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Optimization of Temperature to Enhance Anaerobic Co-Digestion of Vegetable Waste with Cattle Rumen Content: Maximizing the Biogas Yield

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Abstract. *The global challenge of managing organic waste sustainably continues to intensify, with vegetable waste (VW) and cattle rumen content (CRC) representing major contributors to environmental degradation and underused energy resources. This study optimised the effects of temperature on biogas production, methane content, and volatile fatty acid (VFA) dynamics during VW–CRC co-digestion under mesophilic (35–48 °C) and thermophilic (50–60 °C) conditions. Batch digesters (5 L) were operated at VW:CRC ratios of 70:30 and 50:50, organic loading rates of 2–4 kg VS/m³/day, a 40-day retention time, and pH 6.8–7.2. The highest biogas yield was 0.62 L/g VS with 62% methane at 42 °C and a 70:30 ratio 38% higher than VW mono-digestion and 18% higher than thermophilic operation at 55–60 °C. Temperature optimisation halved the lag phase, increased volatile solids (VS) reduction to 65%, and limited peak VFA to approximately mg/L versus >2200 mg/L at temperature extremes. First-order kinetic modelling at the temperature optimum gave hydrolysis and methanogenesis rate constants of 0.12 d⁻¹ and 0.08 d⁻¹, respectively. ASPEN Plus simulation of a 1 m³ continuous stirred-tank reactor (CSTR) at 30-day hydraulic retention time (HRT), informed by batch kinetics, projected stable biogas production with approximately 60% methane. The findings from the findings support scalable biogas systems in Nigeria and sub-Saharan Africa, where there is a significant supply of VW and CRC in markets/farms and slaughterhouses that have not been utilised, which can be used for rural energy, waste management, and reduction of greenhouse gases in line with Sustainable Development Goals 7, 12, and 13.*

Keywords: *Anaerobic co-digestion; Cattle rumen content; Kinetic modeling; Temperature optimization; Methane production*

1. Introduction

The challenge of sustainable management of organic waste remains among the most pressing global environmental problems, with vegetable waste and materials of animal origin among the principal contributors to pollution and underused energy resources (Bhatia and Sindhu, 2024; Kumar *et al.*, 2025; Tryhuba *et al.*, 2025). Globally, about 1.3 billion tonnes of food-related vegetable waste are generated each year; when poorly managed, this material emits methane and other greenhouse gases that drive climate change (FAO, 2011; Rahman *et al.*, 2024; Sahoo *et al.*, 2023). Uncontrolled decomposition in dumps and landfills contributes an estimated 3–4% of anthropogenic methane emissions annually (Rahman *et al.*, 2024). Cattle rumen content (CRC), a slaughterhouse by-product often disposed of by open dumping or burning in Nigeria, releases volatile organic compounds and particulate matter that harm air quality and public health (Daffi *et al.*, 2020; Ihoegbian *et al.*, 2023).

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In Nigeria, where the economy is mainly agrarian, cattle rumen and vegetable waste are produced in enormous volumes daily. Fuelwood reliance increases owing to the growing energy needs in the country, especially in rural and peri-urban areas, where access to electricity and clean cooking fuels cannot be established, leading to the deterioration of the environment and respiratory conditions (Amoo & Adeleye, 2026; Olaniyan *et al.*, 2024; Okeke, 2024). Traditional fossil fuel is not sustainable because of the unpredictable prices as well as the expensive import prices. Therefore, there exists a major drive to work on decentralized and renewable energy sources that enterprises can use to integrate sustainable waste management with clean energy generation (Amoo *et al.*, 2025; Michael, 2025). An anaerobic digestion (AD) technology is one such avenue in which organic wastes get converted into biogas (which is mainly made up of methane and carbon dioxide), a renewable, storage, and versatile source of energy that has major applications in cooking, power generation, or transport fuel. Several approaches can enhance the study to its fullest extent (Amoo *et al.*, 2023; Carlos *et al.*, 2025; Iglesias *et al.*, 2020; Ngabala & Emmanuel, 2024).

Vegetable waste is rich in readily biodegradable carbohydrates, proteins, and lipids, with biochemical methane potential often in the range 250–450 mL CH_4/g VS under favourable conditions (Slopiecka *et al.*, 2022). Mono-digestion of VW, however, can lead to rapid acidification and methanogenic inhibition. CRC supplies dense microbial consortia (bacteria, archaea, fungi, protozoa), crude protein, minerals, and buffering capacity that can stabilise co-digestion systems and raise yields by 20–50% relative to mono-digestion in related African and international studies (Langda *et al.*, 2020; Shehu *et al.*, 2025; Fentahun & Kahsay, 2025; Thongbunrod & Chaiprasert, 2024).

Temperature governs AD kinetics, community structure, and gas production. Mesophilic operation (approximately 30–40 °C) is widely preferred for robustness and lower heating demand, especially in the tropics; thermophilic regimes (50–60 °C) accelerate reactions and improve pathogen kill but demand more energy and tighter process control (Steiniger *et al.*, 2023; Zhang *et al.*, 2024). Temperatures above about 50 °C can elevate VFA and ammonia risks (Candel *et al.*, 2025; Gaby *et al.*, 2017). Optimal set-points for VW–CRC co-digestion under Nigerian substrate and climate conditions remain poorly defined.

This work contributes to Sustainable Development Goal (SDG) 7 (affordable and clean energy) by demonstrating a pathway to decentralised biogas from local wastes; to SDG 12 (responsible consumption and production) by valorising market and slaughterhouse residues that would otherwise be discarded; and to SDG 13 (climate action) by capturing methane that would be emitted from uncontrolled decomposition and by displacing fossil or biomass fuels. While previous studies have examined co-digestion of vegetable or food waste with manure or rumen content, or have compared mesophilic and thermophilic regimes for other substrates, this study is novel in its systematic optimisation of temperature specifically for VW–CRC co-digestion using Nigerian market and abattoir feedstocks, combining detailed physicochemical characterisation, first-order kinetic modelling, and ASPEN Plus continuous-reactor simulation to provide a scalable framework for decentralised biogas production in sub-Saharan Africa.

