Journal of Information Systems Engineering and Management
2025, 10(57s)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Evaluation of Biogas Production and Composition Including Trace Gases from Local Feedstocks - A Case of Kersa District, Jimma Zone, Ethiopia

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ARTICLE INFO

Received: 21 April 2025

Revised: 30 May 2025

Accepted: 12 Jun 2025

ABSTRACT

This study examines the impact of substrate type and retention duration on the anaerobic digestion yields of biogas and methane produced, as well as the emission reduction of carbon dioxide and trace gases from cattle manure, poultry litter, and their mix. A series of experiments were conducted utilizing three feedstocks—100% cattle manure, 100% poultry litter, and a 50:50 mix—were used in anaerobic digestion tests in two reactors, a 100-liter slurry for poultry litter slurry, 50:50 mix (cattle manure +poultry litter), and 450 liter slurry for cattle manure slurry, adjusted to the reactors, poultry litter produced the highest total yield (0.71835mL/g VS) and average daily output (0.3991 mL/g VS). These findings suggest that optimizing the feedstock ratio could enhance biogas generation efficiency, particularly in rural settings, while simultaneously addressing issues caused by trace gases such as hydrogen sulfide and carbon monoxide that inhibit methane production. Future research endeavors should focus on refining the other feedstock combinations to maximize biogas potential. The Modified Gompertz model demonstrated superior fitting of biogas production data relative to first-order kinetics.

Keywords: Methane yield, carbon dioxide emission, Cattle manure, poultry litter, power of hydrogen, composition.

INTRODUCTION

Anaerobic digestion has gained attention as a successful technique for converting organic, biodegradable resources, such as animal manure and poultry litter, into biogas due to the growing awareness of alternative energy technologies as a crucial tactic for sustainable energy development. When organic materials break down in anaerobic conditions, biogas—a naturally occurring mixture of carbon dioxide and methane—is created. Around the world, it is used as an environmentally beneficial fuel for power generation, lighting, and cooking. Depending on the feedstock and the biomethanation method, biogas typically contains 50–75% methane (CH_4) and 30–40% carbon dioxide (CO_2)(Michailos et al., 2020).

This study addresses the urgent need to identify optimal feedstocks for methane yield and peak biogas production. It aims to measure gas output in cubic meters and analyze gas composition across various substrates. Long-chain organic molecules can hinder fermentation, while materials rich in sugars and starches enhance biogas formation. Cattle manure provides essential nutrients like nitrogen and phosphate, supporting crop growth and yielding clean biogas that reduces air pollution(Mdlambuzi et al., 2021).

Previous studies show that fresh organic waste produces 0.27 m^3 of biogas, while food waste yields 0.32 m^3. However, the adoption of biogas technology is hindered by gaps in community acceptance and a lack of research on less popular feedstocks, particularly in areas like the Kersa District. Furthermore, the quality and peak production

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2025, 10(57s)
e-ISSN: 2468-4376
https://jisem-journal.com/
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time of biogas from various substrates are unknown. Closing these gaps is essential to boosting knowledge and biogas production in certain regions(Hasan et al., 2022).

METHODS AND MATERIALS

The research was conducted in a Ministry of Water and Energy laboratory center, where experiments aimed to evaluate the biogas production & composition, including trace gases and variations in carbon dioxide emission reduction and biogas and methane production with retention time, using double duplicates for every sample (Song et al., 2023)**.**

To gain a fundamental understanding of biogas, methane, and carbon dioxide, a comprehensive background study and extensive literature research were conducted. The properties of biogas, its production process, and its applications were covered in detail in the examined literature. The literature also looked at earlier research on biogas and current studies that use biogas technology(Bahrun et al., 2022) .

2.1. Equipment and supplies utilized

Materials and equipment were employed in the study, including substrates like cattle manure, a four-hundred-fifty-liter slurry reactor adjusted to reactor one (1), and for poultry litter slurry, 50:50 mix (cattle manure +poultry litter), and, a hundred-liter reactor adjusted to reactor two (2), **Cod 949100** RE-BIOMASS (a pilot plant for producing biogas from biomass***),*** and thermometers.

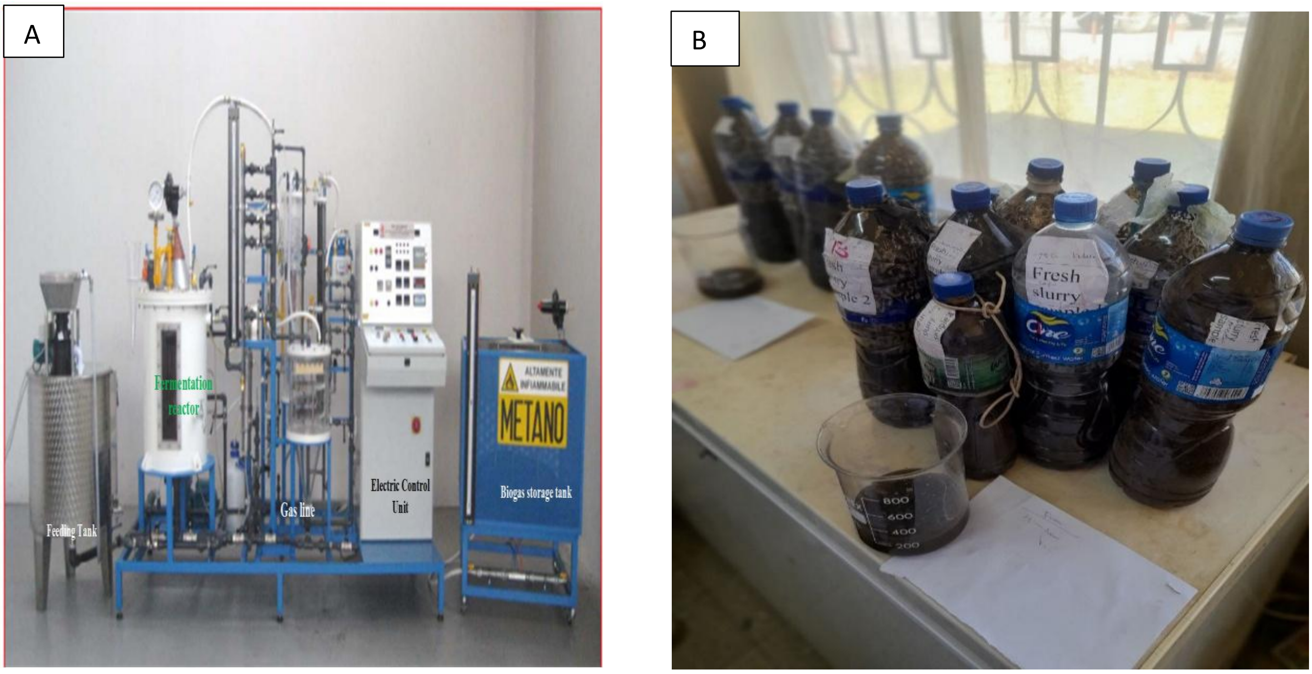

Figure 1: A) Cod 949100 RE-BIOMASS (pilot plant for the production of biogas from biomass) used in the experimental work B) Experimental setup in the laboratory

2.2. Sample Preparation for Biogas Production

Before being placed in the digesters, the feedstocks were inspected for stones and other undesirable materials. The substrates were measured using a computerized weighing scale, and the poultry litter and cattle manure were combined in various amounts after being mixed with water at a 100:0, 50:50, and 0:100 volume ratio as indicated in [Table 1]. After that, this combination was put into the reactor with a capacity of 100 liters for poultry litter, 450 liters of slurry for cattle manure, and for 50:50 mixtures, 100 liters were among the substrates. A thermometer was included with two reactors to monitor temperature differences(Tumusiime et al., 2022).

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Table 1: Amounts of substrate for different treatments

Combination ratio	Treatments/Samples
100% poultry litter	X
50% poultry litter and 50% cattle manure	Y
100% cattle manure	Z

The table shows the experimental setup for treatments X, Y, and Z, each double (2) times.

2.3. Method of Experimentation

As shown in [Table 1, Figure 1], one hundred liters of poultry litter and four hundred fifty liters of cattle manure, adjusted to reactors, which were strong and convenient for waste handling, were used in the laboratory, mainly for biogas. methane production and CO_2. The plant comprises the stirrer, gas pipe, intake and output pipes, and fermentation chamber. For eighteen days, the digester's performance was tracked. The anaerobic fermentation chamber produced biogas without oxygen by breaking down the organic wastes (cattle manure and poultry litter) with the help of countless bacteria of various sizes and roles. The organic wastes were also given time to stabilize. The temperature range that prevailed during the methane generation period was 17°C to 38°C(Jameel et al., 2024). A digital pH meter and gas analyzer were used to measure the mixes' pH. Each reactor had a thermometer to regulate the temperature differential depicted in Figure 1. The smaller cylindrical part of the biogas collection and measuring containers (shown in Figure 1) had an exit pipe with intake and outflow valves at the top. The produced gases were gathered in a tube, and throughout the 18 observation days depicted, the percentages of carbon dioxide (CO_2) and methane (CH_4) gases were determined using a gas analyzer. For the 18 observation days depicted, the percentage of carbon dioxide (CO_2) and methane (CH_4) gases was determined using a gas analyzer after the produced gases were collected in a tube. Code 949100 RE-BIOMASS (Biogas generation pilot plant for biomass). A clean air purge was performed by turning off the gas analyzer by pressing the on/off button for around 35 seconds after each reading was taken (Herath et al., 2023).

