 https://doi.org/10.3311/PPch.40376

Periodica Polytechnica Chemical Engineering, 69(2), pp. 302–312, 2025

Optimizing Biogas Production from Food Waste and Cow Dung: Impact of Mixing Ratios

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Received: 06 March 2025, Accepted: 07 May 2025, Published online: 03 June 2025

Abstract

Optimizing biogas production from organic waste is crucial for sustainable energy and waste management. This study explores the optimal mixing ratio of food waste (FW) and cow dung (CD) in anaerobic digestion (AD) to enhance biogas yield. The 70:30 (w/w) FW and CD ratio achieved the highest biogas yield of 266.4 ± 1.55 mL CH_4/g volatile solids (VS) at 32 °C. Both the modified Gompertz (R^2 = 0.99) and Logistic Function models (R^2 = 0.99) effectively predicted biogas yields, confirming the robustness of this ratio. Fourier-transform infrared spectroscopy (FTIR) analysis indicated significant solubilization of cellulose and lignin, enhancing biogas production. This 70:30 ratio maintained process stability with low volatile fatty acid (VFA) and ammonia levels. The biogas production rate (R_m) ranged from 12.0 to 12.5 mL CH_4 with a 7.27-day lag phase, shorter than reported in previous studies. An integrated purification process efficiently removed gaseous pollutants and moisture, increasing methane content by 75%. This enhanced both the yield and quality of the biogas, making it more suitable for energy applications. The study highlights a commercially viable approach for sustainable biogas production, with significant environmental and economic benefits. The optimized co-digestion and purification process offer a scalable solution for renewable energy generation and effective organic waste management.

Keywords

anaerobic digestion, biogas yield, Gompertz model, GC-TCD analysis, FTIR analysis

1 Introduction

Energy is fundamental to supporting human activities and driving both individual and national growth as the progress of various sectors depends on the availability and accessibility of reliable energy resources. Globally, energy needs are met through a mix of conventional and renewable sources [1]. Clean and renewable alternatives, these energy sources reduce environmental impacts while addressing the increasing global demand for sustainable energy solutions. Food waste (FW) constitutes the second-largest category of municipal solid waste (MSW) sent to landfills, accounting for approximately 18% of the total waste stream. Annually, nearly 30 million tons of FW end up in landfills, with less than 3% diverted, primarily for composting to produce fertilizers [2].

Waste characterization studies highlight the diverse materials disposed of in landfills, with FW standing out due to its high biodegradability and significantly higher volatile solids (VS) degradation rate (86–90%) compared to bio solids. As a result, even with increased feedstock in digesters, the residual output remains relatively low. The primary objective of anaerobic digestion (AD) of FW is to harness its substantial energy potential, which is arguably its most critical aspect. The escalating production of FW, particularly in institutional settings such as school canteens, industrial sectors like food processing plants, and commercial areas such as restaurants, has become a significant concern [3]. State that global economic development and population growth are major drivers of this increase, with projections indicating a 44% rise in global FW production from 2013 to 2025 [4]. Estimated that 12.6 million tons of FW are generated annually, with 90% ending up in landfills. The decomposition of FW in landfills produces CH_4, a potent greenhouse gas that contributes to global warming, while leachate from FW poses a severe threat to groundwater contamination [5]. AD is increasingly recognized as an effective method for

Cite this article as: Saravanan, G., Thiyagarajan, P. "Optimizing Biogas Production from Food Waste and Cow Dung: Impact of Mixing Ratios", Periodica Polytechnica Chemical Engineering, 69(2), pp. 302–312, 2025. https://doi.org/10.3311/PPch.40376

managing organic waste, including FW, animal waste, and sewage sludge [6, 7]. Biogas yield from the co-digestion of FW and sewage sludge (SS), achieving a CH_4 yield of 0.29 L CH_4/g chemical ocygen demand (COD) removed, with COD and VS removal efficiencies of 81.5% and 69.2%, respectively [8]. This process offers a practical avenue for energy and nutrient recovery due to the high organic content of FW compared to other waste types [9]. However, a primary challenge in biogas production through AD is the variability in FW composition, which fluctuates across different locations and over time. This variability is largely influenced by regional dietary patterns, seasonal changes, and waste management practices [10]. Optimal biogas yield of 2244.6 mL, with CH_4 and CO_2 production of 1346 mL and 30.2 mL, respectively, from the co-digestion of FW, algae, chicken, fish and cow manure (CM) [11]. Biogas yield of 147–300 cm^3/g VS from the anaerobic co-digestion (AcoD) of CM and canteen FW (CFW), with the highest yield (300 cm^3/g VS) at a CFW/CM ratio of 4:1, outperforming mono-digestion of CM (135 cm^3/g VS) and CFW (146 cm^3/g VS) [12]. The highest biogas yield of 325 mL/g VS from the AcoD of FW and CM at a 6:2 total solids (TS) ratio, significantly outperforming mono-digestion [13].