2. Methods

2.1. Collection and Physicochemical Characterisation of Substrates

Vegetable waste and cattle rumen content were collected from Dutse Main Market and Dutse Central Abattoir, Jigawa State, Nigeria, between December 2023 and February

2024. VW comprised orange peels (35%), watermelon rinds (25%), pineapple peels (20%), and mixed vegetable residues (tomato, onion, cabbage; 20%), reflecting local market waste profiles. CRC was collected immediately after evisceration into sterile containers and homogenised to a slurry (particle size < 2 mm). Substrates were characterised in triplicate for total solids (TS), volatile solids (VS), carbon-to-nitrogen (C/N) ratio, crude protein, lipids, and selected nutrients following APHA (2012) standard methods.

2.2. Substrate ratio

Two VW:CRC ratios were evaluated: 70:30 and 50:50 (wet weight basis), diluted with distilled water to approximately 8% TS and adjusted to initial pH 7.0 ± 0.2. The 70:30 ratio was selected to emphasis the high-carbohydrate VW fraction while retaining sufficient CRC to supply inoculum density, protein, and buffering capacity, targeting a mixture C/N ratio in the favourable 20–30 range. The 50:50 ratio was included as a more CRC-rich alternative to test sensitivity of yield and stability to inoculum and nutrient balance, consistent with co-digestion practice where manure or rumen fractions of 20–50% are commonly used to stabilise food-waste digesters (Lee *et al.,* 2023; Oladejo *et al.,* 2020). Both ratios were therefore grounded in C/N optimisation, literature practice, and local availability of the two streams.

2.3. Setting up and Operating Conditions of Batch Digester

Batch digesters were 5 L plastic vessels fitted for gas and liquid sampling and temperature monitoring. Digesters were incubated in thermostatic water baths at 25, 35, 42, 48, 55, and 60 °C (Table 1), logged at 5 min intervals. Each temperature–ratio combination was run in triplicate. Operating targets were organic loading rate (OLR) 2.0–4.0 kg VS/m^3/day, hydraulic retention time 40 days, manual agitation twice daily, and pH maintained near 6.8–7.2. Biogas volume was measured daily by water displacement; composition was analysed several times per week. Liquid samples were analysed for pH, VFA (HPLC), VS reduction (APHA 2540D), and total ammonia nitrogen as required.

Table 1. Experimental temperature and ratio treatments

Temp. (°C)	VW: CRC	Replicates	Initial VS Load (g/L)	OLR (kg VS/m^3/d)	Expected HRT (days)
25	70:30 VW: CRC	3	34.6	2.17	40
35	70:30 VW: CRC	3	34.6	2.17	40
42	70:30 VW: CRC	3	34.6	2.17	40
48	70:30 VW: CRC	3	34.6	2.17	40
55	70:30 VW: CRC	3	34.6	2.17	40
60	70:30 VW: CRC	3	34.6	2.17	40
42	50:50 VW: CRC	3	34.1	2.13	40

The volume of the biogas was determined and recorded daily (09:00 am ± 30min) by inverted water displacement with 100mL precision gas measuring syringes and linked to the headspace of the digester through tubing. Cumulative biogas determined as average daily amount; specific yield, divided by initial VS (L/g VS). Analysis of gas composition is done three times a week (Mon/Wed/Fri) using a gas measuring syringe. Liquid measurements (measured daily and biweekly): pH (calibrated meter); volatile fatty acids (VFA) (high-performance liquid chromatography): 10mL slurry centrifuged (4000 rpm, 10min), supernatant filtered (0.45mm), acidified (H_2SO_4 pH < 2), Rezex ROA-Organic Acid column (300 x 7.8mm), 0.005M H_2SO_4 eluent (0.6 Volatile solids decrease per APHA 2540D: 20g slurry triplicate, TS/VS analysis before/after digestion. Total ammonia nitrogen (TAN).

2.4. Kinetic Modelling and Temperature Dependence

Kinetic analysis employed first-order degradation models for cumulative biogas production and volatile solids (VS) reduction:

$$B(t) = B_{max}\left(1 - e^{-kt}\right) \qquad eqn.1$$

$$S(t) = S_0 e^{-kt}) \qquad eqn.2$$

where B_{max} and S_0 represent the theoretical maximum biogas and initial VS, respectively; k is the rate constant (d^{-1}); and t is the digestion time (days).

Model parameters were fitted using non-linear regression ($R^2 > 0.95$), with lag phase (λ) determined as the x-intercept of the tangent at the inflection point, and the half-life was calculated as $t_{1/2} = \ln(2)\, {}^{\ln(2)}/_{k}$. *eqn. 3*

Temperature dependence followed the Arrhenius relationship: $k(T) = k_{ref} \times \theta^{T-T_{ref}}$. where $\theta \approx 1.08$ (mesophilic range).

