e.g., iron, magnesium, and zinc) that support microbial activity in AD. Abubakar et al. [6] and Etta et al. [7] affirmed that the production of biogas using CM doesn't require the addition of microorganisms, as the natural presence of beneficial microbial consortia enhances the hydrolysis and methanogenesis stages. But the ratio at which these are combined is essential for optimal biogas recovery [8][9]. Kayaba et al. [10]'s mixing of chicken droppings and CPs shows how an equal blend (i.e., 50:50 ratio) produced the highest yield. When Ofon et al. [11] studied equal ratio AD of manure and food waste, improved biogas yield was generated at a ratio of 1:1 than sole food residue utilization. Achebe et al. [12] and Opurum et al. [13] also tested the role played by varying ratios of CP and CM in AD. Primarily, biogas production rates are governed by several models, including the modified Gompertz and cone models. The Gompertz model is indeed a mathematical model used to describe sigmoidal (S-shaped) growth curves, including population growth, tumor growth, and microbial growth. And the modified-

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Gompertz version is an adaptation of the classical Gompertz model, specifically tailored to describe cumulative biogas or methane production in AD and bioprocesses [14]. It was originally introduced by Benjamin Gompertz in 1825 to describe human mortality rates, but it has since been applied to various growth phenomena, including biogas production and biological systems. In a similar study, Opurum et al. [13] findings show that CP/poultry manure blend at 3:1 and 2:1 performed best using the modified-Gompertz model. On the other hand, the Cone model (developed by John W. Cone, a researcher in animal nutrition and fermentation studies) is an empirical model developed for evaluating methane production from specific substrates, particularly in AD and ruminal fermentation studies. In this mode, the shape factor (SF) controls the curvature of the methane production profile. If SF = 1, the curve follows a first-order kinetic model without a lag phase (LP), whereas if SF ≠ 1, an LP may be present. Both models describe methane production, but the modified-Gompertz model is widely used in AD, whereas the Cone model is more common in ruminal digestion and specific substrate evaluations. Determining the constant parameters in these models, which describe the biogas production process, can be carried out using the Excel Solver add-on in Microsoft Excel software. Excel Solver provides a cost-effective, efficient, and accessible method for estimating parameters in nonlinear biogas production models. Its optimization capabilities, flexibility in defining objective functions, and ease of visualization make it a valuable tool for researchers working on AD and biogas kinetics without requiring advanced programming skills in MATLAB, Python, or R.

Herein, via 3 different digesting systems, a blend of CP and CM in ratios of 1:1, 1:3, and 3:1 was anaerobically digested to produce biogas. The study accounts for the presence of negligible residual gases in the bioreactors for effective parameter estimation using Excel Solver. Excel Solver was employed because it simplifies the optimization process by using GRG Nonlinear and Evolutionary Algorithms (EA) to minimize the sum of squared errors (SSE) between experimental and predicted values. Excel Solver employs an accessible approach to predicting biogas kinetic parameters compared to MATLAB, Python, AQUASIM, or ADM1, as it requires no programming skills and allows researchers to perform regression analysis using simple spreadsheet functions for quick optimization tasks. While previous studies have modeled biogas kinetics, few have used Excel Solver as a practical tool. This study aims to evaluate its accuracy in parameter estimation and model fitting. Using a simple weight measurement principle, the volume and cumulative biogas volumes (CBV) from these digesters were recorded over a short time interval until further biogas yield was observed. The study also compares the model evaluation statistical parameters determined by using Excel Solver for the best model at a particular (optimal) ratio. Essentially, the study further addresses the waste concerns CPs pose, as previously mentioned in Awogbemi et al. [15]. Apart from merely co-digesting substrates, the supply of additives in mono- or co-digestion of either CM or CP with other biomass, including biochar [16][17], bleed water [18], iron oxide nanoparticles [4], rock salt, etc., have proven effective. Previously, the impact of the substrate-water dilution ratio was investigated [19][20].

2. METHOD

Materials employed in the course of this study are CM, CP, and water. The equipment used to execute the experiments includes digesters, measuring cylinders, gas collectors, a timer, and a pipe. The methodological steps followed are summarized under the flowchart in Figure 1.

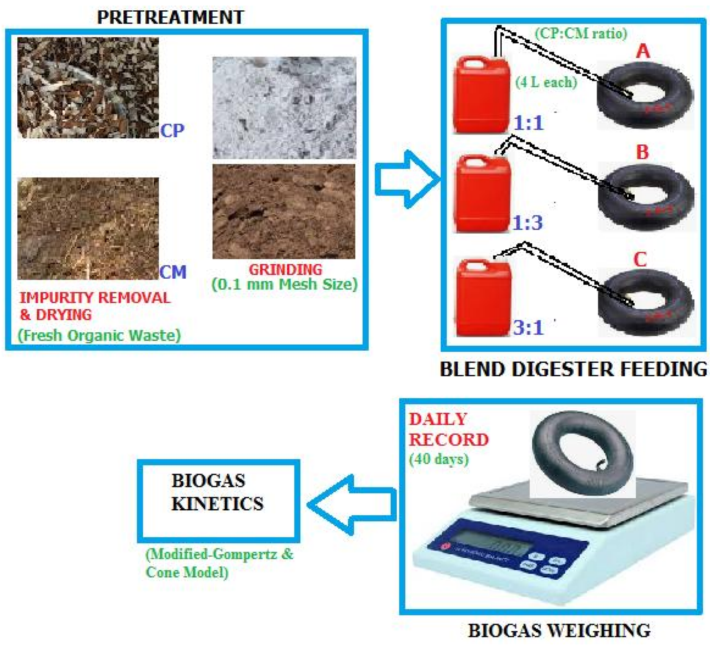

Figure 1. Flow Diagram of Steps Followed.

Broadly, the steps in the Figure were divided into biogas measurement and kinetic study. The temperature effect was not considered, as the ambient temperature was suitable for biogas production, given that anaerobic microorganisms enhancing biogas production could survive in psychrophilic, mesophilic, thermophilic, and hyperthermophilic regimes.

2.1. Biogas Production Setup and Measurement

CPs were washed and sun-dried along with CM before separating them into distinct mixture ratios of 1:1, 1:3, and 3:1 w/w. Before then, the traditional hand-picking method described by Abubakar et al. [21], was used to rid the CM of foreign materials. Each blend was ground into fine powder, sieved with a 0.1 mm mesh size sieve, and kept in 4 L separate container-like digesters (A, B, and C), as conducted by Achebe et al. [12]. A working volume of 2 L, consisting of water (1.6 L) plus the blend (remainder = 400 g solid) used by Nweke & Nwabanne [22], was maintained in each digester. Essentially, digester A contains 400g digestible waste feed, that is 50% CP and 50% CM; digester B consists of 25% CP and 75% CM, and digester C has 75% CP and 25% CM. The three bioreactors shown in Figure 2 were run at atmospheric temperature for a 40-day retention period/time (RT) used in Laiche et al. [23], within the influential temperature range reported by Jauro et al. [1].