In AcoD, the mixing ratio of substrates plays a critical role in determining the efficiency of biogas production [14]. Indicated that a 40:60 substrate mixing ratio of cow dung (CD) to canteen kitchen waste under mesophilic conditions produced the highest CH_4 yield, reaching 249.9 mL CH_4/g VS. The highest biogas yield was achieved by optimizing the mixing ratio of chicken manure and FW with pig manure [15].

The Gompertz model is commonly used to predict CH_4 yield showing superior performance under optimal conditions [16, 17].

This study optimizes biogas production from the AcoD of locally sourced FW and CD, focusing on specific FW:CD mixing ratios (70:30, 60:40, and 50:50). It combines experimental trials with kinetic modeling using the modified Gompertz and Logistic models for precise yield prediction. Advanced analyses like Fourier-transform infrared spectroscopy (FTIR) and gas chromatography-thermal conductivity detector (GC-TCD) track molecular-level changes and gas quality, while MATLAB, (R2023a) [18] ensures accurate data fitting. Notably, the integration of a custom designed 750 L digester with in-line purification and an evaluation of economic feasibility distinguishes this work as a scalable and industrially relevant solution for sustainable biogas production.

2 Materials and methods

2.1 Feedstock collection

The collection of feedstock for the anaerobic digester CD sourced from nearby farms adjacent to the university campus. The sampling process was meticulously conducted to ensure it accurately reflected the typical organic waste characteristics of the region. Additionally, FW was collected from the SRM university canteen, representing a diverse array of organic materials, including leftovers, discarded food items and other edible residues generated during routine operations. Both CD and FW were carefully stored in appropriate containers to preserve their integrity and prevent any pre-digestion degradation. This systematic preparation was essential for maintaining consistency and reliability in the AD experiments.

2.2 Characterization of feed stock and produced biogas

The feedstock was analyzed using standard methods outlined by the American Public Health Association (APHA) [19]. Assessments encompassed TS, VS, moisture content (MC), pH, and determination of total organic carbon, following the procedure outlined by [20]. Additionally, the carbon-to-nitrogen ratio was calculated using the relationship between total organic carbon and total nitrogen (TN) as stated in [21].

In order to investigate the compositional or chemical changes brought on by co-digestion in FW and CD, an FTIR spectrometer scanned in the 400–4000 1/cm range was employed and the analysis was conducted in accordance with ASTM E1252-98(2021) [22]. This analysis focused on identifying changes in functional groups.

GC-TCD is widely used for analyzing inorganic gases and small hydrocarbon molecules under ASTM D1945-14(2019) [23].

3 Anaerobic digestion process

3.1 Small-scale digester

A small digester setup using 20 L water cans was used to determine the optimal mixing ratio of FW and CD for biogas production. Three ratios 50:50, 70:30, and 80:20 were tested, with corresponding mass FW and CD masses mixed with 5 L water. The digestion process was conducted over a 40-day hydraulic retention time (HRT) under mesophilic conditions (32–37 °C), and biogas production was measured using the water displacement method [24].

3.2 Large-scale digester

The study examined biogas production from FW and CD using a modified 750 L anaerobic digester tank with

an internal cone for efficient feedstock addition and an airtight anaerobic environment. A system was designed for continuous feedstock introduction and simultaneous removal of digested material, improving process efficiency. The feedstock was mixed with water to form a slurry, filling 50% of the digester to allow gas generation space. Before feeding, the slurry was homogenized using a stirrer for 20 min. For large-scale operation, 190 kg of FW and 120 kg of CD were mixed with 65 L water and digested under mesophilic conditions for 40 days. Biogas production was measured daily using a BK-G1.6 biogas flow meter. Fig. 1 illustrates the schematic diagram of the biogas production process.

The setup includes a conical bottom anaerobic digester for FW and CD co-digestion. Biogas flows through a three-stage purification system, a pre-filter (removes particulates/moisture), an iron sponge (removes H_2S) and a water scrubber with activated carbon (removes CO_2 and trace gases). Purified gas is stored in a high-density polyethylene (HDPE) bag and compressed for GC-TCD test.