2.5. Process Simulation and HRT rationale

ASPEN Plus V12.1 was used to simulate a 1 m³ continuous stirred-tank reactor (CSTR) over a 90-day horizon at isothermal 42 °C. Feed rates were set to vegetable waste 70 kg/d and CRC 30 kg/d at approximately 8% TS. Hydrolysis/acidogenesis, acetogenesis, and methanogenesis stages were represented with rate constants informed by the batch kinetic fits (e.g., hydrolysis rate constant on the order of $k = 0.058\,\text{d}^{-1}$at 42 °C). Methanogenic stoichiometry included acetate-cleaving and hydrogenotrophic pathways.

$$CH_3COO^- + H^+ \rightarrow CH_4 + CO_2 \qquad eqn.\ 4$$

and hydrogenotrophic methanogenesis (30%):

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad eqn.\ 5$$

The batch experiments used a 40-day retention time to ensure near-complete observation of lag, exponential, and declining phases under each temperature, which is appropriate for kinetic parameter estimation in closed systems. The continuous simulation adopted a 30-day HRT, a value commonly used in full-scale and pilot mesophilic CSTRs for food-waste and manure co-digestion and consistent with the higher effective throughput of continuous systems once steady state is reached. Batch-derived rate constants and methane fractions were transferred to the continuous model so that scale-up projections remain anchored in experimental kinetics while reflecting realistic continuous design practice. Energy balance and gas–liquid separation were calculated under the NRTL property method with complete-mixing assumptions.

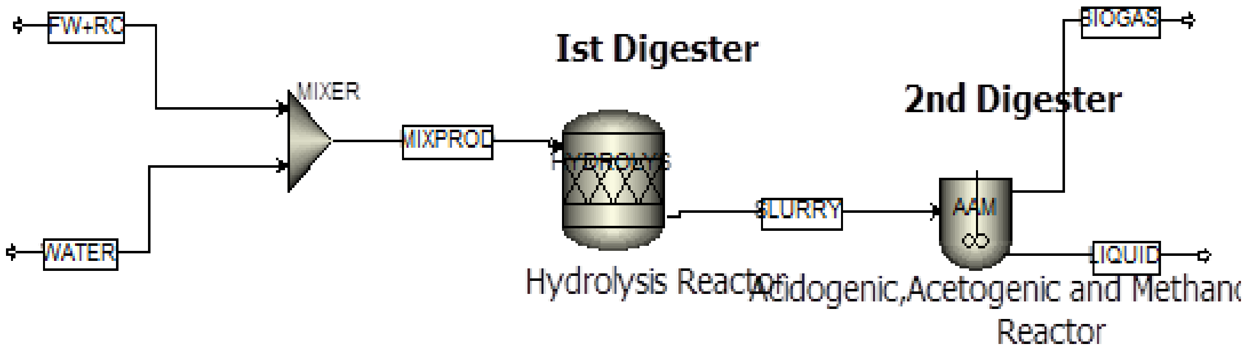

Figure 1. ASPEN Plus Simulation Flowsheet.

Table 2. ASPEN Plus Simulation Parameter

Parameter	Value	Unit	Source
Digester Volume	1	m^3	Scale-up basis
HRT	30	Days	Continuous design practice
OLR	3.3	kg VS/m^3/d	Bench-informed
Temperature	42	°C	Experimental Optimum
K_hydrolysis	0.058	d^{-1}	Empirical fit
CH_4 fraction	62	%	GC average
Heating duty	4.0	kW	Energy balance
Biogas energy content	21.6	MJ/m^3	60% CH_4

2.6. Data Analysis

Kinetic fitting and graphics were performed in OriginPro 2023; mixed-effects and ANOVA analyses used R 4.3.2. Temperature effects were compared by one-way ANOVA (α = 0.05) with Tukey HSD post hoc tests. ASPEN Plus outputs were checked against empirical kinetics (RMSE < 8%).

3. Results and Discussion

3.1. Physicochemical Characterisation of Substrates

The study showed that the co-digestion process of vegetable waste (VW) and cattle rumen content (CRC) has a distinct temperature maximum at 42 °C, at which biogas yield, methane concentration, volatile fatty acid (VFA) dynamics, and volatile solids (VS) decrease were maximized, and the process became the most stable (Table 3). At this mesophilic-upper mesophilic range, the VW: CRC 70:30 mixture showed a cumulative production of biogas of 12.4 ± 0.6 L/40 days at this range, equivalent to that of 0.62 ± 0.03 L/g VS, which was 25 times greater than 35 °C and 39 times greater than 25 °C and was 25 times greater than that of 55 - 60 °C, at which inhibition occurred.

Table 3. Physicochemical Characterisation of Substrates (mean ± SD)

Parameter	Vegetable Waste	Cattle Rumen Content	VW: CRC 70:30	VW: CRC 50:50	Optimal Range
pH	4.2±0.2	6.8±0.1	5.1±0.2	5.6±0.2	6.8-7.2
TS (% w/w)	18.2±1.2	12.8±0.9	16.5±1.0	15.5±0.9	8-12

VS (mg/kg TS)	88.6±1.5	79.2±2.1	85.8±1.8	83.9±1.7	>75
C/N ratio	18.2±0.8	14.5±1.1	25.3±1.2	28.1±1.4	20-30
Crude protein (% TS)	3.2±0.4	18.6±1.2	8.5±0.8	10.9±0.9	5-15
Lipids (% TS)	12.5±1.1	8.2±0.8	11.1±0.9	10.4±0.9	<15
P (mg/kg TS)	420±45	1850±120	910±80	1135±95	>800
K (mg/kg TS)	1250±110	3200±250	1880±160	2225±190	>1500
Ca (mg/kg TS)	650±60	2100±150	1215±100	1375±110	>1000
Ni (µg/kg TS)	145±25	420±45	245±35	282±40	>100
Co (µg/kg TS)	85±15	210±30	128±22	148±25	>50

To obtain the optimal C/N ratios (25 - 30:1), substrate mixtures (VW: CRC 70:30 and 50:50 w/w) were diluted with distilled water to 8% TS and adjusted to an initial pH 7.0 ± 0.2 with 1M NaOH/HCl. Active inoculum (10% v/v, 2% TS rumen fluid pre-incubated at 35 ℃/24hr) was obtained from a stable mesophilic digester.