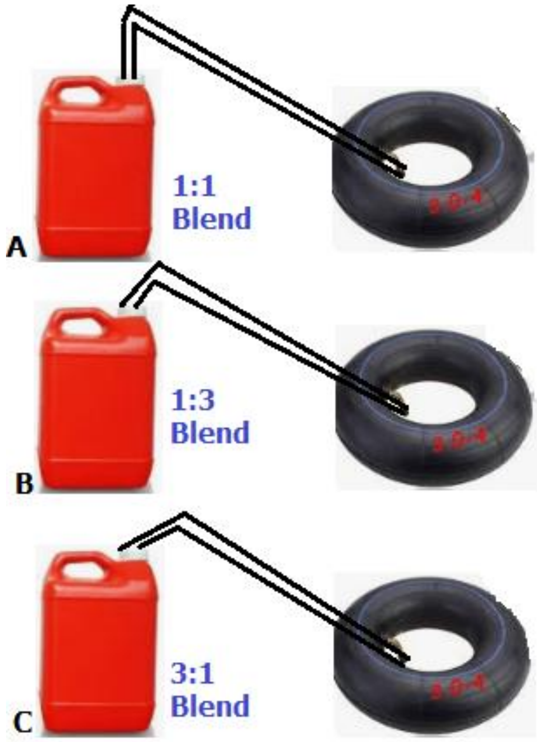

Figure 2. Schematic Representation of the Digesters Setup

At RT = 0 days, the setup was initiated by connecting the gas outlet stream to a gas holder or tube. To avoid error, tightly sealed bioreactors were employed. Initially, the weight of the tube for each setup was measured and recorded. As digestion occurs, the gas holder is expected to swell gradually, indicating an increase in mass or a kick-start in biogas production. To account for this increase over time, the weight of the gas holder was measured after 2-day intervals in each reactor and subtracted from the initial weight of the tube. The result was then tabled as the weight of biogas produced (m_{Biogas}). An undisturbed process (no stirring) was set up, as opposed to the experiment carried out by Jijai et al. [24] to maintain microbial stratification, allowing syntrophic bacteria and methanogens to establish stable microenvironments, which can enhance methane yield and reduce energy consumption.

2.2. Kinetics Using Existing Models and Fit

At the start of biogas production (day 0), a trace amount of biogas, equivalent to 0.0001 kg, was presumed as a negligible initial volume attributed to the presence of residual gases or volatile organic compounds already existing in the anaerobic digester before the digestion process begins. For convenience, the weights recorded for biogas production at 2 2-day interval were converted to volume (V_{Biogas}), using biogas density (ρ_{Biogas}) 1.2 kg/m^3 reported by Abubakar et al. [25] – as shown in Equation 1.

$$V_{Biogas} = \frac{m_{Biogas}}{\rho_{Biogas}} \quad (1)$$

Since the modified Gompertz and Cone models of biogas kinetics are presented in CBV, as expressed in Equations 2 [14] and 3, respectively, the CBV values were determined by successively adding current V_{Biogas} with the immediate next ones, up to the last RT.

$$\ln CBV = \ln BP - 2.718282\, e^{\frac{k.e}{BP}(LP-RT)} \quad (2)$$

$$\ln CBV = \ln BP - \ln[1 + (k.RT)^{-SF}] \quad (3)$$

Where, CBV = cumulative biogas volume at a digestion time (m^3), RT = retention time (day), SF = shape factor (dimensionless), LP = lag phase (day), BP = biogas production potential (m^3/day), e = mathematical constant (2.718282) and k = maximum biogas production rate (m^3/day). The CBV obtained in this way was labeled as experimental (CBV sub, Expt. end subscript) to differentiate it from the predicted ones (CBV sub, Prdct. end subscript), which were obtained through regression analysis for both modified Gompertz and Cone models. Using eight designed steps for obtaining the coefficient of determination (R^2) proposed by Abubakar et al. [26], the unknown constant parameters in the two models employed were estimated for every ratio for bioreactor A, B and C. It involves the determination of the total sum of squares (TSS) = $\sum(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2$ and the sum of squared error (SSE) = $\sum(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$. A plot of $CBV_{Prdct.}$ and $CBV_{Expt.}$ versus RT was carried out to observe the extent of fit. This was also complemented by a plot of CBV sub versus a plot of CBV sub, Product of $CBV_{Prdct.}$ against $CBV_{Expt.}$.

3. RESULTS AND DISCUSSION

3.1. Effect of Blend Ratio on Biogas Mass

Absence of recorded biogas mass towards the end of digestion (days 32–40) in Table 1 can be attributed to substrate depletion, microbial activity decline, temperature and environmental conditions, accumulation of inhibitory compounds, substrate composition and C/N ratio, pH imbalance, and process completion [5]. Different CP:CM ratios in Table 1 affected the rate of biogas production and the point at which the process was completed. The 1:3 ratio (higher CM content) produced the highest biogas yield (peaked at 30 g – Figure 3) and maintained gas production for a more extended period before declining around RT = 30 days; comparable to the same period examined by Dinneya-Onuoha et al. [27]. Thus, suggests that CM provided a more favorable nutrient balance, particularly in terms of nitrogen content, supporting sustained microbial activity.

Table 1. Biogas Mass Recorded from Each Anaerobic Co-digestion

RT (day)	m_{Biogas} (g)		
	Ratio 1:1	Ratio 1:3	Ratio 3:1
0	0	0	0
2	10	10	10
4	15	20	15
6	15	20	15
8	20	25	15
10	23	30	18
12	25	30	18
14	25	30	18
16	25	30	15
18	25	25	15
20	23	25	15
22	20	20	10
24	15	10	10
26	15	10	5
28	10	10	5
30	10	5	5
32	5	0	0
34	5	0	0
36	0	0	0
38	0	0	0
40	0	0	0