2.4. Anaerobic Digestion Process

Anaerobic digestion was the main biochemical process used in the complex biogas manufacturing process from organic materials such as cattle manure and poultry litter. The various steps of this process can be represented by a few essential equations and formulae that can be used to simplify the entire reaction (Heiker et al., 2021).

2.4.1. Production of Biogas

The production of methane (CH_4) can be represented by the following simple equation:

$$C_6H_{12}O_6 = 3CH_4 + 3CO_2 \quad (1)$$

2.4.2. Stoichiometry Equations

The stoichiometric equations for cattle manure and poultry litter, which are high in proteins, lipids, and carbohydrates, may vary depending on the content. The following is a generalized representation:

Carbohydrates: $C_6H_{10}O_5 + H_2O = 3CH_4 + 3CO_2$ (2)

Proteins: $C_2H_5N + 2H_2O = CH_4 + CO_2 + NH_3$ (3)

Fats: $C_{57}H_{110}O_6 + 16H_2O = 57CH_4 + 57CO_2 + 6NH_3$ (4)

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2.5. Equation and overview of the First-Order Kinetic model and the Modified Gompertz model.

According to [Table 2], mathematical models were employed in the field of biogas generation to forecast and optimize the process. The first-order kinetic model and the modified Gompertz model are two popular models used to explain the kinetics of biogas production. Here is a summary of each:

1. Kinetic Model in First Order: Concept: According to this model, the pace at which biogas is produced is directly correlated with the amount of organic matter, the biodegradable substrate, that is still present at any given moment. This straightforward model is founded on a basic idea in chemical kinetics. Equation: The fundamental equation is frequently shown as follows:

d (V)/dt = k * (Vmax - V) ` (5)

Where:

* `d(V)/dt` is the biogas production rate at time t.

* `k` is the first-order rate constant (representing the degradation rate).

* `Vmax` is the maximum biogas potential.

* `V` is the cumulative biogas production at time t. Benefits: It is straightforward, requires few parameters, and is easy to comprehend and apply. Drawbacks: It frequently oversimplifies the intricate biological processes involved in anaerobic digestion.

2. Modified Gompertz Model: * Idea: This empirical model more accurately depicts the sigmoidal (S-shaped) curve frequently seen in the production of biogas. The lag phase and the fact that the rate of biogas production fluctuates during the process are taken into consideration.

* The equation is commonly expressed as follows:

`V = Vmax * exp {-exp [e/Vmax * (λ - t) + 1]}` (6)

Where:

* `V` is the cumulative biogas production at time t.

* `Vmax` is the maximum biogas potential.

* `λ` is the lag phase duration.

* `e` is the base of the natural logarithm (approximately 2.718).

* `t` is the time.

* `μ` is a constant representing the maximum biogas production rate. (Sometimes 'e' and 'μ' are combined into a single parameter)

According to [Table 2], while the simplicity of the first-order kinetic model was useful, the Modified Gompertz model usually provides a more realistic and accurate representation of the kinetics of biogas production. The choice of model depends on the specific application, the available data, and the level of precision needed. Researchers often compare the two models' goodness-of-fit (e.g., R-squared value) to determine which model best describes their experimental data. Remember, these are models, and they are only approximate representations of real biological processes.

Table 2: Model comparison

characteristics	First-Order Kinetic Model	Modified Gompertz Model
Complexity	Simple	More complex
Lag phase	Not explicitly modeled	Explicitly modeled

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https://jisem-journal.com/

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Rate constancy	Assumes a constant rate	Accounts for variable rate
Curve shape	Exponential	Sigmoidal (S-shaped)
Data Fit	Often a poor fit	Generally better fit
Parameter Estimation	Easier	More challenging

2.6. Instrument Uncertainty

Each of the instruments utilized in this study has its own uncertainty and readability.

Table 3: An overview of the instrument's readability and uncertainty.

parameters	Uncertainty	Readability	Instrument names
Potassium(mg/L)	±1	1nm	Spectro photo meter 6000
Phosphorus (mg/L)			
pH	±0.01	0.01pH	pH Bench Meter Man manufacturer, Supplier, and Exporter in Ethiopia (EDS-PM-1100)
Biogas Volume (mL)	±0.5	1mL	Graduate cylinder
Methane (%)	±0.01	0.01	Geotech Biogas 5000 portable analyzer, UK.
Volatile solid (%)	±0.001	0.001g	Multiple PH/Temp/TDS/EC meter
Total solid (%)			
OC (%)	±1	1	Horiba's TOC-Analyzer (HT-110)
TN (mg/L)	±0.001	0.001g	BKN-986 Kjeldahal apparatus
C/N ratio	±1	0.001	CN 802 Analyzer (Carbon Nitrogen Analyzer)

2.7. Determining the Volume of Methane and Carbon Dioxide at a Given Time Interval

Biogas and methane gas yield, and carbon dioxide emission tests were performed on the samples during the laboratory-scale batch experiment. A gas analyzer known as the Cod 949100 RE-BIOMASS (pilot plant to produce biogas from biomass) was used to quantify the quantities of carbon dioxide and methane. (Figure 1) illustrates how the tube from the sample (treatment) was attached to the gas inlet port. The Cod 949100 RE-BIOMASS gas analyzer was turned off by pressing the on/off button for approximately 35 seconds after each reading. This was the time for a clean-air cleanse. The mixture that produced the most methane at a certain moment was identified and recorded. This finding was supported by (Maj, 2022a), who indicated that more methane gas was produced from the feedstock that had more starch and sugars.

RESULTS AND DISCUSSION

The study examined the variations in the emissions of carbon dioxide, methane, biogas, and other trace gases from the use of poultry litter and cattle manure as substrates, both independently and in combination. We also examined the composition of the top biogas-producing substrates. The average results of the double duplicates were shown for each sample.

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Table 4 : Results of physicochemical analysis of cattle manure and poultry litter

No	Parameters	Cattle manure value		Poultry litter value	
		Fresh slurry	Digestate slurry	Fresh slurry	Digestate
1	pH	6.95	7.26	6.99	7.3
2	TemperaturesoC	20 ºc	39ºC	20.2 ºc	33ºC
3	VS (Kg)	78	76	65	68
4	TS (Kg)	25	27	30	34
5	C: N	20	25	10	14
6	Total nitrogen (%)	1.5	2.5	3.5	3
7	Organic Carbon (%)	40%	30	35%	25%
8	Ash (%w/w)	15	18	20	24
9	phosphorus	3240mg/L	5341mg/L	3545mg/L	8345mg/L
10	Potassium	5060mg/L	6070mg/L	11645mg/L	8192.3mg/L
11	BOD	20,000 mg/L	5000mg/L	30000mg/L	7000 mg/L
12	COD	80,000mg/L	30000mg/L	100,000mg/L	35,000mg/L
13	Moisture Content (%)	75	84	70	80