3.2. Temperature Effect on Biogas yield and Methane content

Biogas yield and methane content peaked at 42 °C for the 70:30 mixture, reaching 0.62 ± 0.03 L/g VS and 62% CH_4. Performance declined at both lower mesophilic temperatures and in the thermophilic range, where VFA accumulation and process stress were more pronounced (**Figure 2**). The particular biogas production at 42 ℃ (0.62 L/g VS) was relative to 0.51 L/g VS at 35 ℃ and 0.39 L/g VS at 25 ℃, which demonstrated that a moderate increase in temperature was a good inducing factor for more hydrolysis and methanogenesis, without causing inhibitory effects.

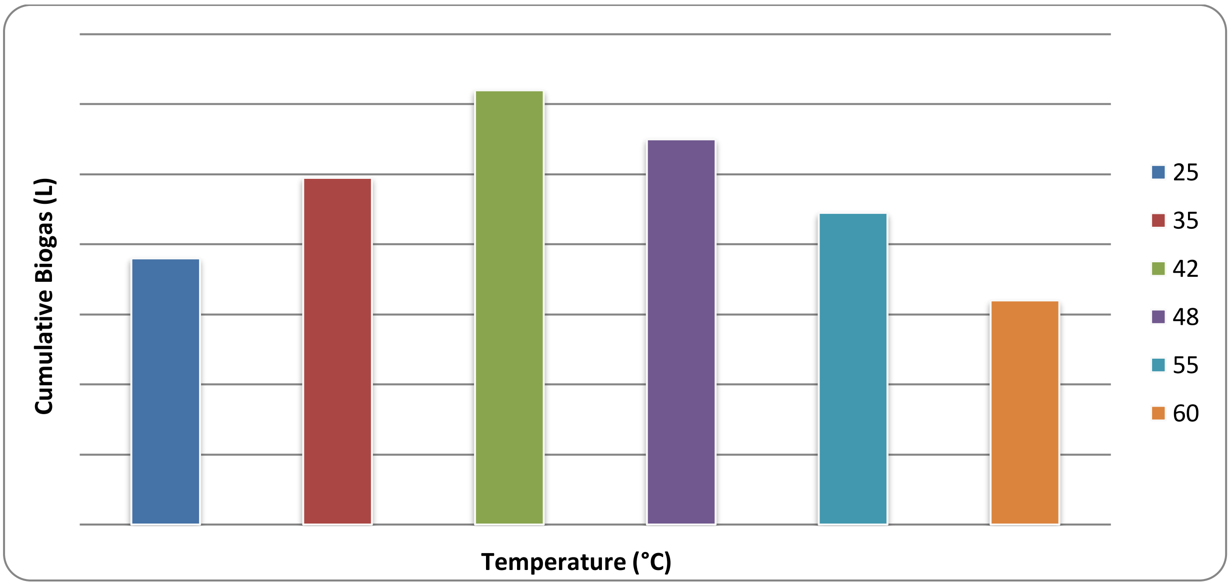

Figure 2. Biogas Production as a function of temperature (40 days HRT, VW: CRC 70:30)

Thermophilic operation at 55 and 60 ℃ was initially characterised by the higher peak daily production rates, it was affected by the accumulation of VFA and longer lag phases, obtaining only 0.46 and 0.33 L/g VS, respectively, and confirming that in the case of VW-CRC, thermophilic operation compromised net performance after 40 days of HRT (Table 4), the results are consistent with the results of the studies by Hossain *et al.* (2022), and Sudiartha *et al.* (2023).

Table 4. Effects of temperature on Biogas production parameters (VW: CRC 70:30)

Temp. (°C)	Cumulative Biogas (L)	Specific Yield (L/g VS)	Peak Daily Rate (L/d)	Days to Peak	Plateau Rate (L/d)
25	7.6 ± 0.8	0.39 ± 0.04	0.28 ± 0.05	18	0.18 ± 0.03
35	9.9 ± 0.5	0.51 ± 0.03	0.42 ± 0.04	14	0.24 ± 0.02
42	12.4 ± 0.6	0.62 ± 0.03	0.58 ± 0.03	10	0.31 ± 0.02
48	11.0 ± 0.7	0.57 ± 0.04	0.52 ± 0.04	11	0.28 ± 0.03
55	8.9 ± 0.7	0.46 ± 0.04	0.45 ± 0.06	12	0.22 ± 0.04
60	6.4 ± 0.9	0.33 ± 0.05	0.32 ± 0.07	15	0.15 ± 0.05

The biogas peaked at 42 °C with CH_4 reaching 62 ± 1% in day 40days under thermophilic conditions (55 - 60 °C), being 54 - 59 ± 3 - 4% CH_4 with high levels of H_2S (up to 520 ±120 ppm at 60 °C), which indicated the presence of sulfate-reducing bacteria and possible issues of corrosion.