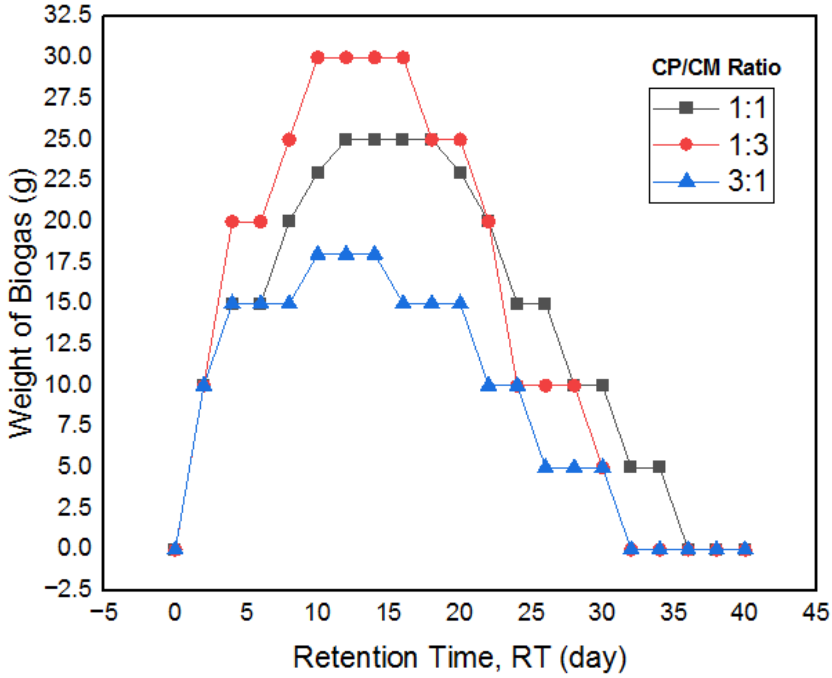

Figure 3. Weight of Biogas Produced with RT at Different CP/CM Blend Ratios

In contrast, the 1:1 ratio exhibited a moderate biogas yield, peaking around day 12–18 before gradually declining Figure 3, indicating a balanced substrate composition that allowed for efficient digestion but eventually became depleted. As against the findings reported by Opurum et al. [13], the 3:1 ratio (higher CP content) had the lowest biogas yield and exhibited an earlier decline in gas production in this study, suggesting that excessive CPs may have led to suboptimal impact. In a nutshell, a balanced C/N ratio is crucial for optimal digestion, as an excess of carbon-rich material (i.e., CPs) can lead to slow degradation and acidification. At the same time, excessive nitrogen (in CM) may cause ammonia inhibition. The 1:3 ratio demonstrated the best performance, indicating that an increased proportion of nitrogen-rich material can enhance microbial efficiency and prolong gas production. Rhandouriate et al. [18] and Aisien & Aisien [28] reported a similar trend of biogas volume or mass-time relationship observed in Figure 3. However, beyond a certain point, excessive nitrogen may become inhibitory. Therefore, optimizing the substrate blend is essential for maximizing biogas yield and ensuring a stable digestion process.

3.2. Predicted CBV for Different Blend Ratios

In Table 2, weight in 'g' was converted to 'kg' for uniformity of units, given that the ρ_{Biogas} unit is already in the SI system. For predictive accuracy, the presence of residual gases (RT = 0 days) in all digesters was specified (at 0.0001 kg instead of 0 kg, as entered in Table 1), taking ideality into account. Such residuals might result from prior system operations, the presence of air trapped during substrate loading, or the early decomposition of highly biodegradable components in the feedstock. This minimal biogas volume serves as the baseline for monitoring the CBV over time. It reflects the system's readiness to initiate microbial activity, as the AD process typically takes time to reach its optimal gas production phase due to microbial adaptation (lag phase). Thus, the 0.0001 kg biogas measurement reported in Table 2 serves as a reference point for evaluating subsequent biogas production dynamics and model predictions.

Table 2. Detailed Calculations for Determination of the Predicted CBV

Modified Gompertz (1:1)									
RT (day)	m_{Biogas} (kg)	V_{Biogas} (m^3)	$CBV_{Expt.}$ (m^3)	$\ln CBV_{Expt.}$	$(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2$	$\ln CBV_{Prdct.}$	$\ln CBV_{Expt.} - \ln CBV_{Prdct.}$	$(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$	$CBV_{Prdct.}$ (m^3)
0	0.0001	8.33333E-05	8.33333E-05	-9.392661929	47.60394375	-8.876593243	-0.516068686	0.266326889	0.000139619
2	0.01	0.008333333	0.008416667	-4.777541412	5.218668903	-5.850189182	1.07264777	1.150573238	0.002879354
4	0.015	0.0125	0.020916667	-3.86720899	1.888173313	-4.096076907	0.228867917	0.052380523	0.016637819
6	0.015	0.0125	0.033416667	-3.398700501	0.820110817	-3.079388516	-0.319311986	0.101960144	0.045987369
8	0.02	0.016666667	0.050083333	-2.994066994	0.250967126	-2.490113075	-0.503953919	0.253969552	0.082900592
10	0.023	0.019166667	0.06925	-2.670032134	0.031304696	-2.148567379	-0.521464755	0.271925491	0.116651155
12	0.025	0.020833333	0.090083333	-2.407020111	0.007409885	-1.950606536	-0.456413576	0.208313352	0.142187803
14	0.025	0.020833333	0.110916667	-2.19897611	0.086509334	-1.835867876	-0.363108234	0.13184759	0.159475037
16	0.025	0.020833333	0.13175	-2.026849092	0.217390657	-1.769365028	-0.257484064	0.066298043	0.17044118
18	0.025	0.020833333	0.152583333	-1.880044384	0.375838171	-1.73081979	-0.149224594	0.022267979	0.177139133
20	0.023	0.019166667	0.17175	-1.761715348	0.534924682	-1.708478863	-0.053236485	0.002834123	0.181141124
22	0.02	0.016666667	0.188416667	-1.669099456	0.678978216	-1.695529998	0.026430542	0.000698574	0.183501948
24	0.015	0.0125	0.200916667	-1.604865051	0.788962749	-1.6880248	0.08315975	0.006915544	0.184884347
26	0.015	0.0125	0.213416667	-1.544508843	0.899826704	-1.683674767	0.139165924	0.019367154	0.185690352
28	0.01	0.008333333	0.22175	-1.506204658	0.973963998	-1.681153475	0.174948817	0.030607089	0.186159122
30	0.01	0.008333333	0.230083333	-1.469313717	1.048139995	-1.679692127	0.21037841	0.044259075	0.186431364
32	0.005	0.004166667	0.23425	-1.451366358	1.085210651	-1.678845126	0.227478768	0.05174659	0.186589339
34	0.005	0.004166667	0.238416667	-1.433735436	1.122254978	-1.678354201	0.244618766	0.059838341	0.186680963
36	0	0	0.238416667	-1.433735436	1.122254978	-1.67806966	0.244334225	0.059699213	0.186734089
38	0	0	0.238416667	-1.433735436	1.122254978	-1.67790474	0.244169304	0.059618649	0.186764887
40	0	0	0.238416667	-1.433735436	1.122254978	-1.677809151	0.244073715	0.059571978	0.186782741
Modified Gompertz (1:3)									
RT (day)	m_{Biogas} (kg)	V_{Biogas} (m^3)	$CBV_{Expt.}$ (m^3)	$\ln CBV_{Expt.}$	$(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2$	$\ln CBV_{Prdct.}$	$\ln CBV_{Expt.} - \ln CBV_{Prdct.}$	$(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$	$CBV_{Prdct.}$ (m^3)
0	0.0001	8.33333E-05	8.33333E-05	-9.392661929	49.40110684	-8.989712911	-0.402949018	0.162367911	0.000124686
2	0.01	0.008333333	0.008416667	-4.777541412	5.824845059	-5.681635097	0.904093685	0.817385391	0.003407982
4	0.02	0.016666667	0.025083333	-3.685551664	1.746314228	-3.848870545	0.163318881	0.026673057	0.021303785
6	0.02	0.016666667	0.04175	-3.176055828	0.659321254	-2.833469429	-0.342586399	0.117365441	0.058808468
8	0.025	0.020833333	0.062583333	-2.771256277	0.1658008	-2.270909756	-0.500346521	0.250346641	0.103218234
10	0.03	0.025	0.087583333	-2.435164558	0.00505446	-1.959236487	-0.475928071	0.226507528	0.140966009
12	0.03	0.025	0.112583333	-2.184061591	0.032402968	-1.786561069	-0.397500522	0.158006665	0.167535323
14	0.03	0.025	0.137583333	-1.983525485	0.144814001	-1.690894219	-0.292631266	0.085633058	0.184354597
16	0.03	0.025	0.162583333	-1.816564588	0.299761994	-1.637892197	-0.178672391	0.031923823	0.194389345
18	0.025	0.020833333	0.183416667	-1.695994847	0.446324188	-1.608527644	-0.087467203	0.007650512	0.200182137
20	0.025	0.020833333	0.20425	-1.588410545	0.601647332	-1.592258888	0.003848343	1.48097E-05	0.203465487
22	0.02	0.016666667	0.220916667	-1.509969722	0.729487	-1.583245557	0.073275834	0.005369348	0.205307678
24	0.01	0.008333333	0.22925	-1.472942168	0.794108517	-1.578251928	0.10530976	0.011090146	0.206335472
26	0.01	0.008333333	0.237583333	-1.43723684	0.859019398	-1.575485322	0.138248483	0.019112643	0.206907112
28	0.01	0.008333333	0.245916667	-1.402762554	0.924111686	-1.573952548	0.171189994	0.029306014	0.207224497
30	0.005	0.004166667	0.250083333	-1.385961083	0.956696728	-1.57310335	0.187142266	0.035022228	0.207400546
32	0	0	0.250083333	-1.385961083	0.956696728	-1.572632871	0.186671788	0.034846356	0.207498147
34	0	0	0.250083333	-1.385961083	0.956696728	-1.572372213	0.18641113	0.034749109	0.20755224
36	0	0	0.250083333	-1.385961083	0.956696728	-1.572227801	0.186266718	0.03469529	0.207582215
38	0	0	0.250083333	-1.385961083	0.956696728	-1.572147793	0.18618671	0.034665491	0.207598824
40	0	0	0.250083333	-1.385961083	0.956696728	-1.572103467	0.186142384	0.034648987	0.207608026

