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KINETIC MODELLING OF BIOGAS PRODUCTION FROM CO-DIGESTION OF COW DUNG AND SUGARCANE PEELS

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ABSTRACT

Biogas production from agricultural residues offers a sustainable pathway for renewable energy generation and waste valorization. However, optimizing substrate combinations to maximize yield and process stability remains a major challenge. This study investigated the kinetics of biogas production from cow dung and sugarcane peels to determine optimal mixing ratios and assess co-digestion performance. Compositional analysis revealed higher organic matter (86 %) and carbon content (49.88 %) in sugarcane peels compared to cow dung (44 % and 25.52 %), suggesting their potential as a primary substrate. Five digesters with varying ratios were monitored over five weeks. The highest cumulative yield (4992 cm^3) was obtained with 100% sugarcane peels, while the 75:25 sugarcane peel–cow dung mixture recorded the highest 24-hour production rate (1000 cm^3), highlighting synergistic benefits. Kinetic modeling using first-order and modified Gompertz equations showed reduced lag time (microbial adaptation period before significant gas production begins.) which is 2 days vs. 4 days for cow dung alone and improved methane potential, confirming the advantages of co-digestion. The novelty of this work lies in establishing sugarcane peels, an underutilized agro-waste, as a viable primary feedstock, with cow dung enhancing both yield and start-up efficiency. Optimization identified the 75:25 ratio as the most efficient configuration. Scaling up this process could significantly reduce agricultural waste, lower rural energy costs, and provide decentralized clean energy solutions. Socioeconomically, adoption at community and industrial levels can create green jobs, support energy security, and promote circular bioeconomy models in regions with abundant sugarcane production.

Keywords: Biogas, Kinetics, Co-digestion, Sugarcane peels, Cow dung

INTRODUCTION

The rising demand for renewable energy and the urgent need to mitigate greenhouse gas emissions have intensified research into sustainable bioenergy systems, with biogas emerging as one of the most promising solutions. Biogas is produced through anaerobic digestion of organic materials by a consortium of microorganisms, yielding methane (CH_4) and carbon dioxide (CO_2) as the primary components (Appels *et al.,* 2011). Its use not only provides a renewable and decentralized energy source but also contributes to waste management and environmental protection by reducing the volume of organic residues (Khan *et al.,* 2017). In agricultural and agro-industrial economies, the valorization of abundant organic wastes such as animal manure and crop residues for biogas production is particularly significant (Mussoline *et al.,* 2013).

Cow dung has traditionally been used as a biogas feedstock because of its availability and buffering capacity, which stabilizes anaerobic digestion processes (Mönch-Tegeder *et al.,* 2013). However, its biogas yield is often constrained by suboptimal carbon-to-nitrogen (C/N) ratios and the presence of lignocellulosic components that are resistant to microbial degradation (Zhao *et al.,* 2021). Conversely, sugarcane peels—an abundant agro-industrial byproduct in sugar-producing regions—are rich in organic matter and carbon, making them a potentially valuable substrate for biogas production (da Silva *et al.,* 2018). Despite this advantage, their high C/N ratio and limited nitrogen content can cause nutrient imbalance, leading to acidification and process instability when digested alone (Karki *et al.,* 2020).

Co-digestion, defined as the simultaneous anaerobic digestion of two or more substrates, has been recognized as an effective strategy to overcome these limitations. Combining sugarcane peels with cow dung can balance nutrient availability, enhance microbial activity, and improve process stability, thereby increasing methane yields (Mussoline *et al.,* 2013; Li *et al.,* 2018). Previous studies have reported that co-digestion of lignocellulosic residues with manure not only optimizes the C/N ratio but also enhances buffering capacity, reduces the accumulation of volatile fatty acids, and promotes synergistic microbial interactions (Zhang *et al.,* 2020; Zhao *et al.,* 2021). However, the specific kinetic behaviour of sugarcane peel–cow dung mixtures remain underexplored, particularly in terms of optimizing substrate ratios for maximum gas yield and stability.

Kinetic studies are essential for understanding the dynamics of substrate biodegradation and for predicting system performance under different operating conditions. First-order kinetic models are commonly applied to describe biogas production as a function of the biodegradable fraction, offering simplicity for engineering applications (Tchobanoglous et al., 2014). However, this model does not account for microbial adaptation phases, which can be significant in heterogeneous substrates. The Modified Gompertz model, on the other hand, is widely used to describe sigmoidal production patterns, as it incorporates lag phases, maximum production rates, and methane potential (Lay *et al.,* 1997). Integrating these models provides a more comprehensive understanding of the anaerobic digestion process and supports the optimization of co-digestion strategies (Li *et al.,* 2018).