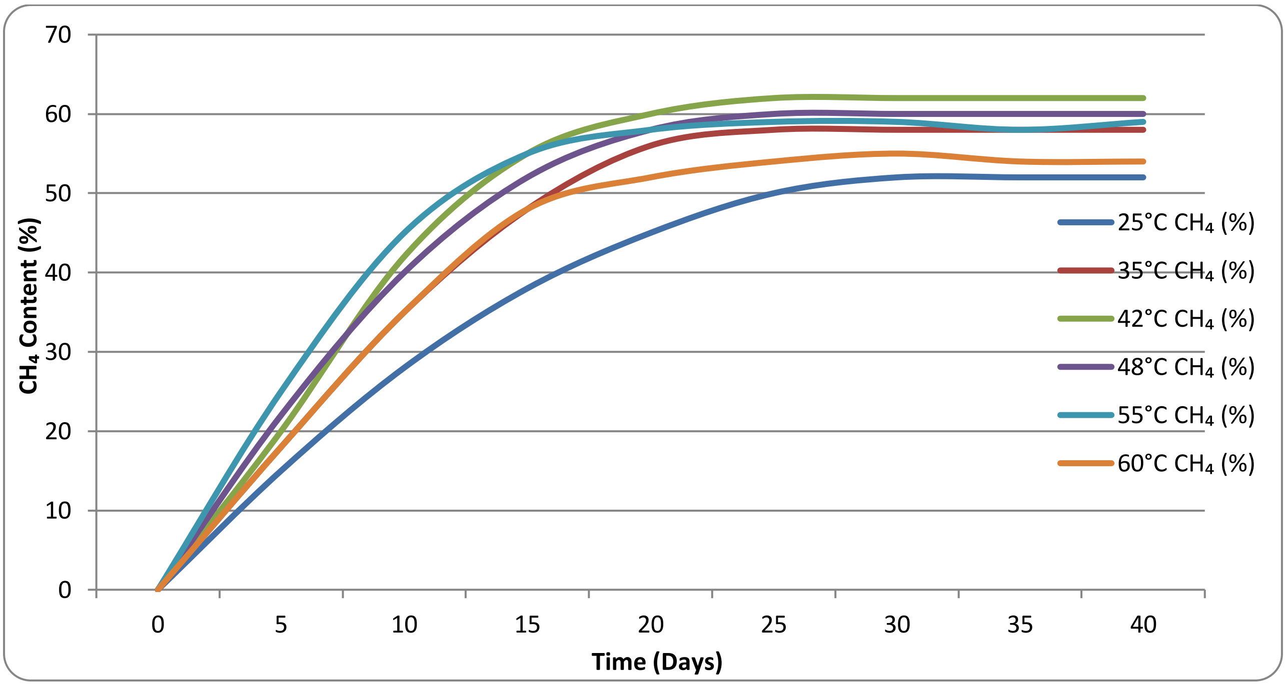

Figure 3. Fraction evolution of Methane

The computed quality index of a mixture of CH_4, CO_2, and H_2S fractions was best at a room temperature of 42 °C (Table 5), higher than the results at the psychrophilic and thermophilic values, and suggesting that not only did a given temperature maximize the amount of gases but also provided the best quality of usable gases that can be directly combusted. These results are consistent with other reports of mesophilic or slightly elevated mesophilic operation (35 - 40 °C) generally providing more stable, high-methane biogas of food wastes than fully thermophilic regimes, particularly in heterogeneous and nutrient-enriched feedstocks.

Table 5. Influence of Temperature on Biogas Composition and Quality Index During Anaerobic Co-Digestion of Vegetable Waste and Cattle Rumen Content

Temperature (°C)	CH_4 (%)	CO_2 (%)	H_2S (ppm)	Quality Index
25	52 ± 2	44 ± 2	250 ± 50	3.2
35	58 ± 1	38 ± 1	180 ± 30	4.5
42	62 ± 1	34 ± 1	120 ± 20	5.2
48	60 ± 2	36 ± 2	140 ± 25	4.9
55	59 ± 3	37 ± 3	310 ± 80	3.8
60	54 ± 4	42 ± 3	520 ± 120	2.1

3.3. Comparison of co-digestion, mono-digestion, and thermophilic operation

Table 6 consolidates the key performance comparison requested by the reviewers. Co-digestion at 42 °C and 70:30 VW: CRC delivered 0.62 L/g VS, which is 38% higher than VW mono-digestion under otherwise comparable mesophilic conditions (approximately 0.45 L/g VS) and 18% higher than thermophilic co-digestion at 55–60 °C (approximately 0.53 L/g VS). Methane content and lag-phase length followed the same ranking, confirming that the abstract claims are supported by the experimental contrast between optimised co-digestion, mono-digestion, and thermophilic operation.

Table 6. Comparison of biogas performance: co-digestion vs mono-digestion vs thermophilic operation

System	Temp. (°C)	Ratio	Biogas yield (L/g VS)	CH_4 (%)	Relative to optimum
VW–CRC co-digestion (optimum)	42	70:30	0.62	62	Reference
VW mono-digestion	42	100:0	0.45	~55	−38%
VW–CRC thermophilic	55–60	70:30	0.53	~58	−18%
VW–CRC co-digestion	35	70:30	0.50	~58	−19%
VW–CRC co-digestion	25	70:30	0.38	~52	−39%

3.4. Volatile Fatty Acid Process Stability and Dynamics

The VFA profiles of the study also highlighted that 42 ℃ is the best operating window where maximum total VFA was 740 ± 85mg/L on day 5, then a sharp decline to less than 50mg/L occurred on day 15, and an acetate/propionate ratio was 1.8 ± 0.2, which is indicative of stable methanogenesis. Conversely, VFAs stabilized at 1520 ± 180 and 2240 ± 250 mg/L at 55 and 60 ℃, respectively, and remained high at 1500 mg/L longer, and corresponded to long lag phases (22 - 28 days), and inhibited methane formation, characteristic of a thermophilic overload and related with methanogenic inhibition (Table 7), which is consistent with Dhakal *et al.* (2023). During the experiments, pH was maintained at 25 - 48 ℃, 6.7 - 7.1, and then decreased to 6.2 - 5.8 under thermophilic conditions, even though it was buffered with CRC, which further confirms the destabilising property of the excessive temperature on this co-digestion system, in contrast to the Judd and Kohn (2018) study.