Modified Gompertz (3:1)									
RT (day)	m_{Biogas} (kg)	V_{Biogas} (m^3)	$CBV_{Expt.}$ (m^3)	$\ln CBV_{Expt.}$	$(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2$	$\ln CBV_{Prdct.}$	$\ln CBV_{Expt.} - \ln CBV_{Prdct.}$	$(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$	$CBV_{Prdct.}$ (m^3)
0	0.0001	8.33333E-05	8.33333E-05	-9.392661929	88.22209811	-8.876593243	-0.516068686	0.266326889	0.000139619
2	0.01	0.008333333	0.008416667	-4.777541412	22.82490194	-5.850189182	1.07264777	1.150573238	0.002879354
4	0.015	0.0125	0.020916667	-3.86720899	14.95530537	-4.096076907	0.228867917	0.052380523	0.016637819
6	0.015	0.0125	0.033416667	-3.398700501	11.5511651	-3.079388516	-0.319311986	0.101960144	0.045987369
8	0.015	0.0125	0.045916667	-3.08092712	9.492111916	-2.490113075	-0.590814044	0.349061235	0.082900592
10	0.018	0.015	0.060916667	-2.798248469	7.830194494	-2.148567379	-0.64968109	0.422085519	0.116651155
12	0.018	0.015	0.075916667	-2.578119032	6.646697741	-1.950606536	-0.627512496	0.393771932	0.142187803
14	0.018	0.015	0.090916667	-2.397811943	5.749502114	-1.835867876	-0.561944067	0.315781134	0.159475037
16	0.015	0.0125	0.103416667	-2.268989144	5.148311734	-1.769365028	-0.499624116	0.249624257	0.17044118
18	0.015	0.0125	0.115916667	-2.154883737	4.643523919	-1.73081979	-0.424063947	0.179830231	0.177139133
20	0.015	0.0125	0.128416667	-2.052475093	4.212654009	-1.708478863	-0.343996231	0.118333407	0.181141124
22	0.01	0.008333333	0.13675	-1.989600838	3.958511493	-1.695529998	-0.294070839	0.086477659	0.183501948
24	0.01	0.008333333	0.145083333	-1.930446989	3.726625577	-1.6880248	-0.242422189	0.058768518	0.184884347
26	0.005	0.004166667	0.14925	-1.902132527	3.618108149	-1.683674767	-0.21845776	0.047723793	0.185690352
28	0.005	0.004166667	0.153416667	-1.874597748	3.514116715	-1.681153475	-0.193444273	0.037420687	0.186159122
30	0.005	0.004166667	0.157583333	-1.84780086	3.414368019	-1.679692127	-0.168108733	0.028260546	0.186431364
32	0	0	0.157583333	-1.84780086	3.414368019	-1.678845126	-0.168955734	0.02854604	0.186589339
34	0	0	0.157583333	-1.84780086	3.414368019	-1.678354201	-0.169446659	0.02871217	0.186680963
36	0	0	0.157583333	-1.84780086	3.414368019	-1.67806966	-0.1697312	0.02880868	0.186734089
38	0	0	0.157583333	-1.84780086	3.414368019	-1.67790474	-0.169896121	0.028864692	0.186764887
40	0	0	0.157583333	-1.84780086	3.414368019	-1.677809151	-0.169991709	0.028897181	0.186782741
Cone Model (1:1)									
RT (day)	m_{Biogas} (kg)	V_{Biogas} (m^3)	$CBV_{Expt.}$ (m^3)	$\ln CBV_{Expt.}$	$(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2$	$\ln CBV_{Prdct.}$	$\ln CBV_{Expt.} - \ln CBV_{Prdct.}$	$(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$	$CBV_{Prdct.}$ (m^3)
0	0.0001	8.33333E-05	8.33333E-05	-9.392661929	47.60394375	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2	0.01	0.008333333	0.008416667	-4.777541412	5.218668903	-2.148122748	-2.629418664	6.913842509	0.116703033
4	0.015	0.0125	0.020916667	-3.86720899	1.888173313	-2.148122745	-1.719086244	2.955257516	0.116703034
6	0.015	0.0125	0.033416667	-3.398700501	0.820110817	-2.148122745	-1.250577756	1.563944724	0.116703034
8	0.02	0.016666667	0.050083333	-2.994066994	0.250967126	-2.148122745	-0.845944249	0.715621672	0.116703034
10	0.023	0.019166667	0.06925	-2.670032134	0.031304696	-2.148122745	-0.521909389	0.27238941	0.116703034
12	0.025	0.020833333	0.090083333	-2.407020111	0.007409885	-2.148122745	-0.258897366	0.067027846	0.116703034
14	0.025	0.020833333	0.110916667	-2.19897611	0.086509334	-2.148122745	-0.050853365	0.002586065	0.116703034
16	0.025	0.020833333	0.13175	-2.026849092	0.217390657	-2.148122745	0.121273654	0.014707299	0.116703034
18	0.025	0.020833333	0.152583333	-1.880044384	0.375838171	-2.148122745	0.268078361	0.071866008	0.116703034
20	0.023	0.019166667	0.17175	-1.761715348	0.534924682	-2.148122745	0.386407397	0.149310677	0.116703034
22	0.02	0.016666667	0.188416667	-1.669099456	0.678978216	-2.148122745	0.479023289	0.229463311	0.116703034
24	0.015	0.0125	0.200916667	-1.604865051	0.788962749	-2.148122745	0.543257695	0.295128923	0.116703034
26	0.015	0.0125	0.213416667	-1.544508843	0.899826704	-2.148122745	0.603613903	0.364349744	0.116703034
28	0.01	0.008333333	0.22175	-1.506204658	0.973963998	-2.148122745	0.641918087	0.412058831	0.116703034
30	0.01	0.008333333	0.230083333	-1.469313717	1.048139995	-2.148122745	0.678809028	0.460781697	0.116703034
32	0.005	0.004166667	0.23425	-1.451366358	1.085210651	-2.148122745	0.696756387	0.485469463	0.116703034
34	0.005	0.004166667	0.238416667	-1.433735436	1.122254978	-2.148122745	0.71438731	0.510349228	0.116703034
36	0	0	0.238416667	-1.433735436	1.122254978	-2.148122745	0.71438731	0.510349228	0.116703034
38	0	0	0.238416667	-1.433735436	1.122254978	-2.148122745	0.71438731	0.510349228	0.116703034
40	0	0	0.238416667	-1.433735436	1.122254978	-2.148122745	0.71438731	0.510349228	0.116703034