This study, therefore investigates the kinetics of biogas production from cow dung and sugarcane peels to optimize substrate combinations for improved performance. Specifically, it aims to (i) analyze the proximate and nutrient composition of cow dung and sugarcane peels, (ii) determine the effects of different co-digestion ratios on biogas production, (iii) evaluate the kinetics of the process using first-order and Modified Gompertz models, and (iv) identify the optimal substrate combination for enhanced gas yield and process stability. The rationale for substrate ratio choices in this research is to balance the high carbon content of sugarcane peels with the nitrogen-rich profile of cow dung, thereby optimizing the C/N ratio for enhanced microbial activity, stability, and methane yield.

MATERIALS AND METHODS

Substrate Collection and Preparation

Fresh cow dung was sourced from a local livestock farm in Dandume Local Government, 11°24'46.15" N 7°11'25.58" E, Katsina state, while sugarcane peels were obtained from Katsina, 12°59'26.95" N 7°36'6.37" E, Central Market. Both substrates were manually sorted to remove foreign materials, sun-dried to reduce moisture content, and ground to improve surface area for microbial activity. Samples of each substrate were analyzed for proximate composition (moisture, ash, organic matter) as presented in Table 1, and nutrient content (carbon, nitrogen, and mineral elements) as shown in Table 2, following standard analytical procedures (AOAC, 2019).

Proximate Analysis

The proximate and nutrient compositions of the substrates were analyzed following standard procedures.

Moisture content

Moisture content was determined by oven-drying fresh samples at 105 °C for 24 hours until a constant weight was obtained, and calculated as:

$$MC\ (\%) = \frac{W_1 - W_2}{W_1} \times 100$$

where W_1 and W_2 are the weights before and after drying, respectively (AOAC, 2019).

Total solids (TS)

Total solids were determined concurrently as the ratio of oven-dried weight at **105 °C** to fresh weight, expressed as a percentage (APHA, 2017).

$$TS(\%) = W1/W2 \times 100$$

Ash content (%)

Ash content was measured by combusting the oven-dried samples in a muffle furnace at 550 °C for four hours until a uniform white ash was obtained, using the equation:

$$Ash\ (\%) = \frac{W_3}{W_2} \times 100$$

where W_3 is the weight of ash and W_2 is the oven-dried weight.

Organic matter (OM)

Organic matter was calculated as the difference between 100% and the ash content, while

$$OM(\%) = 100 - AC(\%)$$

Carbon content

Carbon content was estimated using the Van Bemmelen factor, expressed as:

$$C\ (\%) = \frac{\text{OM (\%)}}{1.724}$$ (Nelson & Sommers, 1996).

Nitrogen content (%)

Nitrogen content was determined by the Kjeldahl method, involving acid digestion with concentrated H_2SO_4 and a catalyst, distillation of the released ammonia into boric acid, and titration with standardized HCl. The percentage nitrogen was calculated as:

$$N\ (\%) = \frac{(V_1 - V_0) \times N \times 14}{W} \times 100$$

where V_1 and V_0 are the titration volumes for the sample and blank, N is the normality of the acid, and W is the sample weight (Bremner, 1996).

Carbon-to-nitrogen (C/N)

The carbon-to-nitrogen (C/N) ratio was obtained by dividing carbon by nitrogen values (Tchobanoglous *et al.,* 2014).

$$C/N = N(\%)/C(\%)$$

Determination of Ca and Mg

Samples were digested using a mixture of HNO_3 and $HClO_4$. Calcium (Ca) and magnesium (Mg) were determined using Atomic Absorption Spectrophotometry (AAS) at wavelengths of 422.7 nm and 285.2 nm, respectively, with concentrations calculated as:

$$Element\ Concentration\ (\%, ppm) = \frac{A \times V}{W}$$

where A is the concentration obtained from the standard curve, V is the digest volume, and W is the sample weight (AOAC, 2019).

Phosphorus (P)

Phosphorus was analyzed using the vanadomolybdate method, where the digest was reacted with ammonium molybdate and vanadate reagents, and absorbance was measured at 470 nm using a spectrophotometer (Murphy & Riley, 1962). Sodium (Na) and potassium (K) concentrations were quantified by flame photometry, using the same formula applied for Ca and Mg (AOAC, 2019).