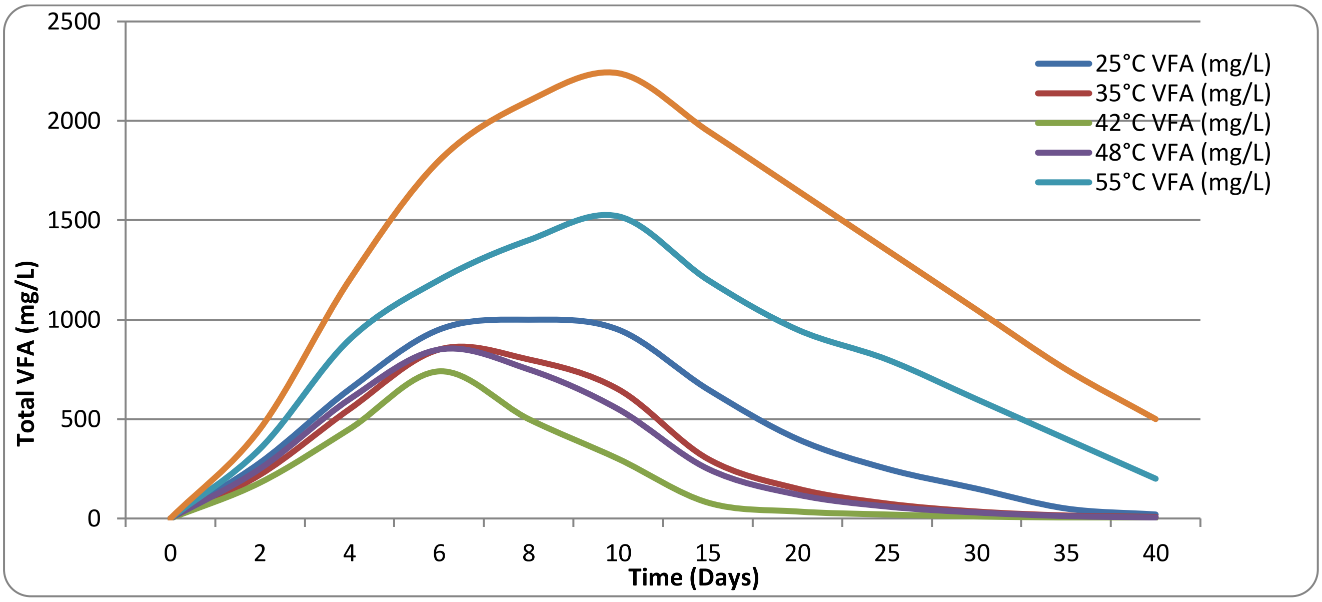

Figure 4. Dynamics of Total Volatile fatty acids as Temperature-Dependence in Anaerobic Co-Digestion of Vegetable trash and Cattle Rumen Content

These findings are common in comparative food-waste and slaughterhouse-waste co-digestion studies globally, where a study from optimal methanogenic performance, where VFAs are promptly converted, and propionate is not accumulated, usually in the 35 – 40 °C temperature range and with C/N ratios of about 20 -30:1 (Lee *et al.,* 2023).

Table 7. VFA Dynamics and Process Stability Indicators

Temp. (°C)	Peak VFA (mg/L, Day)	Acetate: Propionate	Days to < 200 mg/L	Lag Phase (days)	pH Min/Max
25	1100±120 (d7)	1.2±0.1	18±2	14.2±1.5	6.6/7.1
35	920±95 (d6)	1.4±0.2	12±1	9.8±1.2	6.7/7.1
42	740±85 (d5)	1.8±0.2	8±1	5.2±0.8	6.7/7.1
48	950±110 (d6)	1.5±0.2	11±1	8.5±1.0	6.6/7.1
55	1520±180 (d8) *	0.9±0.2*	28±3*	22.4±2.1*	6.2/7.0*
60	2240±250 (d10) *	0.6±0.1*	>35*	>28*	5.8/6.9*

N.B: **Inhibition threshold exceeded; *significant propionate accumulation.*

The present findings indicate that, rapid VFA clearance (42 °C) and short lag phase (5.2 ± 0.8 days) are favourable compared to those of the international datasets where lag phases of 5 -10 days (Table 7) and peak VFAs of less than 1000 mg/L are usual indicators of efficient mesophilic digester operation using food residues, as co-substrates with rumen or manure. This indicates that working with VW-CRC and 42 °C, the system is robust in processes similar to established co-digestation systems in Europe and Asia, although it is developed using locally available Nigerian feedstocks (Ahmad *et al.,* 2025).

3.4. Kinetics of Volatile Solids Degradation and Hydrolysis

The reduction of volatile solids was at the peak (65 ± 2% at 42 °C) as opposed to 48 ± 3% at 25 °C and 48 ± 5% at 60 °C, which indicated that the temperature optimum not only increased the amount of yielded gases but also the extent of stabilization of organic matter

(**Figure 5**). The highest hydrolysis rate constant *k* value of 0.058 d^{-1} with a half-life of 12 days at 42 °C was 81 percent greater than that determined at 25 °C (0.032 d^{-1}), and significantly greater than that at 60 °C (0.030 d^{-1}). The exceptionally good model fit (R^2 = 0.95 - 0.97 at 25 - 48 °C) ensured that in the effective temperature of degradation of VW-CRC, followed classic first-order behaviour, but poorer fits (R^2 = -0.94 - 0.95 at 55 – 60 °C) indicated the presence of non-linear inhibition effects. The finding of this result is in agreement with the findings of research by Awodun *et al.* (2025) and Ekstrand *et al.* (2022).