3.1. Characterization of Cattle Manure & Poultry Litter

According to [Table 4] the mixture of cattle manure and poultry litter was utilized as a substrate for the production of biogas. Based on the findings of the physicochemical analysis of bovine manure and poultry litter [Table 4] and the biogas yield from different feedstocks [Tables 4 & 5], a variety of studies and comparisons of the potential for biogas production from different feedstocks can be made. A few possible analyses are as follows: When fresh and digestate forms of cattle manure and poultry litter are compared, multiple significant changes are found across a number of criteria. Cattle manure has a pH of 6.95 (fresh) and 7.26 (digestate), whereas poultry litter has a pH of 6.99 (fresh) and 7.3 (digestate), all of which are neutral to slightly alkaline, creating ideal conditions for microbial activity (Kulichkova et al,2025). Significant temperature rises occur after digestion, with poultry litter going from 20.2°C to 33°C and cattle manure from 20°C to 39°C, both of which signify increased microbial activity. Cattle manure maintains more organic matter (78 kg fresh vs. 76 kg digestate) than poultry litter (65 kg fresh vs. 68 kg digestate) in terms of volatile solids, indicating a larger potential output for biogas. A more concentrated nutritional profile is shown by the higher total solids in poultry litter (30 kg fresh vs. 34 kg digestate) compared to cattle manure (25 kg fresh vs. 27 kg digestate). Poultry litter has a higher nitrogen content (10 fresh vs. 14 digestate) than cattle manure (20 fresh vs. 25 digestate), according to the C:N ratio, which increases the fertilizer value of the former (Maj,2022a). In comparison to cattle manure (1.5% fresh vs. 2.5% digestate), poultry litter has a higher total nitrogen concentration (3.5% fresh vs. 3% digestate). Compared to poultry litter (35% fresh vs. 25% digestate), cattle manure maintains more organic carbon (40% fresh vs. 30% digestate), which is essential for enhancing soil structure. Compared to cattle manure (15% fresh vs. 18% digestate), poultry litter has a higher ash level (20% fresh vs. 24%), which indicates a higher mineral value. Cattle manure has higher phosphorus levels in the digestate form (3240 mg/L fresh vs. 5341 mg/L digestate), whereas poultry has the highest overall (3545 mg/L fresh vs. 8345 mg/L digestate). Additionally, poultry litter has a higher potassium content (11645 mg/L fresh vs. 8192.3 mg/L digestate) than cattle manure (5060 mg/L fresh vs. 6070 mg/L digestate), which makes it appropriate for crops that require potassium (Mirsky et al.,2023). Both varieties exhibit a notable decrease in biological oxygen demand (BOD), with poultry litter going from 30,000 mg/L to 7000 mg/L and cattle manure going from 20,000 mg/L to 5000 mg/L, demonstrating efficient organic matter decomposition. Reductions in chemical oxygen demand (COD), such as those in poultry litter (from 100,000 mg/L to 35,000 mg/L) and cattle manure (from 80,000 mg/L to 30,000 mg/L), significantly support the efficiency of digestion. Lastly, the digestates have a higher moisture content, with 70% (rising to 80%) poultry litter and 75% (increasing to 84%) cattle manure, which affects handling and application logistics. Overall, cattle manure offers more organic carbon that is good for soil health, whereas poultry litter generally offers higher nutrient concentrations, especially in nitrogen, phosphorus, and potassium. This suggests that the choice between the two should take particular crop requirements and agricultural needs into account (Mokif LA, et al.,2023).

Table 5: Results of physicochemical analysis of 50:50 cattle manure and poultry litter

50:50 (cattle manure + poultry litter)		
No	**Parameters**	Value
1	pH	7.5
2	Temperatures0C	32
3	VS (Kg)	85
4	TS (Kg)	32
5	C: N	22:1
6	Total nitrogen (%)	2.5
7	Organic Carbon (%)	45
8	Ash (%w/w)	22
9	Phosphorus (%)	0.9
10	Potassium (%)	1.5
11	BOD (mg/L)	4500
12	COD (mg/L)	8000
13	Moisture Content (%)	80

3.2. Physicochemical Analysis of 50:50 (mix ratio) of Cattle Manure and Poultry Litter

According to [Table 5], a wealth of organic matter and nutrients is added to the soil with this 50:50 blend of poultry and cattle manure. To maximize its advantages and reduce any potential disadvantages, its features must also be carefully managed. Rich in Nutrients: The mixture contains a significant amount of essential nutrients, including potassium (1.5%), phosphorus (0.9%), and nitrogen (2.5%)(YAHAYA et al., 2023). This implies that it could be a valuable fertilizer for crops that require a high level of nutrients. High Organic Matter Content: A significant input of organic matter was indicated by the high levels of organic carbon (45%) and volatile solids (85% on a dry weight basis). This can enhance microbial activity, water retention, and soil structure. A balanced ratio of C to N With a C: N ratio of 22:1, nitrogen mineralization should proceed at a decent pace because there was a good quantity of carbon present, but not too much(Islam et al., 2021). This implies that plants should be able to access nitrogen without being unduly hampered by soil microorganisms. Moderate Ash level: The presence of inorganic minerals, which can both increase soil fertility and build up over time, was indicated by the ash level of 22%. Crops typically thrive at a pH of 7.5, which is close to neutral, though some soil and plant requirements may call for modifications. Rich organic matter was indicated by high BOD (4500 mg/L) and COD (8000 mg/L); digestion was necessary for environmental safety to prevent soil oxygen depletion. Fresh manure typically has a high moisture content (80%); composting was advised to enhance handling and storage. Fertilizer with Promise: Rich in organic matter, N, P, and K, it lessens reliance on

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2025, 10(57s)
e-ISSN: 2468-4376
https://jisem-journal.com/
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synthetics. Soil Amendment Potential: Enhances microbial activity, water retention, and soil structure. Needs careful management: Monitor pH and nutrients to prevent imbalances, and control BOD/COD to prevent oxygen depletion. Environmental Benefits: Improves soil health for sustainable agriculture, recycles nutrients, and decreases waste(Mazibuko et al., 2025).

Table 6 : Physico-chemical comparison of feedstocks composition

No.	Parameter	Cattle Manure (Fresh)	Cattle Manure (Digestate)	Poultry Litter (Fresh)	Poultry Litter (Digestate)	Co-Digested (50:50)
1	pH	6.95	7.26	6.99	7.30	7.5
2	Temperature (°C)	20	39	20.2	33	32
3	Volatile Solids (kg)	78	76	65	68	85
4	Total Solids (kg)	25	27	30	34	32
5	C:N Ratio	20	25	10	14	22:1
6	Total Nitrogen (%)	1.5	2.5	3.5	3.0	2.5
7	Organic Carbon (%)	40	30	35	25	45
8	Ash (% w/w)	15	18	20	24	22
9	Phosphorus (mg/L)	3240	5341	3545	8345	9000 (≈0.9%)
10	Potassium (mg/L)	5060	6070	11645	8192	15000 (≈1.5%)
11	BOD (mg/L)	20000	5000	30000	7000	4500
12	COD (mg/L)	80000	30000	100000	35000	8000
13	Moisture Content (%)	75	84	70	80	80

According to [Table 6], the best C: N ratio (22:1), high volatile solids (85 kg), and excellent nutritional profile (TN 2.5%, P 0.9%, K 1.5%) make co-digestion the most balanced feedstock for biogas production and biofertilizer use. pH & stability: Digestates, particularly co-digestates, have a near-neutral pH (~7.3-7.5), which is ideal for microbial activity and improves their buffering capability. Rich in nutrients: These nutrients overcome the drawbacks of using only one feedstock. Pollution reduction: Digestates effectively decompose and stabilize organic materials by reducing BOD/COD(Szekely and Jijakli, 2022). The result from co-digestion has the lowest BOD/COD. Moisture content: Although digestates with high moisture content make pumping easier, they can also dilute the energy content; thus, moisture management is crucial. In conclusion, the most effective and sustainable solution is to co-digest cattle manure and poultry litter, which produces a high-quality feedstock with a lower possibility for pollution(Jasińska et al., 2023).

3.3. Measurements of Biogas from Various Treatments of X, Y, and Z Samples Results

Table 7: Biogas yield from different feedstocks in Liters (L)

Days	X (100% Poultry litter)		Y (50% poultry litter & 50% cattle manure)		X (100% cattle manure)	
	Biogas in L	Temp °C	Biogas in L	Temp °C	Biogas in L	Temp °C
1	0	27.1	0	26.3	0	26.3

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e-ISSN: 2468-4376
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Days	X (100% Poultry litter)		Y (50% poultry litter & 50% cattle manure)		X (100% cattle manure)	
	Biogas in L	Temp °C	Biogas in L	Temp °C	Biogas in L	Temp °C
2	0	27.1	1.464	27.2	1.572	27.8
3	0.384	27.2	1.572	27.1	5.1	27.3
4	2.544	26.4	2.052	27.3	6.372	27.8
5	18.618	29.13	12.06	27.2	25.26	27.7
6	19.2	28.7	12.72	27.5	15.24	27.8
7	19.38	27.43	13.92	25.9	11.46	26.6
8	19.86	28.5	13.92	27.2	10.26	27.1
9	13.28	28.1	10.004	27.8	6.68	27.8
10	13.36	28.1	11.84	28.1	13.36	29.0
11	13.68	29.1	15.32	29.2	23.72	30.0
12	22.08	29.2	25.48	29.2	5.32	30.5
13	42.432	30.1	25.088	30.1	7.104	31.0
14	20.16	29.2	19.968	20.3	6.592	30.1
15	13.568	28.1	6.464	28.4	5.824	29.0
16	13.376	28.7	12.224	28.6	5.824	29.1
17	12.608	30.1	8.384	29.7	5.248	30.0
18	7.488	30.1	7.808	29.6	4.8	30.0

According to [Table 7], comparison of Biogas Yields: On days 5 and 6, pure poultry litter (X) produced the most biogas, with notable production continuing until day 18. Overall, less biogas was created from cattle manure (Gohil et al., 2021). The findings show that pure poultry litter either works better for producing biogas than cattle manure or a combination of the two. Poultry litter's better performance was probably a finding of its high Volatile solids and organic carbon content (Jarosz et al., 2022).