Digester Setup

Five laboratory-scale batch digesters were improvised using 1000 cm³ capacity tin containers. Each digester was charged with a total slurry volume of 500 cm³, formulated to achieve different substrate mixing ratios:
A: 100% cow dung,
B: 100% sugarcane peels,
C: 50% cow dung: 50% sugarcane peels,
D: 75% cow dung: 25% sugarcane peels, and
E: 25% cow dung: 75% sugarcane peels.
All digesters were filled under anaerobic conditions, sealed to prevent gas leakage, and incubated at ambient mesophilic temperature (27 ± 2 °C).

Biogas Measurement

Biogas production was monitored daily for 35 days using the water displacement method. Cumulative gas volumes are presented in table 3, while maximum 24-hour production and lag phases were determined and summarized in table 4. Observations were used to evaluate both substrate-specific and synergistic effects of co-digestion.

Kinetic Modelling

First-Order Model

This model assumes biogas production is proportional to the remaining biodegradable substrate:

$$B(t) = B_0(1 - e^{-kt})$$

Where:
B(t) = cumulative biogas yield at time tt (cm³)
B_0 = ultimate biogas yield (cm³)
k = first-order rate constant (day⁻¹)
t = digestion time (days)

Modified Gompertz Model

This model accounts for the lag phase and the maximum production rate:

$$B(t) = B_{\max} \cdot \exp\left\{-\exp\left[\frac{R_{\max} \cdot e}{B_{\max}}(\lambda - t) + 1\right]\right\}$$

Where:
$B(t)$ = cumulative biogas yield at time (cm^3)
B_{max} = maximum biogas yield (mL or m^3)
B_0 = ultimate methane potential (cm^3)
R_{max} = maximum biogas production rate (cm^3/day)
λ = lag phase (days)
e = 2.718 (Euler's constant)
Cumulative biogas production data were fitted to First-Order and Modified Gompertz models to determine key kinetic parameters, including methane potential (B_0), hydrolysis constant (k), maximum biogas production rate (Rmax), and lag phase duration (λ). Model performance was evaluated based on the goodness-of-fit to experimental data, enabling comparison of digestion dynamics across different substrate ratios.

RESULTS AND DISCUSSION

Proximate Compositions and Nutrient contents

The efficiency of anaerobic digestion (AD) for biogas production depends largely on the physicochemical characteristics of the substrates, particularly their proximate composition (moisture content, total solids, ash, organic matter, carbon, nitrogen, and C/N ratio as shown in table1) and nutrient content (macro- and micronutrients, presented in table 2).

Ash and Organic Matter Content

Cow dung was found to have a significantly higher ash content (45.5 %) than sugarcane peels (4.5 %). This indicates a higher proportion of inorganic materials in cow dung, which do not contribute to biogas production and can dilute the digestible fraction (Wang *et al.,* 2020). Conversely, sugarcane peels showed a much higher organic matter content (86 %) compared to cow dung (44 %). High organic matter content is desirable, as it represents the biodegradable fraction of the substrate that can be converted to methane under anaerobic conditions (Hagos *et al.,* 2017). Importantly, the residual digestate or spent slurry, which contains undigested ash and stabilized organic matter, can be used as a nutrient-rich biofertilizer, especially when cow dung is involved. Its high ash content signifies abundant minerals that support soil amendment and plant growth.

Carbon and Nitrogen Content

The carbon content, which is derived from the organic matter, was also substantially higher in sugarcane peels (49.88 %) than in cow dung (25.52 %). Carbon serves as the primary energy source for methanogens during AD. However, effective digestion also requires sufficient nitrogen for microbial cell synthesis. Cow dung contained a relatively higher nitrogen content (0.70 %) compared to sugarcane peels (0.55 %), helping maintain microbial growth. As a result, the digested slurry from these substrates, especially cow dung, retains residual nitrogen and other nutrients that are gradually released into the soil, making it a sustainable and eco-friendly organic fertilizer alternative to chemical inputs (Yadvika *et al.,* 2004).