3.3 Biogas storage bag and purification

The biogas storage system utilized a three-layer storage bag designed for durability and gas impermeability, consisting of an inner HDPE layer resistant to acidic biogas components, a barrier layer of ethylene–vinyl alcohol copolymer (EVOH) or nylon to prevent gas escape, and an outer UV-stabilized HDPE layer for protection against environmental conditions. A three-stage pre-filter purification system was employed to enhance biogas quality by securely filtering out impurities such as water vapor and H_2S through airtight couplings to prevent leakage. The purified biogas was then stored in the biogas storage bag and compressed to 10 bar using a 1.5 kW compressor for further storage. To evaluate purification efficiency, raw and purified biogas samples were analyzed using GC-TCD, providing a detailed composition breakdown, focusing on CH_4, CO_2, and trace impurities.

H_2S in biogas is a corrosive trace gas that can damage equipment and lower gas quality. An effective desulfurization method involves using iron oxide pellets or wood chips coated with iron oxide, known as an iron sponge, to convert H_2S into iron sulfide, achieving over 99.9% removal, reducing concentrations from 3600 ppm to 1 ppm [25]. As raw biogas enters the purification chamber, H_2S reacts with steel wool, forming Fe_2S_3, which significantly reduces H_2S levels and enhances CH_4 concentration as described in Eq. (1):

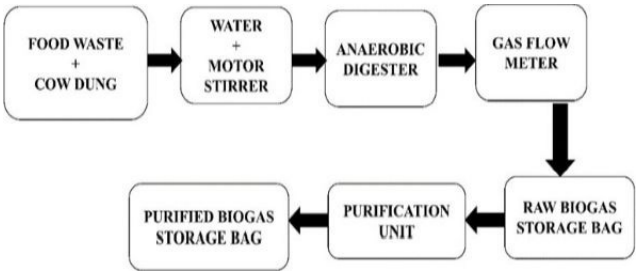

Fig. 1 Schematic diagram of biogas production and purification process

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O. \quad (1)$$

The water scrubbing method improves biogas quality by utilizing the higher solubility of CO_2 and H_2S in water compared to CH_4 [26]. As raw biogas passes through the scrubber, CO_2 dissolves into the water and forms H_2CO_3 in a reversible reaction, effectively reducing CO_2 levels while CH_4 remains in the gas phase as described in Eq. (2):

$$CO_2 + H_2O \rightarrow H_2CO_3. \quad (2)$$

Micro-spherical activated carbon (sourced from Active Carbon India Pvt. Ltd.) serves as a highly porous adsorbent, selectively trapping CO_2 and H_2S through physical and chemical interactions [27]. It also adsorbs moisture, removing water vapor from raw biogas. This dual function improves biogas composition by reducing impurities and enhancing CH_4 content. Its high surface area and optimized pore size distribution make it highly effective for CO_2 and H_2S removal under specific conditions.

3.4 Physiochemical characterization

The FW and CD mixtures (50:50, 70:30, and 80:20) were characterized for pH, TS, VS, MC, TN, and the carbon to nitrogen ratio. TS and VS were determined following APHA Standard Methods [19] while pH and ammonia concentrations were measured using a pH meter and standard methods, respectively. Volatile fatty acid (VFA) concentrations were analyzed *via* gas chromatography (GCMS-QP2010, Tamil Nadu, India), and free ammonia (FA) concentration was calculated using Eq. (3) [28]:

$$C_{FA} = \frac{C_{TAN}}{1 + 10^{-pH} / K_a}, \quad (3)$$

where C_{FA} and C_{TAN} represent the concentrations of FA and total ammonia nitrogen (TAN), respectively. The dissociation constant, K_a, is 1.097×10^{-9} at 35 °C.

To assess the individual VFA concentrations responses to ammonia inhibition, a significant value (Z) is computed according to Eq. (4) [29]:

$$Z = \frac{C - C_0}{SD}. \quad (4)$$

In Eq. (4) C (mg/L) represents the measured value of the VFA concentration while C_0 (mg/L) denotes the average value of the VFA concentration during the base period and standard deviation (SD) stands for the SD of the VFA concentration during the base period.

To assess the relative fluctuation of individual VFA concentrations, the fluctuation ratio of VFA concentration (r) is determined using Eq. (5) [30]:

$$r = \frac{C - C_0}{C_0}. \tag{5}$$

3.5 Kinetic models for biogas production

Biogas production kinetics for potential upscaling were analyzed using the modified Gompertz and Logistic Function models (Eqs. (6) and (7)). These models, widely used by researchers, were crucial in examining the kinetics of biogas production [31].

$$Y(t) = A\exp\left\{-\exp\left[\frac{\mu_{mXe}}{A}(\gamma - t) + 1\right]\right\} \tag{6}$$

$$Y(t) = \frac{A}{1 + \exp X\left(\frac{4\mu_{m(\gamma - t)}}{A + 2}\right)} \tag{7}$$

Equations (6) and (7) describe the relationship between cumulative biogas production (Y) and time (t), with variables a representing biogas production potential, μ_m indicating the maximum biogas production rate (R_m), and γ denoting the lag phase duration, Xe is the daily gas production, X is the variable. Non-linear regression analysis in MATLAB, (R2023a) [18] was used to determine these parameters fom observed data (Y, t). These models help predict CH_4 generation kinetics, assisting in designing anaerobic digesters and understanding system performance [32].