one Model (1:3)									
RT (day)	m_{Biogas} (kg)	V_{Biogas} (m^3)	$CBV_{Expt.}$ (m^3)	$\ln CBV_{Expt.}$	$(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2$	$\ln CBV_{Prdct.}$	$\ln CBV_{Expt.} - \ln CBV_{Prdct.}$	$(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$	$CBV_{Prdct.}$ (m^3)
0	0.0001	8.33333E-05	8.33333E-05	-9.392661929	49.40110684	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2	0.01	0.008333333	0.008416667	-4.777541412	5.824845059	-2.012640232	-2.76490118	7.644678536	0.13363538
4	0.02	0.016666667	0.025083333	-3.685551664	1.746314228	-2.012640229	-1.672911435	2.79863267	0.13363538
6	0.02	0.016666667	0.04175	-3.176055828	0.659321254	-2.012640229	-1.163415599	1.353535856	0.13363538
8	0.025	0.020833333	0.062583333	-2.771256277	0.1658008	-2.012640229	-0.758616048	0.575498308	0.13363538
10	0.03	0.025	0.087583333	-2.435164558	0.00505446	-2.012640229	-0.422524329	0.178526809	0.13363538
12	0.03	0.025	0.112583333	-2.184061591	0.032402968	-2.012640229	-0.171421362	0.029385283	0.13363538
14	0.03	0.025	0.137583333	-1.983525485	0.144814001	-2.012640229	0.029114744	0.000847668	0.13363538
16	0.03	0.025	0.162583333	-1.816564588	0.299761994	-2.012640229	0.196075641	0.038445657	0.13363538
18	0.025	0.020833333	0.183416667	-1.695994847	0.446324188	-2.012640229	0.316645382	0.100264298	0.13363538
20	0.025	0.020833333	0.20425	-1.588410545	0.601647332	-2.012640229	0.424229684	0.179970824	0.13363538
22	0.02	0.016666667	0.220916667	-1.509969722	0.729487	-2.012640229	0.502670506	0.252677638	0.13363538
24	0.01	0.008333333	0.22925	-1.472942168	0.794108517	-2.012640229	0.539698061	0.291273997	0.13363538
26	0.01	0.008333333	0.237583333	-1.43723684	0.859019398	-2.012640229	0.575403389	0.33108906	0.13363538
28	0.01	0.008333333	0.245916667	-1.402762554	0.924111686	-2.012640229	0.609877675	0.371950779	0.13363538
30	0.005	0.004166667	0.250083333	-1.385961083	0.956696728	-2.012640229	0.626679146	0.392726751	0.13363538
32	0	0	0.250083333	-1.385961083	0.956696728	-2.012640229	0.626679146	0.392726751	0.13363538
34	0	0	0.250083333	-1.385961083	0.956696728	-2.012640229	0.626679146	0.392726751	0.13363538
36	0	0	0.250083333	-1.385961083	0.956696728	-2.012640229	0.626679146	0.392726751	0.13363538
38	0	0	0.250083333	-1.385961083	0.956696728	-2.012640229	0.626679146	0.392726751	0.13363538
40	0	0	0.250083333	-1.385961083	0.956696728	-2.012640229	0.626679146	0.392726751	0.13363538
Cone Model (3:1)									
RT (day)	m_{Biogas} (kg)	V_{Biogas} (m^3)	$CBV_{Expt.}$ (m^3)	$\ln CBV_{Expt.}$	$(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2$	$\ln CBV_{Prdct.}$	$\ln CBV_{Expt.} - \ln CBV_{Prdct.}$	$(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$	$CBV_{Prdct.}$ (m^3)
0	0.0001	8.33333E-05	8.33333E-05	-9.392661929	44.25084613	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2	0.01	0.008333333	0.008416667	-4.777541412	4.14941149	-2.40792444	-2.369616972	5.615084592	0.090001905
4	0.015	0.0125	0.020916667	-3.86720899	1.269403332	-2.407924437	-1.459284552	2.129511404	0.090001905
6	0.015	0.0125	0.033416667	-3.398700501	0.433187116	-2.407924437	-0.990776064	0.981637209	0.090001905
8	0.015	0.0125	0.045916667	-3.08092712	0.11586953	-2.407924437	-0.673002682	0.45293261	0.090001905
10	0.018	0.015	0.060916667	-2.798248469	0.003331308	-2.407924437	-0.390324032	0.15235285	0.090001905
12	0.018	0.015	0.075916667	-2.578119032	0.026377642	-2.407924437	-0.170194594	0.0289662	0.090001905
14	0.018	0.015	0.090916667	-2.397811943	0.11745634	-2.407924437	0.010112494	0.000102263	0.090001905
16	0.015	0.0125	0.103416667	-2.268989144	0.222351706	-2.407924437	0.138935294	0.019303016	0.090001905
18	0.015	0.0125	0.115916667	-2.154883737	0.342982696	-2.407924437	0.253040701	0.064029596	0.090001905
20	0.015	0.0125	0.128416667	-2.052475093	0.473420906	-2.407924437	0.355449344	0.126344236	0.090001905
22	0.01	0.008333333	0.13675	-1.989600838	0.563896082	-2.407924437	0.4183236	0.174994634	0.090001905
24	0.01	0.008333333	0.145083333	-1.930446989	0.656236076	-2.407924437	0.477477448	0.227984714	0.090001905
26	0.005	0.004166667	0.14925	-1.902132527	0.702911971	-2.407924437	0.505791911	0.255825457	0.090001905
28	0.005	0.004166667	0.153416667	-1.874597748	0.749840367	-2.407924437	0.53332669	0.284437358	0.090001905
30	0.005	0.004166667	0.157583333	-1.84780086	0.796967071	-2.407924437	0.560123577	0.313738422	0.090001905
32	0	0	0.157583333	-1.84780086	0.796967071	-2.407924437	0.560123577	0.313738422	0.090001905
34	0	0	0.157583333	-1.84780086	0.796967071	-2.407924437	0.560123577	0.313738422	0.090001905
36	0	0	0.157583333	-1.84780086	0.796967071	-2.407924437	0.560123577	0.313738422	0.090001905
38	0	0	0.157583333	-1.84780086	0.796967071	-2.407924437	0.560123577	0.313738422	0.090001905
40	0	0	0.157583333	-1.84780086	0.796967071	-2.407924437	0.560123577	0.313738422	0.090001905