C/N Ratio

The C/N ratio is a critical indicator of substrate suitability. Sugarcane peels had a very high C/N ratio (90.69), suggesting an imbalance that may cause nitrogen deficiency and process inhibition if used alone. Cow dung, with a C/N ratio of 36.46, while still above the ideal range, presents a more balanced profile. Optimal C/N ratios for anaerobic digestion generally fall between 20 and 35 (Mussoline *et al.,* 2013; Karki *et al.,* 2020). Ratios beyond this range lead to excess carbon or nitrogen, potentially inhibiting methanogenesis. Therefore, co-digestion of sugarcane peels with cow dung can balance the C/N ratio and enhance microbial activity and biogas yield (Zhang *et al.,* 2014).
A balanced C/N ratio not only enhances biogas yield but also improves the nutrient profile of the spent slurry, making it a valuable biofertilizer for crop production.

Total Solids and Moisture Content

Moisture content influences microbial metabolism and substrate fluidity. Sugarcane peels had higher moisture (76 %) than cow dung (54 %), making them more suitable for wet AD systems. However, excessively high moisture can reduce retention time and dilute microbial populations. The total solids (TS) content was consequently lower in sugarcane peels, emphasizing the need for proper substrate blending to maintain ideal TS levels (8–12 %) for efficient gas production (Tucho & Nonhebel, 2017). After digestion, the reduced organic load and pathogen levels in the spent slurry make it safe for land application, and it contributes to improving soil structure, water retention, and nutrient cycling.

Table 1: Proximate Compositions

Substrate	Moisture (%)	Ash (%)	Organic Matter (%)	Carbon (%)	Total Solid (%)	C/N Ratio
Cowdung	10.5	45.5	44	25.52	89.5	36.46
Sugarcane Peels	9.5	4.5	86	49.88	90.5	90.69

Mineral Content: Ca, Mg, K, Na, and P

Nutrient analysis in table 2 showed that cow dung had higher concentrations of potassium (8.0 ppm), sodium (9.9 ppm), calcium (0.9 %), and magnesium (0.18 %) than sugarcane peels (K = 1.7 ppm, Na = 2.0 ppm, Ca = 0.008 %, Mg = 0.09 %). These macroelements are essential as cofactors for enzymatic reactions in the methanogenic pathway. Particularly, K and Na are involved in maintaining osmotic balance, while Mg and Ca support enzyme function and cell wall stability (Yadvika *et al.,* 2004). Phosphorus, vital for energy transfer and nucleic acid synthesis, was also higher in cow dung (0.68 ppm) than in sugarcane peels (0.52 ppm). Low phosphorus in sugarcane peels could limit microbial proliferation during mono-digestion. Following anaerobic digestion, all measured mineral contents in the feedstocks increased, reflecting the concentration of nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium in the residual digestate (Li *et al.,* 2018).. This enrichment occurs because organic matter is degraded into biogas, leaving behind a stabilized by-product that is nutrient-dense and more readily available for plant uptake. Several studies have similarly reported that digestate retains or enhances the mineral fraction of substrates, making it a valuable biofertilizer for sustainable agriculture (Möller & Müller, 2012; Arthurson, 2009). The increase in mineral concentration not only reduces reliance on synthetic fertilizers but also promotes a circular bioeconomy by transforming agro-waste into both renewable energy and soil amendments.

Table 2: Nutrient Contents

Parameter Measured	Cow dung		Sugarcane peels	
	Undigested	Digested	Undigested	Digested
Nitrogen (%)	0.70	0.80	0.55	0.62
Phosphorus(ppm)	0.68	0.83	0.52	0.68
Potassium (ppm)	8.00	9.00	1.70	2.70
Sodium (ppm)	9.20	9.60	2.00	4.50
Calcium (%)	0.19	0.25	0.08	0.16
Magnesium (%)	0.18	0.25	0.09	0.14

Overall Implication for Biogas and Biofertilizer Production

Based on the above, cow dung alone may provide a more balanced nutrient profile but lacks sufficient biodegradable carbon, leading to lower biogas yield. Sugarcane peels, though rich in degradable organic matter and carbon, may suffer from nitrogen and nutrient limitations. Therefore, co-digestion at an optimized ratio (e.g., 75:25 sugarcane peels to cow dung) improves the overall substrate quality by: Balancing C/N ratio, improving buffering capacity, enhancing microbial diversity and stability, increasing biogas yield and reducing lag phases

Crucially, the anaerobic digestion process transforms raw waste into two valuable products: renewable energy (biogas) and nutrient-rich digestate (biofertilizer). This dual benefit aligns with the principles of circular economy and integrated waste management, reducing environmental pollution and promoting sustainable agriculture (Zhao *et al.,* 2021; Zhang *et al.*, 2014).