3.3.1. The Effect of Temperature:

According to [Table 7], the temperature throughout the biogas production process fluctuates slightly depending on the feedstocks, but it always stays within the ideal range of 26°C to 31°C. Analysis: Microbial activity and the rates at which biogas is produced can be greatly impacted by temperature. Temperature variations might not be a limiting factor in this investigation, given the very steady temperatures. Finally, according to the data, poultry litter is generally a better feedstock for biogas production than cattle manure because of its more significant quantities of organic carbon, volatile solids, and nitrogen balance. However, due to their physicochemical characteristics, both feedstocks are appropriate for anaerobic digestion. This result was aligned with (Mutungwazi et al., 2022), who indicated that poultry litter and cattle manure are suitable for methane production. This dataset analyzes the 18-day temperature fluctuations, carbon dioxide (CO_2) levels, and methane (CH_4) output from three feedstocks used in anaerobic digestion: Y: 50% poultry litter and 50% cattle manure; X: 100% poultry litter, Z: Cattle manure, 100%. Each was observed every day to evaluate microbial activity and gas yields, which are essential markers for improving biogas production systems and 100% Poultry Litter Feedstock X

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Important Findings by Feedstock: CH_4 Yield: The highest of all substrates, reaching a peak of 41.12 L on Day 13.

- CO_2 Pattern: 0.0–31.9 ppm, with subsequent rises coinciding with the decline in CH_4.

Temperature: Increased gradually to about 30°C, allowing for mid-cycle peak microbial activity.

Feedstock Y (Mix): CH_4 Yield: gradual, more even gas production with a moderate peak at 24.97 L (Days 12–13). CO_2 Pattern: By Day 13, the CO_2 level had increased to around 38.9 ppm, indicating active microbial respiration.

- Temperature: Relatively constant between 26 and 30°C, reflecting the effectiveness of digestion.

100% Cattle Manure Feedstock Z, CH_4 Yield: a rapid fall after a robust start (Day 5: 24.98 L).

- CO_2 Pattern: Early peak (33.3 ppm, Day 4), followed by drop, which may be a sign of substrate depletion.
- Temperature: increased steadily, reaching a peak of 31°C; however, CH_4 yields did not continue.

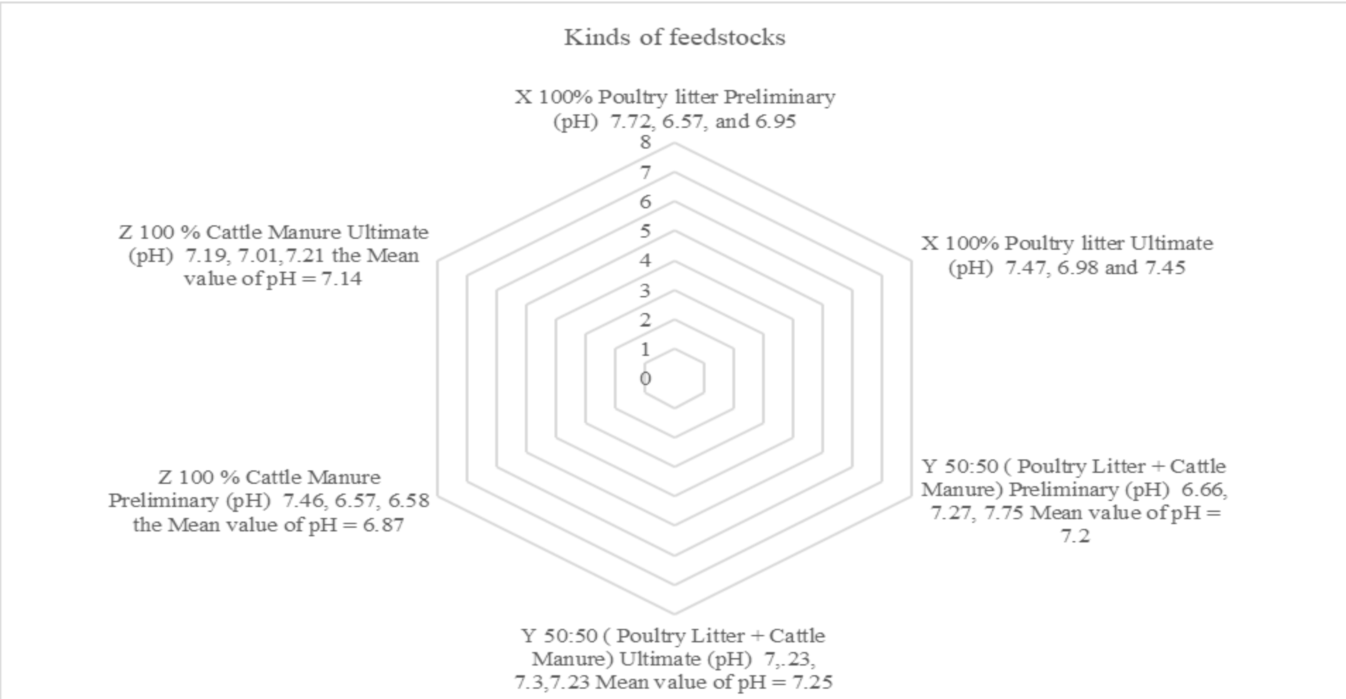

Figure 2: The preliminary and ultimate pH of the three treatments

Comparison of pH for three feedstocks: According to [Figure 2], to determine the best pH values for methane production from the three feedstocks (100% Poultry Litter, 50:50 Poultry Litter + Cattle Manure, and 100% Cattle Manure), we can analyze the provided pH values and their implications for anaerobic digestion.

Summary of pH Values:

100% Poultry Litter (X): Preliminary pH: 7.72, Ultimate pH: 6.57, and Mean pH: 7.05,50 %:50% (Poultry Litter + Cattle Manure (Y)): Preliminary pH: 7.47, Ultimate pH: 6.98 & Mean pH: 7.27 and 100% Cattle Manure (Z); Preliminary pH: 6.66, Ultimate pH: 7.75, & Mean pH: 7.25

Analysis of pH Values**:** Optimal pH Range: The optimal range for methane production is between 6 and 8.

Mean pH Values: X (100% Poultry Litter): 7.05, Y (50:50 Poultry Litter + Cattle Manure): 7.27, and Z (100% Cattle Manure): 7.25

Comparison: All treatments fall within the optimal pH range for methane production (Maj, 2022a) revealed that the efficiency of methane yield was more than 70% when the substrate slurry pH was above 7.0.

- The mean pH values indicate that the 50:50 Poultry Litter + Cattle Manure (Y) treatment has the highest mean pH at 7.27, followed closely by 100% Cattle Manure (Z) at 7.25 and 100% Poultry Litter (X) at 7.05. Furthermore, it was also observed that biogas production was only significantly affected when the pH of the slurry medium was between comparison a yield of 6.5 and 7. 5(Tang et al., 2022).

Table 8 (a) Comparative study of biogas yields from cattle manure and poultry litter (b) Comparison of previous with current studies in biogas production

(a)

No. I	Source	Poultry litter (PL) Biogas Yield	Cattle Manure (CM) Biogas Yield
1.1	Ojolo et al., 2007	0.0318 dm^3/day	0.0230 dm^3/day
1.2	Ojolo et al., 2007	0.0332 dm^3/day	0.0238 dm^3/day
1.3	Kumari, 2019	1952 L/kg DM/day*	1007 L/kg DM/day*
1.4	Ojo, 2022	0.1741 m^3 total	0.1020 m^3 total
1.5	Alfa et al., 2014	0.211 m^3 total	0.191 m^3 total
1.6	Soom et al., 2016	0.42 L/kg	0.71 L/kg
1.7	Obada et al., 2014	0.06 m^3/day	0.04 m^3/day
1.8	Akanni et al., 2012	3.84 ml avg.	3.19 ml avg.
1.9	Adeniran et al., 2014	3.84 ml avg.	3.19 ml avg.
1.10	Osuji et al., 2024	0.20 (ratio)	0.11 (ratio)
1.11	Wang et al. (2021)	Poultry: 550 (ratio)	Cattle: 220 (ratio)
1.12	Diagi EA, et al.,2019	60.7ml/day	29.9ml/day

(b)

S/N	*Kinds of feedstock*	*Previous results in%*		*Current study in %*		*Reference*
		CH_4	*CO_2*	*CH_4*	*CO_2*	
1	*Poultry litter*	*60*	*35*	*70*	*2.1*	*(Onwosi CO, et al.,2023)*
2	*Cattle manure*	*65*	*34*	*73.7*	*2.2*	*(Mostafaeipour M, et al.,2022)*
3	*Poultry litter + cattle manure*	*63*	*32*	*72*	*2.3*	*(Mostafaeipour M, et al.,2022)*

3.4. Biogas Yields from Cattle Manure and Poultry Litter Comparison

According to [Table 8], the findings of the comparison between past and present results for the production of biogas, A study of the comparison between past and present results for the yields of biogas from various feedstocks (poultry litter and cattle manure was presented below, based on the data provided above.