Observed biogas volumes were recorded at various RTs, increasing over time as the digestion process progressed. At RT = 0 days, $CBV_{Expt.}$ begins near zero, reflecting the system's initial state. As digestion proceeds, cumulative gas production exhibits a characteristic rise, peaking at 0.238, 0.244, and 0.187 m^3, respectively, for 1:1, 1:3, and 3:1 ratios, around RT = 34-40 days. Maximum cumulative biogas production (418 mL g^{-1} VS) was achieved during co-digestion of food waste with pig manure > CM (408 mL g^{-1} VS) >

goat manure (319 mL g^{-1} VS) at a ratio of 1:1 each [11]. The logarithmic values of $CBV_{Expt.}$ ($\ln CBV_{Expt.}$) were calculated to linearize the data and assess the model fit. The squared differences between logarithmic values of $CBV_{Expt.}$ and their average $\{(\ln CBV_{Expt.} - \ln CBV_{Expt.avg})^2\}$ quantify the spread of the experimental data around its mean. The computation revealed a $\ln CBV_{Expt.avg} = \frac{\sum \ln CBV_{Expt.}}{21}$ = –2.493, –2.364 & –2.364 for 1:1, 1:3 and 3:1 CP/CM ratio employing the modified-Gompertz model and –2.493, –2.364 & –2.741 while analyzing the data using the Cone model, respectively. Similarly, the differences and squared differences between $\ln CBV_{Expt.}$ and $\ln CBV_{Prdct.}$ evaluates the deviation of model predictions. In Table 2, predictions ($CBV_{Prdct.}$) derived from the Modified Gompertz model generally align with the experimental data, but show deviations in certain intervals. As biogas production stabilizes after RT = 20 days, both models closely approximate the observed data, as evidenced by smaller $(\ln CBV_{Expt.} - \ln CBV_{Prdct.})^2$ values. Figures 4 and 5 are the respective plots of $CBV_{Prdct.}$ and $CBV_{Expt.}$ versus RT at the specified ratios based on the modified Gompertz and Cone models used herein to analyze CP:CM digestion.

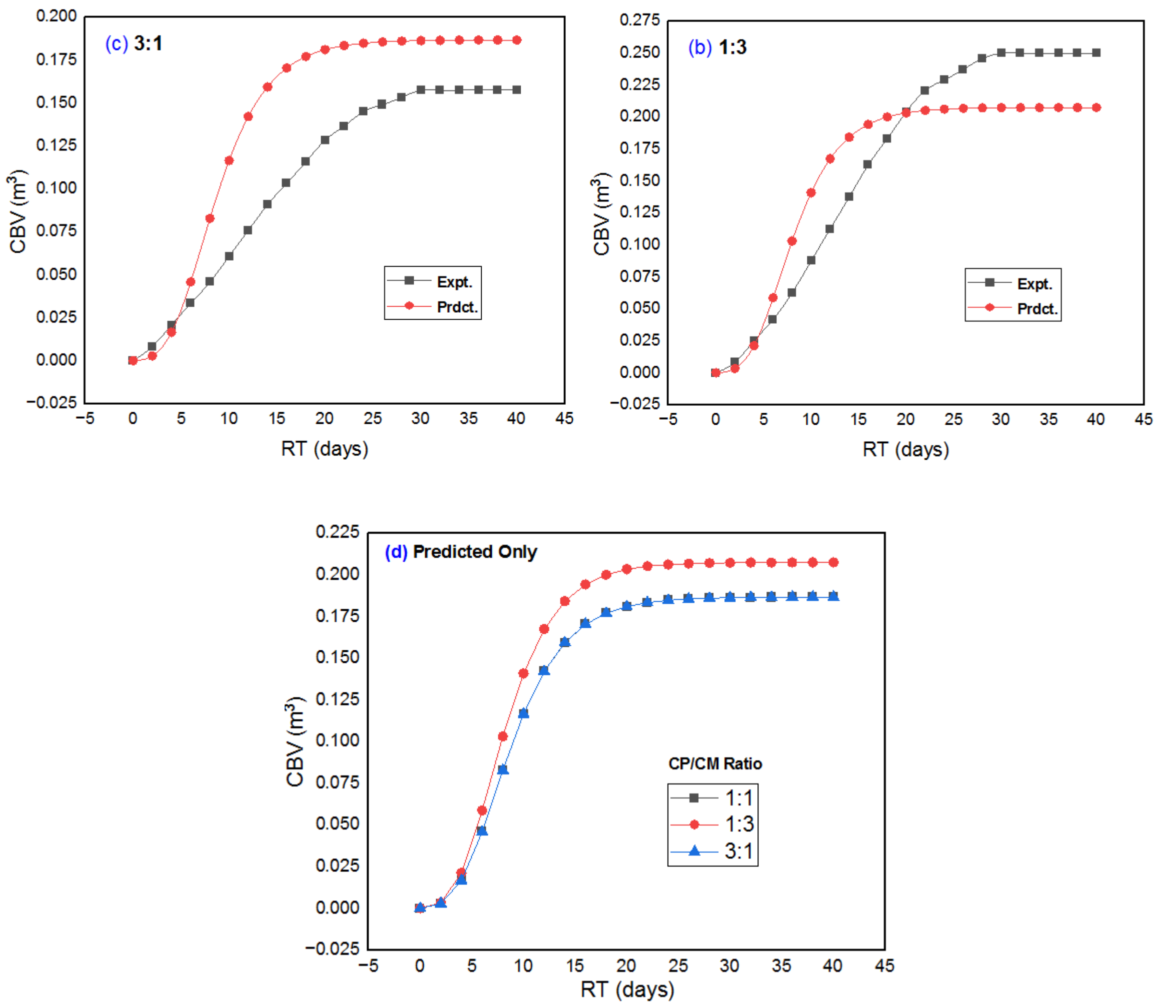

Figure 4. Fit Correlation Based on the Modified Gompertz Kinetic Model at (a) 1:1, (b) 1:3 and (c) 3:1 Ratio