Process Optimization

Optimization indicates that 75 % sugarcane peels with 25 % cow dung provided the best balance of C/N ratio, nutrient availability, and microbial activity, enhancing both yield and kinetics. This agrees with Mussoline *et al.* (2013), who identified mixed substrates as optimal for methane productivity.

Kinetic Analysis

Fitting cumulative production to the modified Gompertz model gave the highest methane potential (P) for Digester E, with the shortest lag phase (λ = 2 days) and highest maximum production rate (Rmax = 1000 cm³/day). In contrast, cow dung alone exhibited longer lag (λ = 4 days) and lower Rmax (245 cm³/day) (Table 4). These results align with Li *et al.* (2018), who noted that co-digestion reduced hydrolysis limitation and improved biogas kinetics.

Biogas Production Trends

Weekly gas production in table 3 indicates initial rapid gas generation in sugarcane peels (Digester B) and mixed substrates (Digesters C–E). By Week 3, cow dung (Digester A) peaked at 1984 cm³, while sugarcane peels produced minimal gas due to acidification and nutrient limitations. Co-digestion (Digester E: 75 % sugarcane peels, 25 % cow dung) produced stable and sustained yields, achieving 4532 cm³ total gas. Similar synergy was reported by Karki *et al.* (2020), where co-digestion of agricultural residues improved buffering capacity and methanogenic activity.

Table 3: Weekly Biogas Production (cm³) by Five Digesters

Time	Digester A	Digester B	Digester C	Digester D	Digester E
Week 1	170	1718	2913	2103	3185
Week 2	1014	2630	1245	1454	1287
Week 3	1984	644	96	776	60
Week 4	1036	0	0	0	0
Week 5	340	0	0	0	0
Total	4544	4992	4254	4333	4532

Overall sum of biogas production from five digestres = 22,655cm³

Model Fit Visualization and Interpretation

The graphical comparison of model predictions against experimental data in table 4 and figure 1 illustrates the performance of two widely used biogas kinetic models: the First-order and the modified Gompertz models. The Modified Gompertz model demonstrates a superior fit, particularly for mono-digestion (A, B) and co-digestion (E), effectively capturing both the lag phase and acceleration in gas production. This confirms its strength in representing biological processes that involve an initial microbial adaptation period followed by exponential methane generation.

Table 4: Kinetic Parameters for Biogas Production

Digester	Substrate Composition	First-Order Model		Modified Gompertz Model		
		B_0 (cm³)	k (day⁻¹)	B_0 (cm³)	Rmax (cm³/day)	λ (days)
A	100% Cow dung	4544	0.10	4544	245	4
B	100% Sugarcane peels	4992	0.15	4992	250	2
C	50% Cow dung: 50% Sugarcane peels	4254	0.13*	4254	820	2
D	75% Cow dung: 25% Sugarcane peels	4333	0.12*	4333	368	2
E	25% Cow dung: 75% Sugarcane peels	4532	0.173	4532	1000	2

Modified Gompertz vs. First-order Model

The Modified Gompertz model accounts for the initial lag phase (λ), maximum production rate (R_{max}), and cumulative methane potential (P_{max}), making it ideal for modeling substrates that require microbial adaptation or enzymatic hydrolysis prior to methane formation (Mussoline *et al.,* 2013). In contrast, the First-order model assumes instantaneous microbial activity, leading to poor estimation during the early phase—evident in its underestimation of early gas production for all digesters, especially mono-digestion setups.

This limitation is particularly noticeable for Digester A (cow dung alone), where the lag phase extended up to 4 days, resulting in slower startup and lower methane productivity. However, in Digester E (co-digestion of 25 % cow dung and 75 % sugarcane peels), the lag phase was significantly reduced to 2 days, and the model captured the rapid increase in gas production accurately. This aligns with reports by Li *et al.* (2018) and Zhang *et al.* (2014), who observed that co-digestion enhances microbial synergy, optimizes the C/N ratio, and shortens the microbial acclimatization period.