Clarifications and Consequences: Superiority of Poultry Litter: In 90% of the trials, the biogas produced by poultry litter was much higher than that of cattle manure. This is attributed to increased protein and nitrogen content, quicker breakdown, and improved methanogenesis assistance from microbes (Soom et al., 2016). The Relative Stability of Cattle Manure: Although less effective, cattle manure frequently produces more stable gas production over extended periods. Additionally, it's easier to find in rural places. The ideal mix ratio. In co-digestion trials, a 3:1

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ratio (poultry litter: cattle manure) consistently produced the greatest biogas, indicating a synergistic impact. Environmental and Economic Significance: Utilizing poultry litter yields a higher return on investment in biogas energy production, in addition to improved waste management (Diagi EA, et al.,2019).

In conclusion, poultry litter's biochemical makeup and degradability allow it to routinely produce more biogas than cattle manure. The production of biogas is further improved using a co-digestion method with an ideal ratio (3:1 PL: CM). Because of this, poultry litter is a more efficient and profitable substrate for small- to medium-sized biogas systems, especially in areas where poultry farming is prevalent (Wang et al., 2021).

3.5. The Comparison of the Previous and Current Results of Biogas Production

Biogas Production: Previous vs. Current Comparison (Summary), Poultry Litter: CH_4: ↑ from 60% to 70%, CO_2: ↓ from 35% to 26%, Insight: Enhanced methane output indicates improved microbial activity and digestion efficiency [(Shindell et al., 2024)]. Cattle Manure: CH_4: ↑ from 65% to 73.7%, CO_2: ↓ from 34% to 23%, Insight: Better substrate quality and digestion yield higher methane levels [(Shindell et al., 2024)]. Cattle + Poultry Blend: CH_4: ↑ from 63% to 72%, CO_2: ↓ from 32% to 22%, Insight: Synergistic feedstock effect enhances biogas quality [(Shindell et al., 2024); (Egwu et al., 2022)].

Overall Trend: All feedstocks show increased methane and reduced CO_2, indicating optimized anaerobic digestion and better biogas quality, supporting energy production goals.

3.6. Daily Biogas Production from Three Feedstocks in mL/g VS

According to [Table 9 and Figure 8] Analysis of daily biogas yield results from three feedstocks: using the information supplied, we could determine the mean, lowest, maximum, and total biogas yield for each of the three feedstocks—100% poultry litter, 50:50% poultry litter + cattle manure, and 100% cattle manure—to examine the biogas generation from each of them. The calculations showed that the 100% poultry litter produced the highest average daily production (mean = 0.3888 mL/g VS) and the best total yield (7.0005 mL/g VS). The 50:50 poultry litter + cattle manure mixture produced more on average each day than the cattle manure, but less than the poultry litter. The 100% cattle manure had the lowest average daily yield (mean = 0.2534mL/g VS) and total yield (4.5667mL/g VS). The 50:50 mix and 100% cattle manure are the least productive feedstocks in this scenario, whereas 100% poultry litter was the most effective feedstock in terms of biogas production efficiency and total yield for the tested period (Maj, 2022a). We used the provided data to calculate the mean, lowest, highest, and peak production times for each feedstock by comparing the daily biogas yield of the three feedstocks: 100% cattle manure, 50:50 poultry litter + cattle manure, and 100% poultry litter. The temperature difference for all experimental days was quite small, with the equivalent temperatures (0°C) for the eleventh, twelfth, and thirteenth days being 29.2, 29.2, and 30.1, respectively.

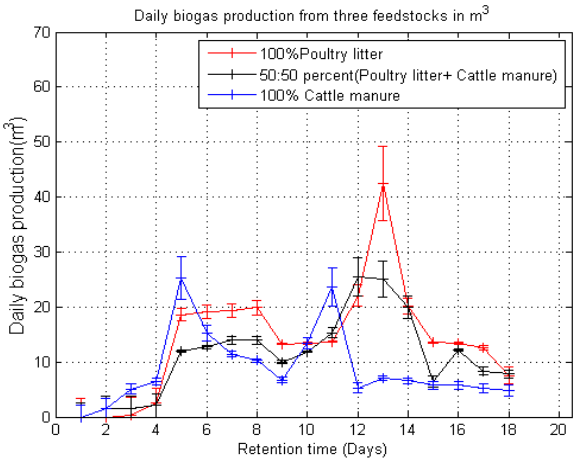

Figure 3: Daily biogas production from three feedstocks in m^3

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Table 9: Summary of daily biogas production results in mL/g VS

Feedstocks	Mean	Minimum	Maximum	Peak time(day)
100% poultry litter	0.3889	0	7.0005	13th
50:50% Poultry Litter + Cattle Manure	0.3096	0	5.5702	12th
100% cattle manure	0.2534	0	4.5639	5th