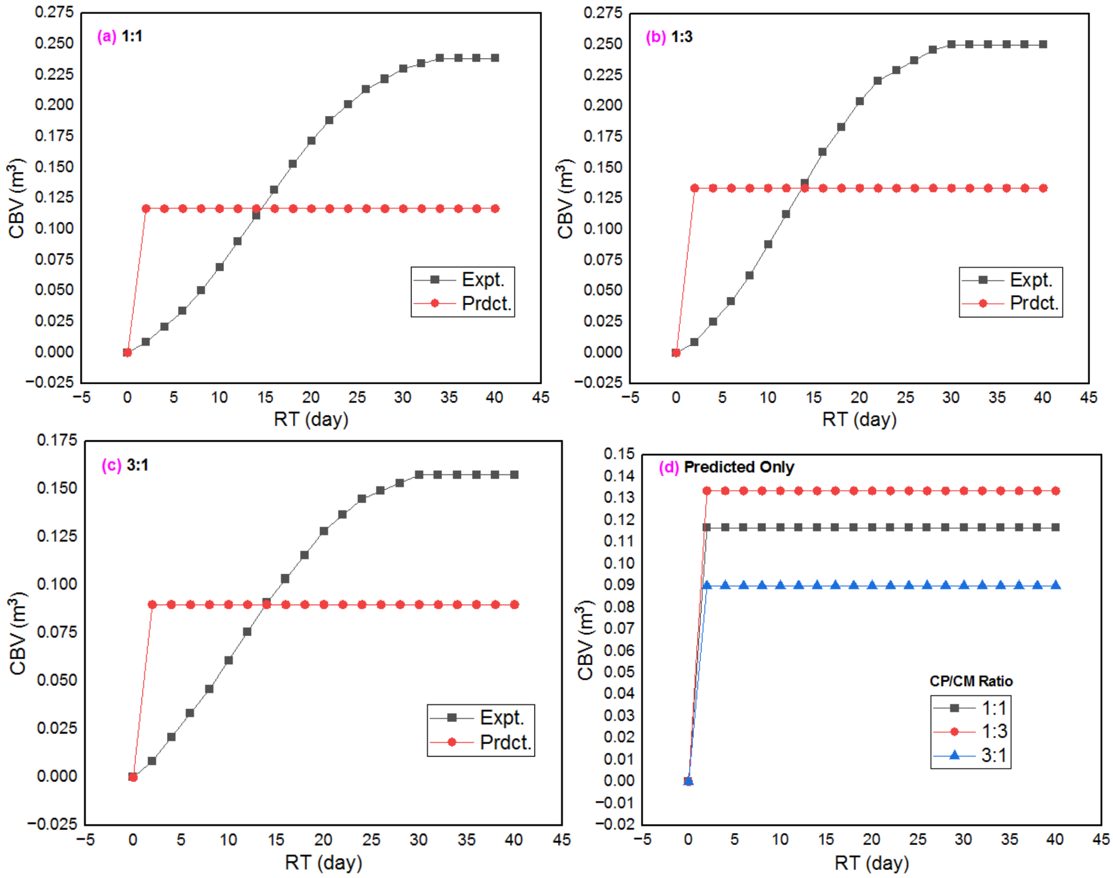

Figure 5. Fit Correlation Based on the Cone Model at (a) 1:1, (b) 1:3 and (c) 3:1 Ratio

In Figure 4, the overall trend follows a typical sigmoidal (S-shaped) curve described by the modified-Gompertz model, where CBV gradually increases, reaches a peak, and then due to substrate depletion and microbial activity decline [22]. For the 1:3 CP:CM ratio, the $CBV_{Expt.}$ peaks at approximately 0.25 m³, while the $CBV_{Prdct.}$ reaches a lower value of 0.21 m³ (Figure 3b). A similar trend is seen for 1:1 and 3:1 ratio (Figure 3a & c), where the predicted values are marginally higher or lower than the actual experimental data at specific intervals. Variations of such, can be attributed to fluctuations in microbial adaptation, substrate composition differences, and environmental factors such as temperature and pH, which are not explicitly accounted for in the Modified Gompertz model. Figure 4 curve generally demonstrates a strong correlation between $CBV_{Expt.}$ and $CBV_{Prdct.}$, with minor deviations at certain time intervals. In Figure 5 for Cone model, $CBV_{Prdct.}$ attained a constant maximum value across all RTs, which are 0.1167, 0.1336 & 0.09 m³ at the respective ratios. Ultimately, the continuous CBV predictions in Figure 5 indicate that the Cone model is less adaptable for describing biogas kinetics compared to the Modified Gompertz model.

3.3. Coefficient of Determination and the Estimated Model Parameters

BP estimated using the Modified Gompertz model is consistently higher than that predicted by the Cone model across all mixing ratios. For the 1:1 ratio, the Modified Gompertz model predicts a BP of 0.1868 m³, whereas the Cone model estimates only 0.1167 m³, reflecting a significant underestimation by the Cone model. Similarly, at the 1:3 ratio, the Modified Gompertz model projects a BP of 0.2076 m³, while the Cone model provides a lower estimate of 0.1336 m³. This trend continues for the 3:1 ratio, where the Modified Gompertz model predicts a BP of 0.1868 m³, whereas the Cone model estimates a much lower BP of 0.0900 m³. The higher BP values from the Modified Gompertz model suggest that it better captures the biogas production potential, likely due to its ability to account for microbial adaptation and growth dynamics during the AD process. In contrast, the Cone model, which is based on a power-law approach, appears to be more conservative in its BP estimates, as shown in Table 3. Moreover, the R^2 values indicate a better fit for the Modified Gompertz model (ranging from 0.9564 to 0.9684) compared to the Cone model (ranging from 0.7460 to 0.7894), further confirming its superior predictive performance

Table 3. Biogas Kinetic Model Parameters Based on CP-CM Analyzed Experimental CBV

Model	Ratio	SSE	TSS	R^2	Parameter	Value
Modified Gompertz	1:1	2.921019	66.99934	0.956402	BP =	0.186807358
					LP =	3.571355096
					k =	0.018741069
	1:3	2.15738	68.37430	0.968447	BP =	0.207619459
					LP =	3.399807457
					k =	0.022552474
	3:1	2.15738	68.37430	0.968447	BP =	0.186807358
					LP =	3.571355096
					k =	0.018741069
Cone Model	1:1	17.01520	66.99934	0.746039	BP =	0.116703034
					k =	3.571355063
					SF =	9.999999818
	1:3	16.50314	68.37430	0.758635	BP =	0.13363538
					k =	3.571355028
					SF =	9.999999632
	3:1	12.39594	58.85933	0.789397	BP =	0.090001905
					k =	3.571355033
					SF =	9.999999654

Best model selection could also be based on the TSS and SSE values, where a lower SSE and a higher TSS indicate a better fit. The Modified Gompertz model consistently exhibits lower SSE values (ranging from 2.157 to 2.921) compared to the Cone model (ranging from 12.395 to 17.015), signifying a better fit to the biogas production data. LP and k in the Modified Gompertz model show variation across different ratios, reflecting the dynamic microbial adaptation and degradation process. On the other hand, in the Cone model, the values of k and the SF remain constant across each ratio. That is, the Cone model assumed a fixed degradation pattern irrespective of substrate composition changes, leading to uniform k and SF values. However, this assumption may limit its ability to capture variations in microbial activity and substrate utilization efficiency. SF in the Cone model is notably high, approaching a value of 10 for all ratios. SF typically determines the curvature of biogas production over time, affecting how rapidly biogas generation stabilizes. A high SF value in this study suggests that the biogas production follows a sharp initial rise, followed by a more prolonged stabilization phase (formerly observed in Figure 5). Broadly, the Modified Gompertz model proves to be the better model due to its lower SSE, higher R^2, and more accurate representation of microbial behavior. Table 3 shows that the best-performing ratio is 1:3, where the Modified Gompertz model shows the highest BP (0.2076 m^3) and the lowest SSE (2.157), indicating optimal conditions for biogas production, at the highest production rate of 0.0226 m^3/day.