4 Results and discussion

4.1 FW and CD co-digestion

Table 1 presents the feedstock characterization data, showing that FW and CD exhibited TS contents of 18.05 ± 1.01% and 20.45 ± 1.01%, respectively, with VS contents of 85.74 ± 1.04% and 78.25 ± 1.23%, indicating the presence of easily degradable organic compounds [33]. These VS values align with previous findings for FW (86.1%) [34].

FW had a slightly higher MC (81.51 ± 0.05%) compared to CD (78.07 ± 0.05%), which is important for maintaining proper moisture levels during co-digestion. While FW had an acidic pH (5.3 ± 0.2), CD was close to neutral (pH 7.2 ± 0.2), which affects microbial survival during AD; co-digestion with CD can raise FW pH to ideal levels [35]. The carbon-to-nitrogen ratio was 22.49 for FW and 17.99 for CD, both within the optimal range (9 to 30) for AD, highlighting the importance of maintaining ideal C/N ratios and ensuring adequate alkalinity and nitrogen levels for efficient co-digestion [36].

Table 1 Physicochemical properties of obtained FW and CD (±standard deviation, %)

Parameter	FW	CD
pH	5.3 ± 0.2	7.2 ± 0.2
TS (%)	18.05 ± 1.01	20.5 ± 1.01
VS (%)	85.7 ± 1.04	78.3 ± 1.04
MC (%)	81.5 ± 0.05	78.07 ± 0.05
Total organic carbon (mg/L)	34.9	27.9
TN (mg/L)	1.6	1.6
C/N ratio	22.5	18

Table 2 summarizes the biogas yields observed for three mixing ratios of FW and CD. The 70:30 ratio achieved the highest biogas yield of 333 ± 1.55 mL CH_4/g VS, followed by the 50:50 (284 ± 1.55 mL CH_4/g VS) and 80:20 (146 ± 1.55 mL CH_4/g VS) ratios [37]. Table 3 summarizes the differences and presents their statistical significance, a one-way MATLAB, (R2023a) [18] was performed, followed by a Tukey honestly significant difference (HSD) post-hoc test. The MATLAB, (R2023a) [18] showed a highly significant effect of the mixing ratio on biogas yield ($F_{2,6}$ (variable) = 9037.13, $p < 0.001$). The Tukey test confirmed that all pairwise differences were statistically significant ($p < 0.001$).

The 70:30 ratio yields significantly more biogas than the other tested ratios, validating its optimality with rigorous statistical backing. This strengthens that 70:30 ratio is the most efficient among the ones tested for biogas production under mesophilic conditions.

Fig. 2 illustrates biogas production data for various co-digestion ratios of FW and CD (50:50, 70:30, and 80:20). Immediate biogas production from day 1 is attributed to the high biodegradability of FW [9]. while the delayed peak production in the 50:50 and 80:20 ratios is due to less readily biodegradable substances like cellulose and lignin in CD [38].

Three mixing ratios of FW to CD (50:50, 70:30, and 80:20) were assessed for methanogenic inhibition based on FA and VFA concentrations. The 70:30 ratio maintained low VFA (234 mg/L) and ammonia (1.3 mg/L) levels, ensuring a stable pH and efficient digestion, as VFAs were effectively consumed by acetogens and methanogens. In contrast, the 50:50 and 80:20 ratios had higher ammonia concentrations (5.5 mg/L and 9.8 mg/L, respectively),

Table 2 Effect of FW and CD ratios on biogas yield and process parameters

Ratio FW/CD	TS (%)	VS (%)	pH	MC (%)	Total biogas yield (mL CH_4/g)	C/N ratio
50:50	21.35 ± 1.01	82.78 ± 1.04	5.1	72.59 ± 0.05	284	19.84
70:30	22.85 ± 1.01	92.04 ± 1.04	6	77.31 ± 0.05	333	21.04
80:20	23.53 ± 1.01	98.64 ± 1.04	5.9	82.01 ± 0.05	146	22.65

Table 3 Statistical comparison of biogas yields from different mixing ratios (one-way ANOVA and Tukey HSD post-hoc test)

Group comparison	Mean difference (mL CH_4/g VS)	Adjusted *p*-value
70:30 vs. 50:50	49.00	<0.001
70:30 vs. 80:20	187.00	<0.001
50:50 vs. 80:20	138.00	<0.001