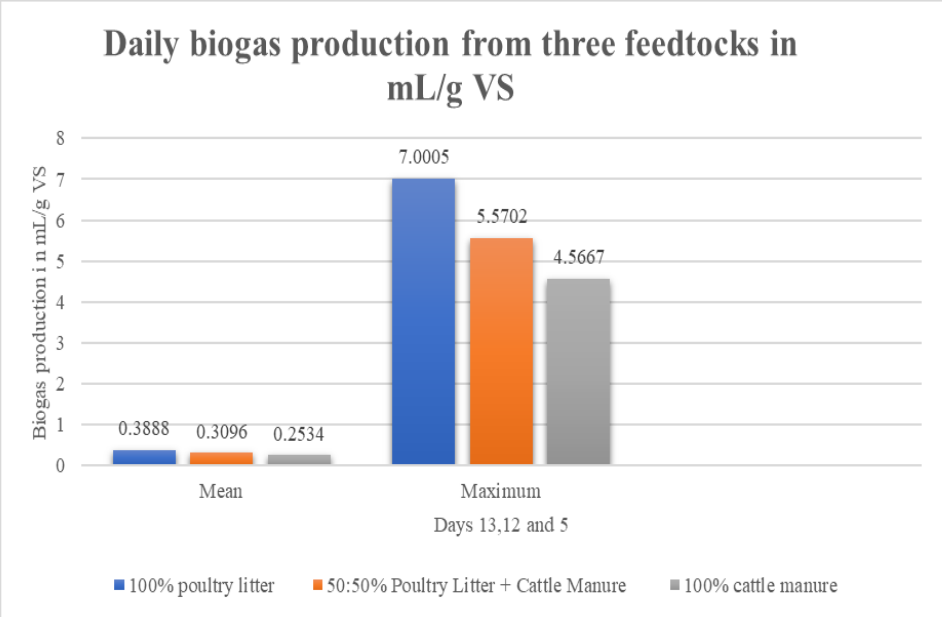

Figure 4 : Summary of daily biogas production results in mL/g VS

3.7. Cumulative Biogas Production from Three Feedstocks in m^3

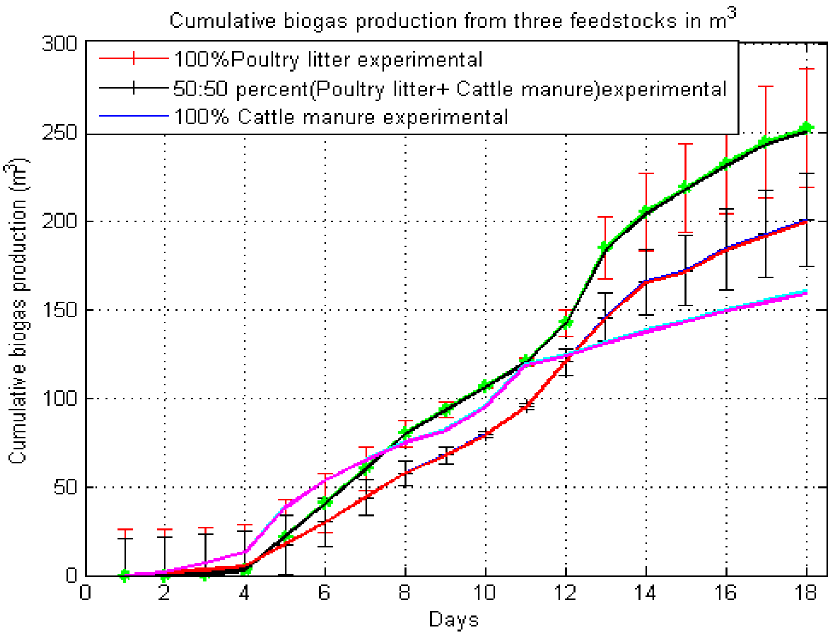

Figure 5 : Cumulative biogas production from three feedstocks in m^3

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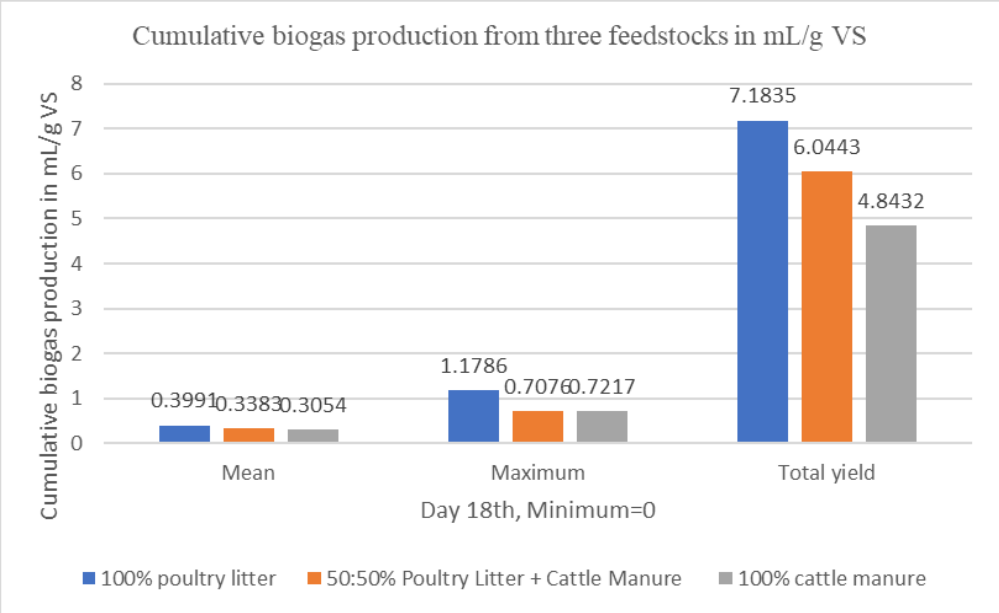

Figure 6: Cumulative biogas production from three feedstocks in mL/g VS

Table 10: Summary of the Result analysis of cumulative biogas production in mL/gVS

Feedstocks	Mean	Minimum	Maximum	Total yield
100% poultry litter	0.3990	0	1.1786	7.1835
50:50% Poultry Litter + Cattle Manure	0.3383	0	0.7076	6.044
100% cattle manure	0.3054	0	0.721.7	4.843

3.7.1. Cumulative Biogas Yield Discussion

According to Figures 3,4,5,6, and Tables 9 and 10, Analysis of cumulative biogas output: Comparing the Production of Biogas from Various Feedstocks. Significant differences in biogas yield were revealed by analyzing the cumulative biogas production (measured in mL/gVS) from three separate feedstocks:

100% poultry litter, a 50:50 blend of poultry litter and cattle manure, and 100% cattle manure.

1. Poultry litter that was 100%. The average yield was 0.3991 mL/gVS. The range is 0 to 1.1786 mL/gVS. Yield Total: 7.1835 mL/g VS

This feedstock has the greatest mean yield, suggesting that it has a high potential for producing biogas. The large range points to performance variability that may be impacted by variables like anaerobic digestion conditions or substrate quality.

2. The mean yield of 50:50% poultry litter and cattle manure was 0. 3383 mL/gVS. The range is 0 to 0.7076 mL/gVS.

Yield Total: 6.0443 mL/gVS

Analysis: Although the combined feedstock has a lower mean yield than 100% poultry litter, it still has a lot of promise for producing biogas. The range suggests that while the combination may improve nutritional balance, it also introduces variability.

3. Cattle manure at 100%: The average yield was 0.3054 mL/gVS. 0 to 0.7217mL/gVS was the range. Yield Total: 4.8432 mL/gVS.

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Out of the three feedstocks, this one has the lowest mean yield. Although it still plays a role in the creation of biogas, it performs worse than poultry litter. The range shows some promise, but it also shows that digestion processes need to be optimized.

Finally, the best feedstock for producing biogas is 100% poultry litter, which is followed by the 50:50 blend and 100% cattle manure. The variation in yields among all feedstocks emphasizes how crucial it is to maximize biogas production by optimizing anaerobic digestion conditions and substrate selection. To increase the overall efficiency of biogas generation, future studies could concentrate on comprehending the mechanisms affecting these yield disparities.

Table 11: Composition of biogas production

Compound	Formula	volume
Methane	CH_4	50-73%
Carbon dioxide	CO_2	25-45%
Hydrogen sulfide	H_2S	0.1%-3%
Nitrogen	N_2	2-8%
Hydrogen	H_2	0-1%

According to [Table 11], the investigation shows that 100% poultry litter is the feedstock that yields the largest amount of biogas (Mozhiarasi and Natarajan, 2025), both in terms of mean and total yield. The 50:50 ratio of cattle manure to poultry litter is the second highest. Of the three feedstocks, the biogas output from 100% animal manure was the lowest. On day 18, the production of all feedstocks peaked. Therefore, of the three feedstocks examined, 100% poultry litter is the greatest option for producing biogas at the highest possible level. The finding showed that poultry litter produced more methane than others did. In addition, cattle manure produces less when compared to other feedstocks. This finding was supported by (Singh et al., 2021) that indicated that the poultry litter was good for biogas production.

3.8. Daily Methane Production from Three Feedstocks in m^3

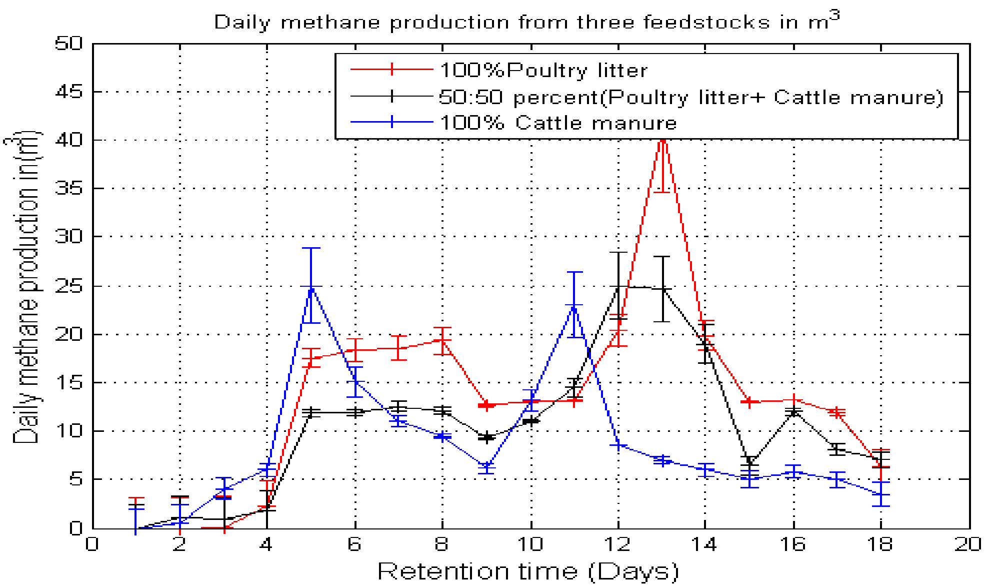

Figure 7: Daily methane production from three feedstocks in m^3

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According to Figure 7, Analysis of Daily Methane Gas Production: We conducted a thorough analysis using descriptive statistics, visualizations, and inferential statistics using the daily methane yield generation data for the three feedstocks (100% poultry litter, 50:50 poultry litter + cattle manure, and 100% cattle manure). An organized method for carrying out this analysis is provided below. 1. Characteristic Data For every feedstock, the following statistics are calculated: Mean Methane yield on average, Minimum, and Maximum: The yield range that was noted. Median: The dataset's middle value.