At a CP:CM ratio of 1:1 and 3:1, the BP, LP, and k parameters' values fall within the bracket under modified-Gompertz model analysis. If the CP:CM ratios of 1:1 and 3:1 provide similar nutrient availability and favorable conditions for microbial consortia, then the kinetic parameters (BP, LP, and k) may remain unchanged. This result suggests that within this experimental setup, increasing CP content beyond a 1:1 ratio does not proportionally enhance biogas production as realized by Kayaba et al. [10], reinforcing the idea that an optimal CP:CM ratio may exist around 1:1 rather than higher proportions of CP. However, a higher R^2 = 0.9684 at 3:1 places the blend above the equal mixture of feedstock used herein. In terms of R^2, 1:3 and 3:1 portrays a better and equal performance (having identical R^2 = 0.9684) – but given that the LP ≅ 3.4 days is shorter for 1:3 still ranks it as the best ratio according to Ore et al. [29]. Dinneya-Onuoha et al. [27] obtained a better fit at R^2 = 0.9949 at a higher LP of 5.9 days, utilizing the modified-Gompertz model for AD data of CM/cow dung blend. Precision in both statistical and model parameters estimated can be attributed to the ability of the Excel Solver add-in to work with large datasets. Consequently, the $CBV_{Prdct.}$ versus actual or $CBV_{Expt.}$ plot in Figure 6 follows a curved trend rather than a perfect straight line due to the nonlinear nature of biogas production, which the Modified Gompertz model best describes.

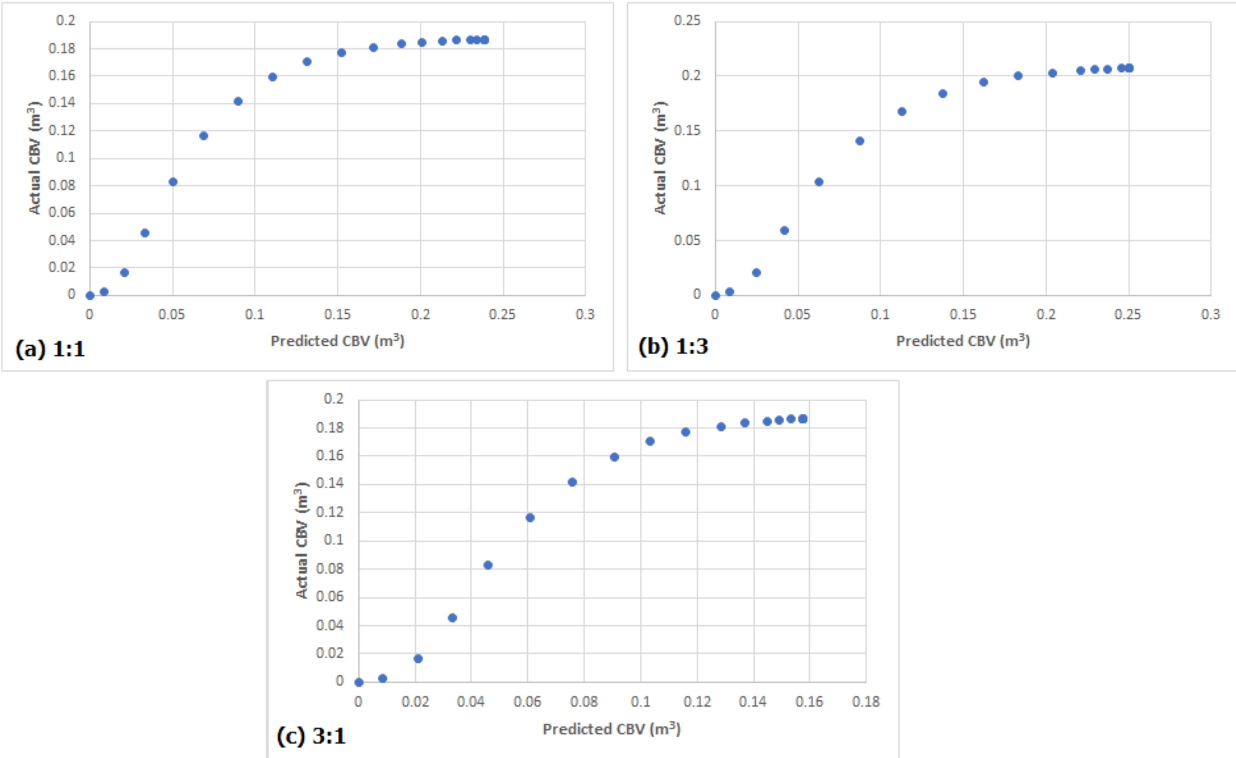

Figure 6. Predicted CBV Versus Actual CBV Representation from Modified Gompertz

Biogas production follows a sigmoidal (S-shaped) curve due to microbial adaptation for all ratios in Figure 6 (a-c). Initially, gas production is slow during the lag phase, followed by a rapid increase (exponential phase) and finally leveling off as substrate depletion occurs (stationary phase). This causes a deviation from a linear correlation. Since the CBV is cumulative (total gas produced over time), initial deviations may amplify as data points accumulate, making the trend appear curved rather than strictly linear. The findings from this study can be applied to actual biogas production plants by optimizing feedstock ratios to enhance biogas yield and process efficiency. The RT is somewhat sensitive to the volume of biogas produced over time, and is also dependent on all other influential factors being stable or non-harmful.

4. CONCLUSION AND LIMITATION

This study successfully utilized Excel Solver for nonlinear regression to estimate kinetic parameters in the modified Gompertz and Cone models for anaerobic co-digestion of CP and CM. Among the tested CP:CM ratios (1:1, 1:3, and 3:1), the 1:3 ratio (higher CM content) produced the highest biogas yield of 0.25 m^3, 0.208 m^3, demonstrating the importance of nitrogen balance in AD. The modified-Gompertz model showed a better fit (higher R^2 and lower SSE) compared to the Cone model, effectively capturing microbial adaptation and substrate degradation dynamics. The Cone model, although useful, exhibited limitations in predicting trends in cumulative biogas production. The results confirmed that Excel Solver provides an accessible and easy tool for biogas kinetic modeling, eliminating the need for specialized software. However, some limitations exist. The study relied on batch AD, which does not account for continuous or semi-continuous digestion processes that are more relevant to large-scale biogas production. Environmental factors such as temperature fluctuations, pH variations, and potential inhibitory compounds (e.g., ammonia accumulation) were not extensively monitored or controlled, which could influence microbial activity and gas production. The findings of the present study can help small-scale farmers optimize their biogas digesters using simple spreadsheet tools.

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