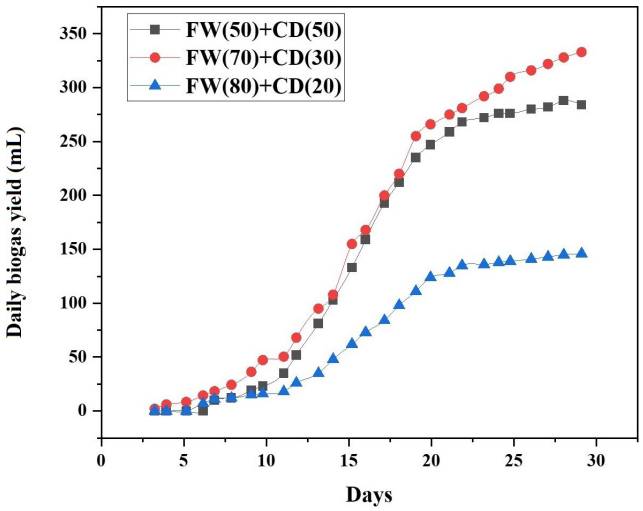

Fig. 2 Daily biogas yield at different ratios of FW and CD

which inhibited methanogenesis due to increased FW and excessive VFA production.

4.2 Large-scale digester for FW and CD at 70%:30%

Fig. 3 shows a significant increase in biogas yield from large-scale digesters with a 70% FW and 30% CD ratio, producing 266 mL CH_4/g VS. This result is higher than the biogas yields obtained by [39]. The C/N ratio, while effective in simpler scenarios lacks the precision needed for managing the digestion of complex organic substrates the higher CH_4 yield in this study is due to the optimal composition and conditions that enhance carbon availability and microbial synergy. While the C/N ratio is important, newer methods focus on the bioavailability of carbon to microbes for more efficient digestion, as noted by [40].

4.3 FTIR analysis of functional group changes in FW and CD before feeding into the digester and after co-digestion

FTIR analysis illustrated in Fig. 4 was performed on the feedstock composed of 70% FW and 30% CD, initially

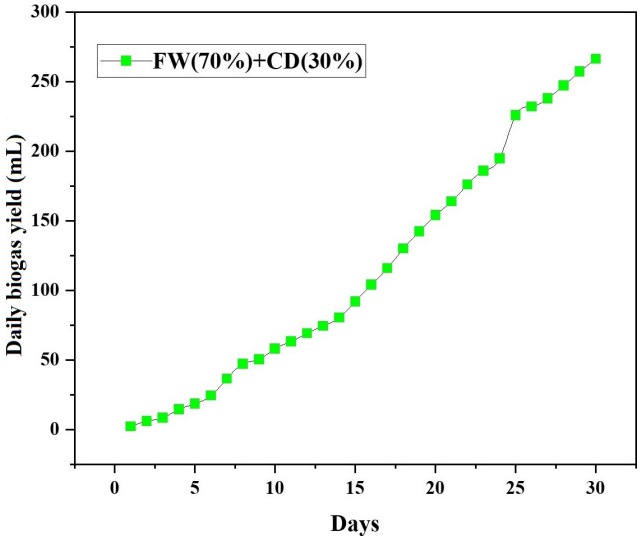

Fig. 3 Biogas production using a 70:30 ratio of FW and CD

in a semi-solid form, before being fed into the digester on day 1. After a 40-day retention period, both the initial feedstock and the residual waste from the digester were analyzed using a SHIMADZU IRTRACER 100 FTIR spectrometer (Tamil Nadu, India), with spectra recorded in the 4000–500 1/cm range at a resolution of 4 1/cm.

The analysis revealed a peak at 3657 1/cm in the initial sample, corresponding to the O–H functional group, which disappeared post-digestion, indicating the solubilization of cellulose and soluble lignin [41]. Other peaks, such as at 3216 1/cm and 1735 1/cm, indicated the presence of cellulose and lipids, while the 1018–1020 1/cm peak suggested cellulose C–O–C stretching. After co-digestion, a shift to 3220 1/cm indicated breakdown of cellulose O–H stretching, and a decrease at 1020 1/cm signified changes in cellulose structure [42].

The 1625 1/cm peak, associated with aromatic C–C ring stretching, highlighted significant alterations in functional groups, reflecting enhanced solubilization of organic matter, which improves biogas yield by making cellulose and lignin more accessible to microbial communities. Despite a reduction in volatile organic matter, some biodegradable material remained, suggesting opportunities for further optimization of microbial activity to maximize biogas production [43].