Table 12: Daily Methane Production in mL/gVS: Summary of Descriptive Statistics

Feedstocks	Mean	Minimum	Maximum
100% poultry litter	0.2964	0	1.1422
50:50% Poultry Litter + Cattle Manure	0.1831	0	0.6947
100% cattle manure	0.1857	0	0.7137

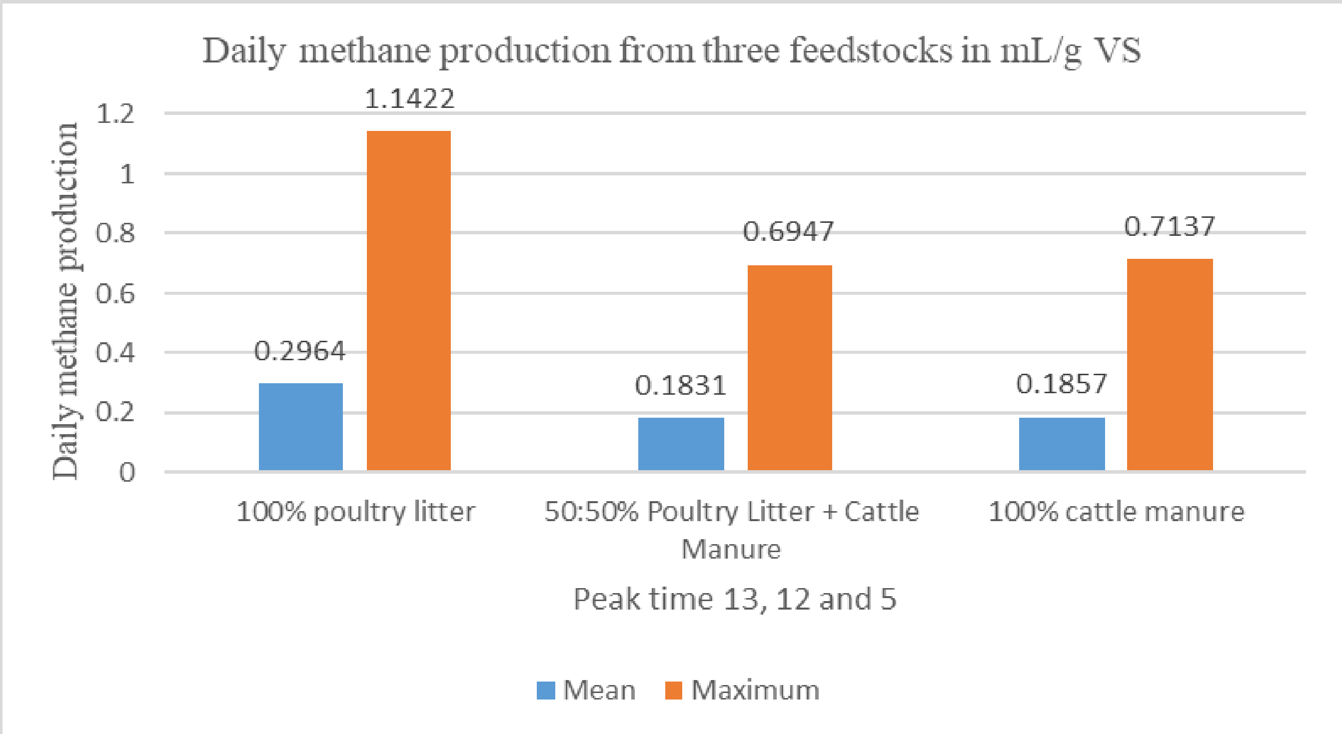

Figure 8 : Summary of Daily Methane Production in mL/gVS

According to [Figure 8 and Table 12], it concluded that the results of the investigation and descriptive statistics shed light on the variability and central tendency of methane yields for every feedstock.

- Visualizations aid in the illustration of distributions and trends.
- ANOVA provides a statistical tool to assess group differences. Combining these evaluations allows us to determine how well each feedstock produces methane, which guided our studies of real-world uses of methane production from organic waste (Akpasi et al., 2024).

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3.9. Daily Carbon Dioxide Emission from Three Feedstocks in ppm

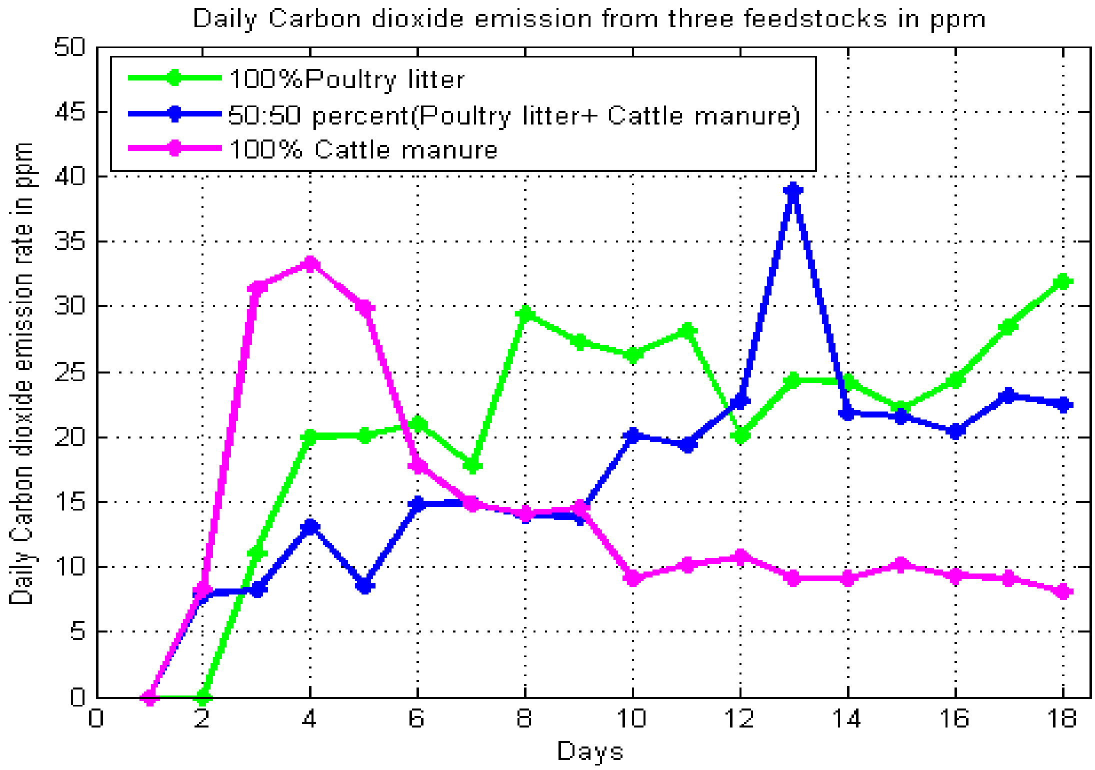

Figure 9: Daily carbon dioxide emission from three feedstocks in ppm

Analysis of Carbon Dioxide Emission Results from Three Feedstocks:

According to [Figure 9], we computed the mean, maximum, and minimum carbon dioxide (CO2) emissions for each of the three feedstocks to compare them. Finally, analysis of carbon dioxide results from three-feedstocks100percentage poultry litter: mean ≈ 19.5, maximum = 31.9, and minimum = zero, 50:50percentage % Cattle Manure + Poultry Litter: Mean ≈ 17.6, maximum = 38.9, minimum = zero.

- 100% Cattle Manure: Average ≈ 15, Maximum = 33.3. Lastly, we concluded that in 18 days, more carbon dioxide emissions were recorded in the 100 %cattle manure, followed by the 50:50%

poultry litter + cattle manure results, and the last emission was recorded in the X sample, as indicated in Figure 26 (Anderson et al., 2021). supported this finding**.**

According to the maximum emissions value, the highest maximum emission rate, 38.9, was found for a 50:50 mixture of cattle manure and poultry litter. With a mean emission rate of almost 19.5, the 100% poultry litter had the highest mean emissions. The low concentrations of CO_2 emissions at the start of the measuring time may be attributed to relatively anaerobic conditions caused by the high moisture content of cattle manure and poultry litter. This finding was reported and supported by Anderson et al. (2021). The carbon dioxide proportion of sample Z fell after the 14th day and, from the 11th to 18th days, was 10.2, 9.3, 9.1, and 8.1(Abid et al., 2021). Who stated that the determining time might be credited to relatively anaerobic conditions caused by the high moisture content of cattle manure?

Therefore, the feedstock with the highest average emission is 100% poultry litter, while the feedstock with the most significant maximum emission value is a 50:50 mixture of poultry litter and cattle manure. The experimental assessment conducted a detailed analysis by generating a biogas production process to determine the maximum methane production at the peak time (Admasu et al., 2022) supported this finding. The carbon dioxide proportion of sample Y fell after the 13th day and the 14th to 16th days, and the carbon dioxide proportion of 100% cattle manure fell after the 14th day and, from the 15^{th} to 18^{th} days, which we 10.2, 9.3, 9.1, and 8.1 (Niraula et al., 2019).