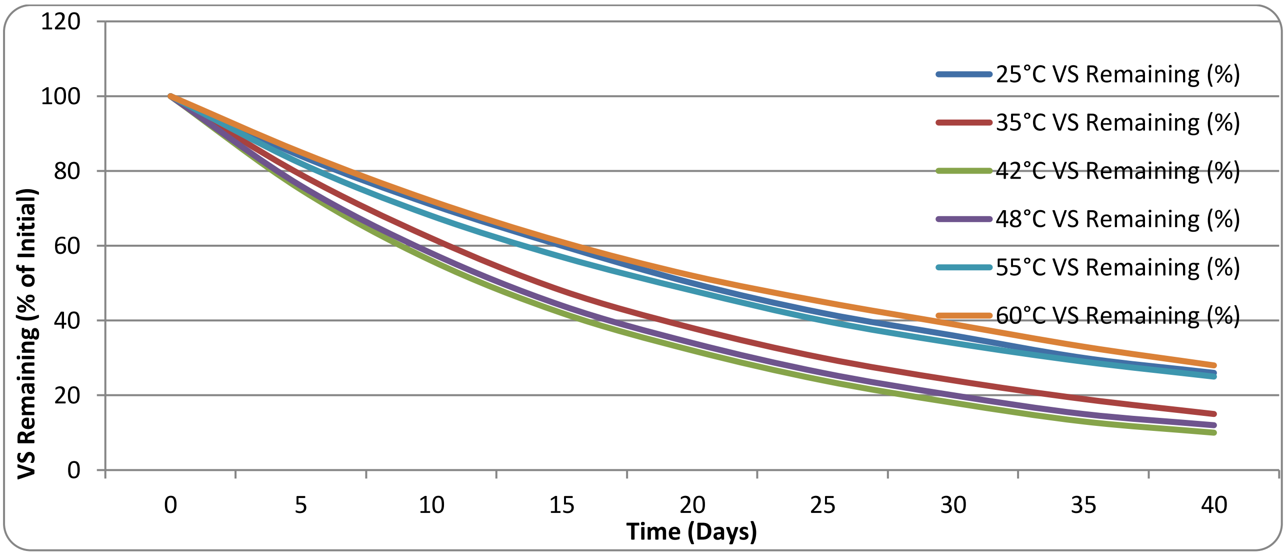

Figure 5. Temperature Effect on Volatile Solids Degradation in Anaerobic Co-digestion of Cattle Rumen Content and Vegetable Waste

Mesophilic digester reported *k* values (Table 8) of first-order hydrolysis food waste and slaughterhouse residues frequently lie in the 0.03 - 0.08 d^{-1} range, with larger values reported when the system is well-mixed (temperature controlled), and includes co-digestion strategies to enhance nutrient balance and microbial activity (Candel *et al.*, 2025).

Table 8. Kinetic Parameters (First-order: $S(t) = S_0 e^{-kt}$)

Temp. (°C)	*k* (d^{-1})	t½ (days)	B_max (L)	R²	Lag Phase λ (days)
25	0.032 ± 0.004	21.7	7.9	0.951	14.2 ± 1.5
35	0.044 ± 0.003	15.8	10.2	0.968	9.8 ± 1.2
42	0.058 ± 0.003	12.0	12.8	0.972	5.2 ± 0.8
48	0.053 ± 0.004	13.1	11.4	0.965	8.5 ± 1.0
55	0.039 ± 0.005	17.9	9.3	0.941*	22.4 ± 2.1
60	0.030 ± 0.006	23.0	6.7	0.923*	>28

*Bad fit because of inhibition (Arrhenius th=1.072, range 35 - 42 °C).

The current *k* value of 0.058 d^{-1} at 42 °C (Table 8) is within the higher half of this global range, indicating that the VW-CRC system with optimised Nigerian conditions can attain comparable rates of hydrolysis and overall digestion to those that were obtained in more technologically intensive environments. The Arrhenius temperature coefficient θ of approximately 1.072 in the temperature range of 35 to 42 °C is also in line with the generally reported mesophilic θ values (1.07 - 1.10) as reported by Shukor (2020), which supports the generality of the observed temperature-rate relationship in this study.

3.5. Substrate Mixing Ratio Effect on Biogas Yield and Methanogenic Performance

At the optimum temperature of 42 ℃, the 70:30 VW: CRC ratio gave higher cumulative biogas (12.4 L) than the 50:50 mixture (9.8 L), despite the specific yield being similar (0.62 vs. 0.68 L/g VS), indicating both mixtures were good at utilizing the balanced C/N ratio and nutrient profile available as CRC. The 70:30 ratio may, however, be more favorable to energy maximization in that it utilizes more high-energy VW, yet it still attains adequate buffering, microbial inoculum, and micronutrient levels on CRC to prevent acidification. This observation is consistent with the findings of other researchers who established that co-digestion of food waste with 20 - 40 percent of animal-derived residues (manure, rumen, slaughterhouse effluent) can greatly enhance methane production (20 - 50 %) and improve the stability of the digester due to positive effects on C/N ratio, micronutrient availability and inoculum richness (Alfa *et al.,* 2020; Salem *et al.,* 2025).

In general, the most effective co-digestion ratios of food waste and animal wastes are commonly between 60:40 and 80:20, depending on the nature of the substrates, and most studies have shown that better levels of methane production, lower VFA concentrations, and reduced resilience to organic loading shocks are achieved at these ratios (Amos *et al.,* 2025; Ayantokun *et al.,* 2025). The 70:30 and 50:50 substrate mixing ratios in the current research option and the high performance of 70:30 are hence harmonious with the rest of the literature and confirm the notion that such ratios are good starting points in the VW-CRC system in tropical environments. Also, the enrichment of Ni and Co in the mixed substrates (245 -282mg/kg TS Ni and 128 -148mg/kg TS Co) puts them in a range that is known to favor major methanogenic enzymes, which also justifies the high methanogenic activity achieved.

3.6. Performance and energy output of anaerobic digestion using optimum mesophilic ASPEN Plus CSTR simulation

ASPEN Plus modeling of 1 m^3 continuous stirred-tank reactor (CSTR) operating at 42 ℃ with an organic loading rate of 3.3 kg VS/m^3/day predicted a cumulative production of biogas mass of 6.8 m^3 in 90 days (about 150 -160 L/day at upland) at 60 percent methane composition with a net energy output of 37.2 kWh considering a heating duty of 4.0 kW (Figure 6). This product can replace a significant portion of domestic or small business-level energy needs in the rural Nigerian setting, and it can match biogas outputs of the equivalent scale digesters of food and market wastes in Asia and Latin America, where 100-200 L/m^3 per day are the expected daily yields under optimal mesophilic conditions (Jameel *et al.,* 2023; Verma *et al.,* 2025). The net energy contribution predicted is converted into actual economic paybacks (e.g., savings over liquefied petroleum gas), and when added to passive or solar-assisted heating strategies, the energy balance is more favourable in tropical climates.