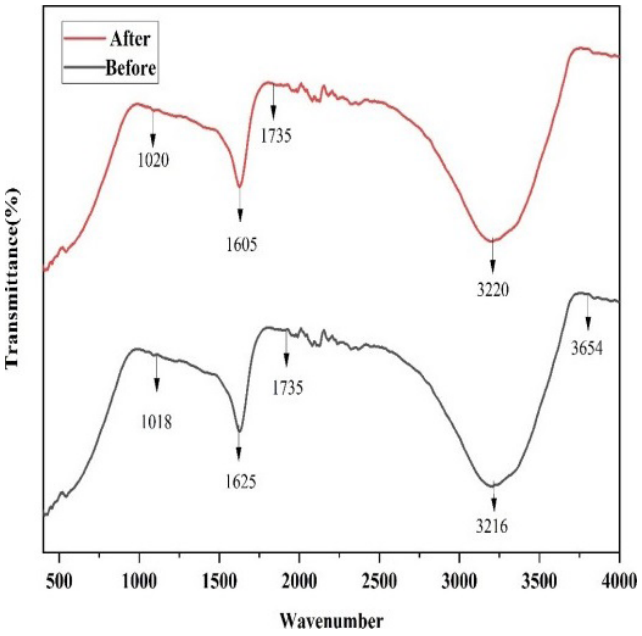

Fig. 4 FTIR analysis of feedstock before and after anaerobic digestion

4.4 GC-TCD test

Table 4 [44] presents the GC-TCD analysis of biogas samples before and after purification. Before purification, biogas contained approximately 50% CH_4, 35% CO_2, and 15% other gases. After purification, CH_4 concentration rose to 75%, while CO_2 dropped to 15%, and other gases made up 10%. The GC-MS results confirm that the purification method significantly enhanced the CH_4 content, improving the biogas quality and energy potential.

Fig. 5 illustrates the changes in gas composition, with a notable increase in CH_4 and a decrease in CO_2 and other impurities.

4.5 Polynomial regression

The regression model, developed using polynomial regression in MATLAB, (R2023a) [18], analyzed biogas yield and feedstock composition. Table 5 presents experimental biogas yields (dependent variable) measured over 30 days from the co-digestion of 70% FW and 30% CD, along with corresponding modelled values. The model shows a good fit to the experimental data, demonstrating the predictive accuracy of the polynomial regression approach.

Table 4 Composition of biogas before and after purification process

Serial No.	Parameters	Test methods	Before purification	After purification
1	CH_4	GC-TCD	50%	75%
2	CO_2	GC-TCD	35%	15%
3	O_2	GC-TCD	4%	6%
4	H_2S	IS 5182 (Part 7) [44]	8%	3%
5	N_2	GC-TCD	3%	1%

The coefficient of determination (R^2) was used to assess the model's fit, with higher R^2 values indicating better predictive accuracy. Fig. 6 shows the polynomial curve fitting the experimental biogas yield data, closely matching the observed data points. The corresponding polynomial equation is provided in Eq. (8):

$$Y = -3.2X^3 + 12.8X^2 + 90.1X + 103.6, \quad (8)$$

where Y represents cumulative biogas yield, and X denotes time (days) during AD. The polynomial curve demonstrates the relationship between time and biogas yield, with the highest coefficient indicating the optimal biogas production from the FW and CD mixture.

The coefficients of the polynomial regression model, including the intercept (P1 = −3.2), and the slopes for the first independent variable (P2 = 12.8), second independent variable (P3 = 90.1), and the interaction term (P4 = 103.6), were derived from experimental data to model biogas yield accurately. These values reflect how biogas yield changes with variations in the FW and CD mixture. The model's reliability was assessed by examining residual errors, which ranged from −5 to 14, as illustrated in Fig. 7 and the standard error of regression, which was 3.311.

The adjusted R^2 value of 0.99, sum of squares of 211045.8, and root mean square error (RMSE) of 5.2 confirm that the model fits the data well, with high predictive accuracy and minimal error, demonstrating its effectiveness in predicting biogas yield.

4.6 Kinetic model

After determining that a 70:30 ratio of FW to CD is optimal for biogas production, the data for this ratio was entered into two kinetic models the modified Gompertz model and the Logistic Function model, as shown in Fig. 8 and Table 6. The modified Gompertz model predicted a cumulative biogas production of 270.34 mL CH_4, with R_m ranging from 12.03 to 12.5 mL CH_4/d and a γ of 7.27 days, yielding an R^2 value between 0.921 and 0.99, consistent with previous studies [45].

In contrast, the Logistic Function model predicted 242.34 mL CH_4/d in cumulative biogas production, with R_m values around 35.55 mL CH_4/d and a γ of 8.13 days, achieving an R^2 value of 0.991.