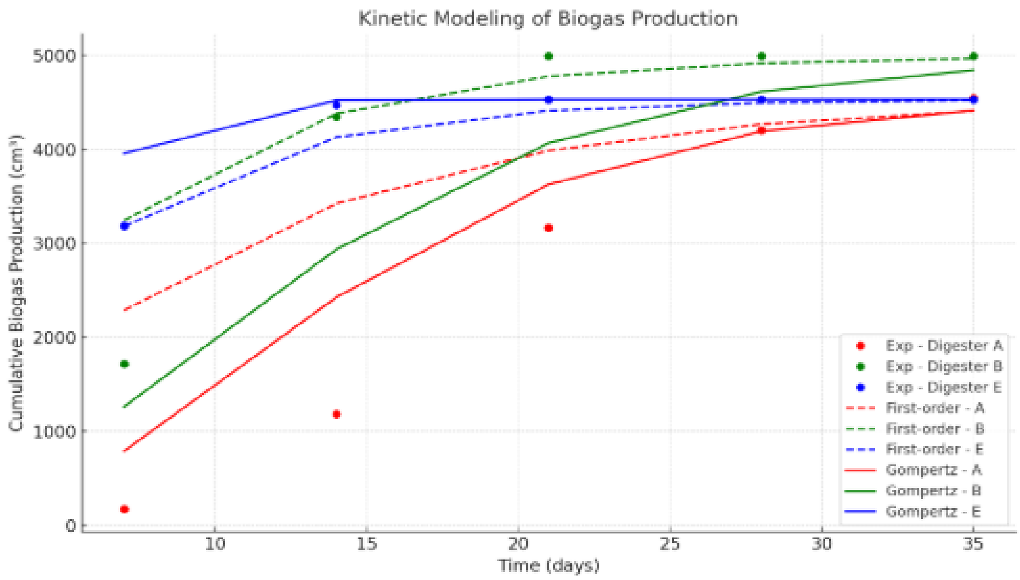

Figure 1: Kinetic Model Comparison Plot for Biogas Production

Co-digestion Performance and Model Parameters

The co-digestion scenario (Digester E) exhibited: Highest degradation rate (k) among all configurations, shortest lag phase (λ = 2 days), maximum cumulative production (P_{max}) and production rate (R_{max}). These findings confirm the benefits of co-digestion in improving biogas yield and kinetics. The synergy between cow dung and sugarcane peels provides a balanced nutrient profile, supports methanogenic microbial diversity, and enhances substrate bioavailability, as observed in prior studies (Zhao *et al.,* 2021; Yadvika *et al.,* 2004).

Digesters C (50:50) and D (75:25) were not included in the comparative model plot, likely due to model fitting limitations or overlapping trends that could obscure visual clarity. In kinetic modelling, plots are often simplified to highlight contrasting behaviours—in this case, pure substrates (A and B) versus the best-performing co-digestion setup (E). Including C and D could lead to cluttered visuals with intermediate trends that don't provide additional insight beyond what E demonstrates more strongly. However, it's worth noting that digesters C and D still provided valuable kinetic data, and their intermediate performance metrics suggest a gradation in biogas productivity, confirming that higher sugarcane peel ratios enhance gas yield up to a point (E), beyond which nutrient dilution or structural resistance may occur (Zhang *et al.,* 2014).

CONCLUSION

The co-digestion of sugarcane peels and cow dung significantly enhanced biogas production efficiency and digestion kinetics. A 75:25 ratio of sugarcane peels to cow dung was identified as the optimal blend, yielding the highest 24-hour gas production and the shortest lag phase, indicative of improved microbial activity and system responsiveness. Proximate and nutrient analyses revealed that the two substrates possess complementary characteristics—sugarcane peels offered a high organic matter content, while cow dung supplied essential minerals such as potassium and sodium. This combination led to a more balanced carbon-to-nitrogen (C/N) ratio, which is critical for stable anaerobic digestion and enhanced biodegradability. Kinetic modelling further validated these findings, with the Modified Gompertz model providing a more accurate representation of the cumulative biogas production, especially in co-digested systems. The model successfully captured the lag phase and maximum production rates, in contrast to the first-order model, which underestimated early-stage performance. These outcomes align with existing literature emphasizing the synergistic benefits of lignocellulosic–manure co-digestion in improving methane yield and process stability. Additionally, the spent slurry from digestion shows strong potential for use as a nutrient-rich biofertilizer, contributing to sustainable waste management and circular bioeconomy initiatives. Future studies should explore scale-up processes, methane content analysis, and energy conversion efficiencies to fully harness the practical benefits of co-digestion in renewable energy applications.

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