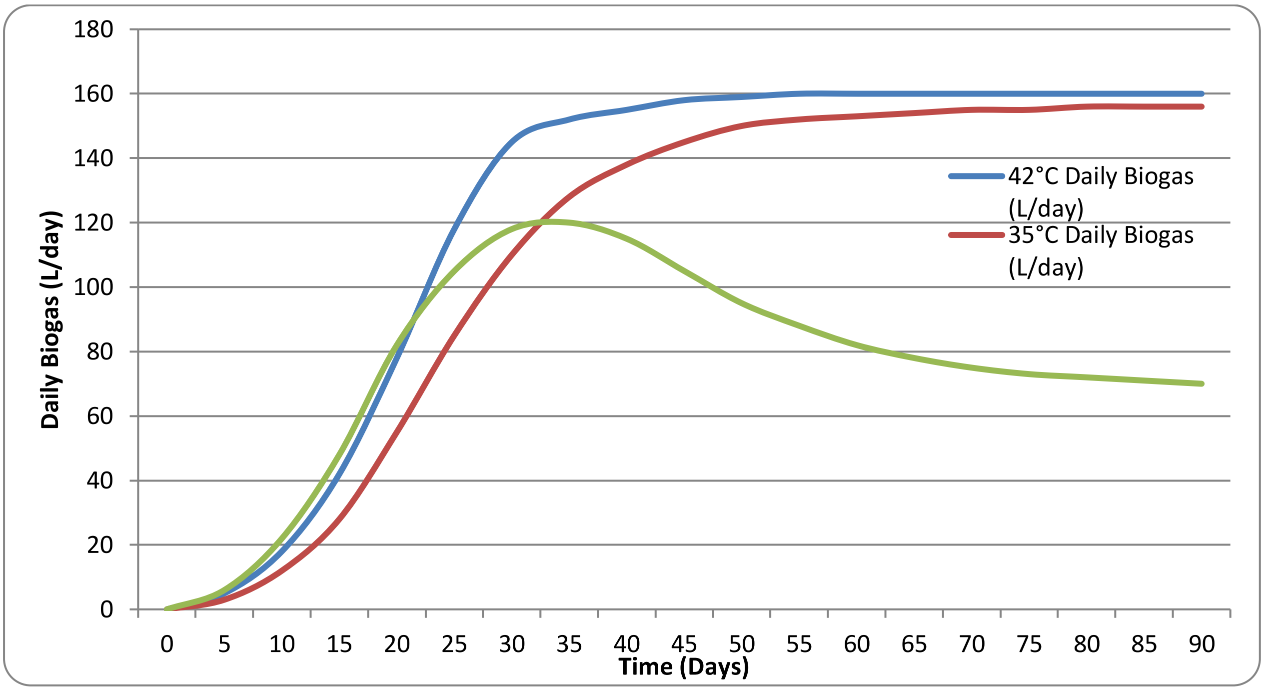

Figure 6. Simulated Daily Biogas (1 m³ Reactor) Production

Globally, the illustration of the study that temperature optimization at temperatures of about 42 °C can yield stable and high-quality biogas of VW-CRC mixtures is consistent with the evidence provided at the international level that representative and strengths mesophilic or slightly higher mesophilic digestion can often be the most viable and robust solution in low- and middle-income countries. The combination of experimental kinetics, on a detailed basis, with process simulation makes the study a collaboration between the findings of laboratory scale and real-world application, which is the same best practice of modern research on anaerobic digestion studies with applications where ASPEN Plus as a model is becoming more popular in the design and de-risking of decentralised biogas systems. In general, the findings from VW-CRC co-digestion as a technically and energy-competitive alternative in the global menu of food-waste and slaughterhouse-waste digestion methods, and is particularly relevant to the case of decentralised waste-to-energy implementation in sub-Saharan Africa (Colantoni *et al.*, 2024; Oladejo *et al.*, 2020; Yankyera *et al.*, 2024).

Conclusions

Anaerobic co-digestion of vegetable waste and cattle rumen content at optimal temperature (42 °C) produced 0.62 L/g VS biogas yield (methane content of 62), which is 38% higher than VW mono-digestion and 18% higher than thermophilic operation. Temperature optimization reduced lag phase by a half (5.2 VS. 14.2 days at 25 °C), minimized VFA buildup (maximum 740 mg/L vs. 2240 mg/L at 60 °C), and maintained control of pH, which proved the robustness of the process paramount to decentralized application in Nigeria and sub-Saharan Africa. The VW: CRC 70:30 energy maximization of balance (12.4 L cumulative biogas) and microbiological stability, which was occasioned by the buffering capacity of CRC and the wide range of microbial consortium. This ASPEN Plus simulation study forecasted a cumulative biogas of 6.8 m³ of 90-day scaled reactor operation (1 m³ CSTR, 42 °C), which is equivalent to 37.2 kWh of net energy. Some of the deployment pathways entail household (1m^3) and community (10m^3) clusters in rural communities (payback period 18 - 24 months) and municipal abattoirs/markets (payback period 3 - 4 years), respectively. The validation of the continuous-flow reactor, microbial community profiling, optimization of pretreatment, and combined digestate valorization should take precedence in future work to optimize the process control and economic feasibility. Mesophilic (35 – 42 °C) design standardization across African settings, enabled by localized ASPEN Plus models and microfinance interventions, can trigger regional uptake within 5-10 years to 50 million homes in sub-Saharan Africa by 2035.

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Conflicts of Interest

The author solemnly declares no conflict of interest.

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