Both models showed good fits, with the modified Gompertz model yielding 277.7 mL CH_4/g and the Logistic Function model producing 242.34 mL CH_4/g,

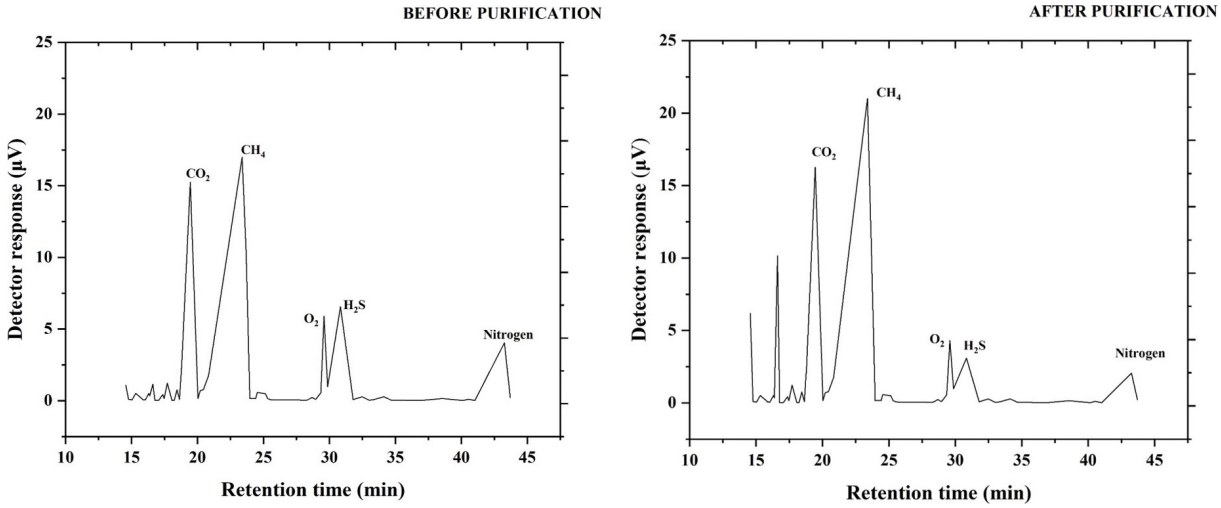

Fig. 5 GC-TCD spectra before and after purification

Table 5 Experimental biogas yield and polynomial regression modelled values

Days (independent variable)	Biogas yield (dependent variable) (mL)	Polynomial regression (modelled values)
1	2	−0.999
5	18.4	20.9
10	58	55.8
15	92	98.8
20	154	150
25	226	209.8
30	266.4	277.6

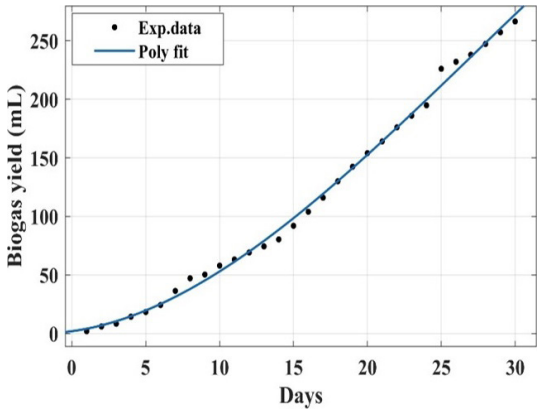

Fig. 6 Polynomial fit for biogas yield for 70:30 FW and CD

demonstrating their effectiveness in predicting biogas production [46].

The percentage error is calculated by taking the absolute difference between predicted and experimental rates, dividing by the experimental rate, and multiplying by 100. For the 70% FW and 30% CD feedstock, the experimental CH_4 yield was 266.4 mL CH_4/g. The modified Gompertz model predicted 270.34 mL CH_4/g with a 1.48% error, while the Logistic Function model predicted 242.34 mL CH_4/g

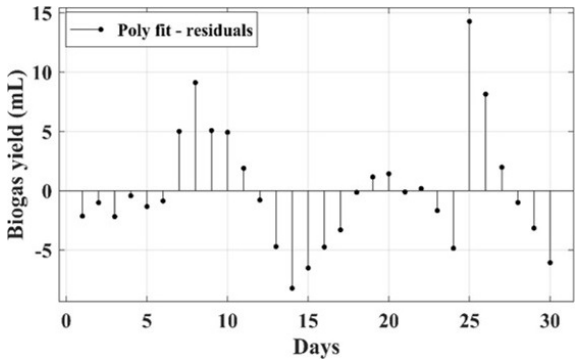

Fig. 7 Residual plot for biogas yield for 70:30 FW and CD

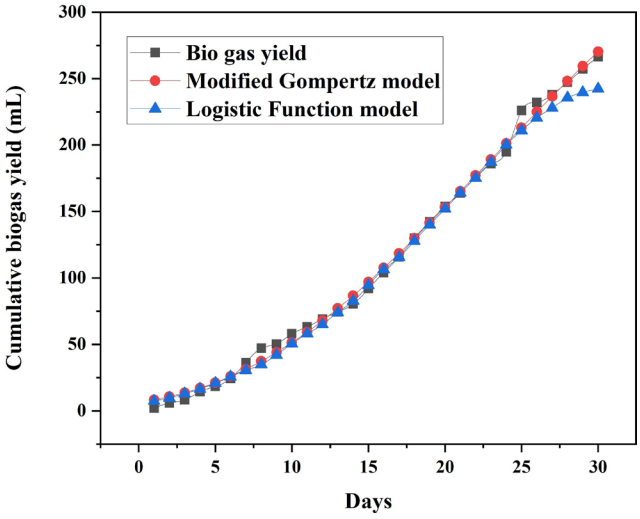

Fig. 8 Cumulative biogas yield according to Gompertz model and Logistic Function model

with a 2.78% error, indicating that the modified Gompertz model is more accurate.

Table 7 [47–50] compares the predictive accuracy of the Gompertz and Logistic models for various feedstocks based on their R^2 values. FW + CD shows the highest R^2

Table 6 Kinetic model

Model	Feed stock	M* (mL/d)	R_m (mL CH_4/d)	γ (d)	R^2
Modified Gompertz model	70:30 (FW:CD)	270.34	12.6	7.27	0.997
Logistic Function model	70:30 (FW:CD)	242.34	35.6	8.13	0.991

* Bio gas production rate

Table 7 Comparison of experimental and predicted CH_4 R_m for various feedstocks using modified Gompertz and Logistic Function models

Feedstock	Experimental rate (mL CH_4/g)	Modified Gompertz model (mL CH_4/g)	Logistic Function model (mL CH_4/g)	Error (Gompertz (%))	Error (Logistic (%))	Gompertz R^2	Logistic R^2	Reference
FW + CD (70:30)	266.4	270.34	242.34	1.48	2.78	0.99	0.99	This study
FW + waste activated sludge	135	72.3	56.77	–	–	0.98	0.99	[47]
Pineapple waste + CD	179.08	170.44	–	–	–	0.99	–	[48]
FW + chicken manure	–	–	–	–	–	0.95	0.94	[49]
CD + horse dung	13.6	–	–	–	–	0.99	–	[50]

values for both models (0.99 for Gompertz model and 0.99 for Logistic Function model), indicating the best fit. FW + waste activated sludge has strong predictability, with the Logistic Function model (0.99) slightly outperforming the Gompertz model (0.98). Pineapple waste + CD has a moderate Gompertz R^2 of 0.96, while FW + chicken manure shows similar R^2 values for both models (Gompertz: 0.95, Logistic Function: 0.94). CD + horse dung has a high Gompertz R^2 of 0.99, but lacks Logistic Function evaluation. These results suggest that feedstock composition affects the models predictive accuracy.

5 Conclusion

The co-digestion of FW and CD at a 70:30 ratio has proven to be an efficient method for enhancing biogas production, achieving a high CH_4 yield of 266.4 mL CH_4/g VS while optimizing key parameters like C/N ratio and pH balance. FTIR analysis revealed significant solubilization of cellulose and lignin, improving organic matter accessibility to microbes and enhancing biogas quality. GC-TCD analysis confirmed the effectiveness of the purification process, increasing CH_4 content to 75%.

The modified Gompertz and Logistic models provided reliable predictions of biogas production, with the Gompertz model showing the best fit (R^2 = 0.9971). While these results highlight the potential of co-digestion for waste management and renewable energy generation, scaling up the process presents challenges. Feedstock variability, process stability at a larger scale, and the need for efficient reactor design must be addressed to ensure consistent CH_4 yields. Additionally, economic feasibility remains a key factor–capital and operational costs, purification expenses, and integration into existing energy infrastructure must be assessed to determine commercial viability. Future research should focus on optimizing process conditions, evaluating lifecycle costs, and integrating predictive models with environmental and economic assessments. Exploring the co-digestion of other organic wastes and conducting techno-economic analyses will be crucial in making biogas production a scalable, sustainable and commercially viable solution.

Acknowledgements

We acknowledge research instrument facilities provided by the Nanotechnology Research Centre (NRC) and Engine testing laboratory of automobile department SRM Institute of Science and Technology.

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