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3.10. Daily Carbon Monoxide Emissions from Three Feedstocks in ppm

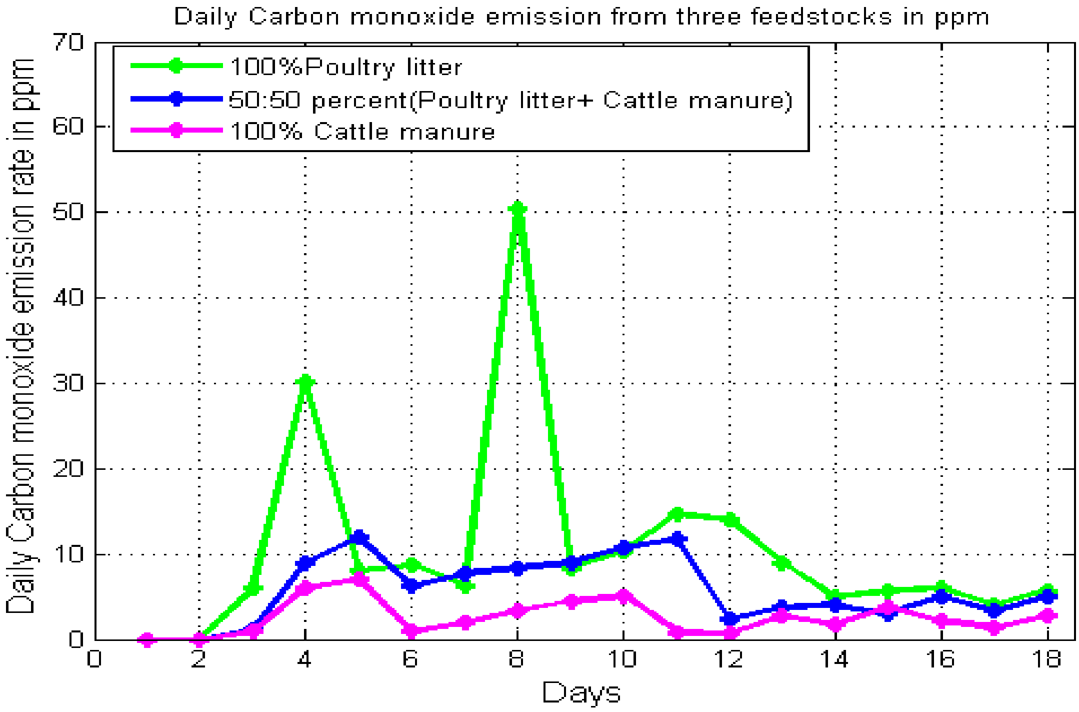

Figure 10: Daily carbon monoxide emission from three feedstocks in ppm

According to [Figure 10], Analysis of carbon monoxide emissions, To analyze the daily carbon monoxide (CO) emissions from the three feedstocks—100% Poultry Litter, 50:50 percentage Poultry Litter + Cattle Manure, and 100% Cattle Manure—we will calculate the following statistics: mean, minimum, maximum, and standard deviation for each feedstock. This helped us determine which feedstock has higher emissions.

Minimum Emissions: 100% Poultry Litter Minimum: 0, 50:50% Poultry Litter + Cattle Manure Minimum: 0, and 100% Cattle Manure Minimum: 0

Maximum Emissions: 100% Poultry Litter Maximum: 50.4, 50:50% Poultry Litter + Cattle Manure Maximum: 11.9, and 100% Cattle Manure Maximum: 7

Summary of Findings of carbon monoxide emissions from three feedstocks

Mean Emissions: 100% Poultry Litter: ~13, 50:50Percentage Poultry Litter + Cattle Manure: ~4.6 and 100% Cattle Manure: ~2.72

Minimum Emissions: All feedstocks have a minimum emission of zero.

Maximum Emissions: 100% Poultry Litter has the highest maximum emission of 50.4. The maximum for 50:50 percentage poultry litter + cattle manure is 11.9, and for 100% cattle manure, it is seven.

Finally, based on the analysis, the feedstock with the highest mean CO emissions is 100% poultry litter, followed by 50:50% poultry litter + cattle manure, and then 100% cattle manure. The maximum emissions observed were also highest for 100% poultry litter. Therefore, in terms of CO emissions, 100% poultry litter has the most emissions compared to the other two feedstocks, while 100% cattle manure has the least emissions overall. We concluded that on the 18th day, more carbon monoxide emissions were recorded in the X sample, which was 5.7 ppm, followed by the Y treatment, which was 5 ppm, and the last emission was recorded in the 100% cattle manure, which was 2.8 ppm, as indicated in Figure 27. (Liu et al., 2017) supported this finding**.** Who indicated that poultry litter and cattle manure have a higher emission rate of carbon monoxide?

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3.11. Daily Hydrogen Sulfide Emission from Three Feedstocks in ppm

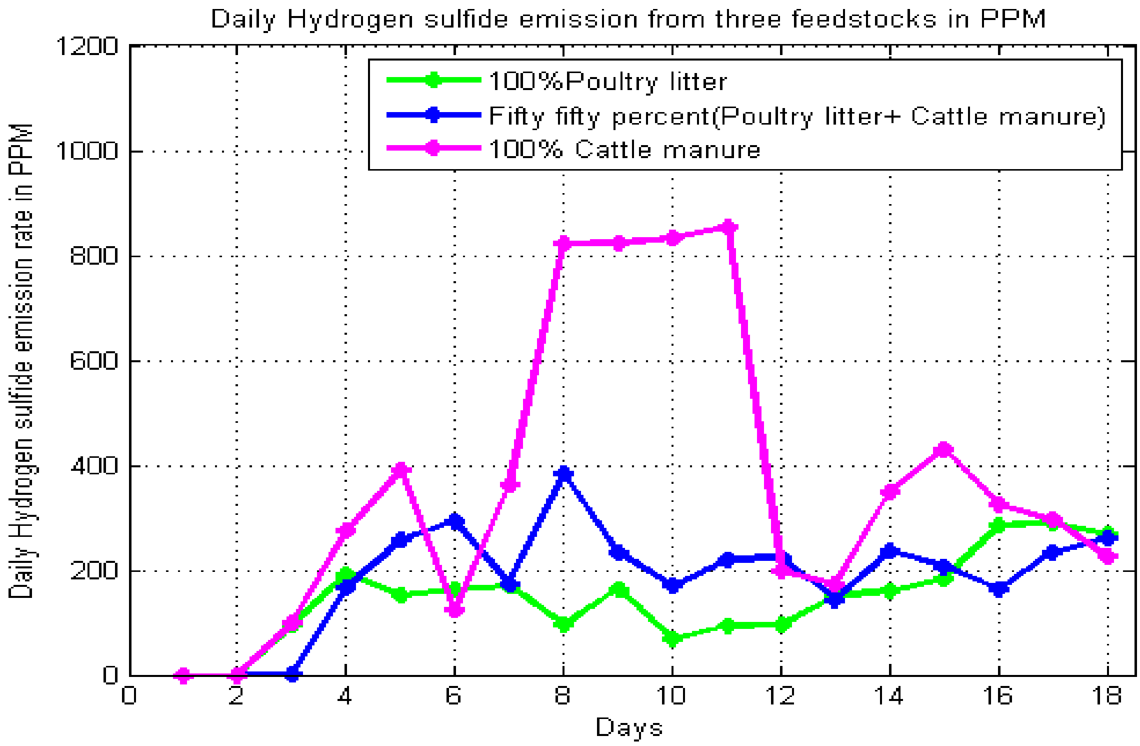

Figure 11 : Daily hydrogen sulfide emission from three feedstocks in m3

According to [Figure 11], Analysis of daily hydrogen sulfide (H_2S) emission: According to Figure 27, to analyze the daily hydrogen sulfide (H_2S) emissions from the three feedstocks—100% Poultry Litter, 50:50% Poultry Litter + Cattle Manure, and 100% Cattle Manure—we will calculate the mean, minimum, maximum, and identify the peak times for both the lowest and highest emission values for each feedstock.

Minimum Emissions: 100% Poultry Litter Minimum: 0, 50:50% Poultry Litter + Cattle Manure Minimum: 0, and 100% Cattle Manure Minimum: 0. We concluded that in 18 days, less hydrogen sulfide emissions were recorded, which was 226 ppm as indicated in Figure 28. (Sadegh et al., 2024) supported this finding.

Maximum Emissions: 100% Poultry Litter Maximum: 290, 50:50% Poultry Litter + Cattle Manure Maximum: 382.7, and 100% Cattle Manure Maximum: 833

Peak Times: The lowest emissions for all feedstocks occurred on Days 1 and 2. The Highest emissions occurred on: Day 17 for 100% Poultry Litter, Day 8 for 50:50 percentage Poultry Litter + Cattle Manure, Day 10 for 100% Cattle Manure

Finally, based on the analysis, the feedstock with the highest mean H_2S emissions is 100% Cattle Manure, followed by 50:50% Poultry Litter + Cattle Manure, and then 100% Poultry Litter. The maximum emissions observed were also highest for 100% Cattle Manure, indicating it has the most emissions compared to the other two feedstocks.

- Thus, in terms of H_2S emissions, 100% cattle manure has the most emissions overall, while 100% poultry litter has the least (Maj, 2022a).

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3.12. Cumulative biogas production in the Modified Gompertz model from three feedstocks in m^3

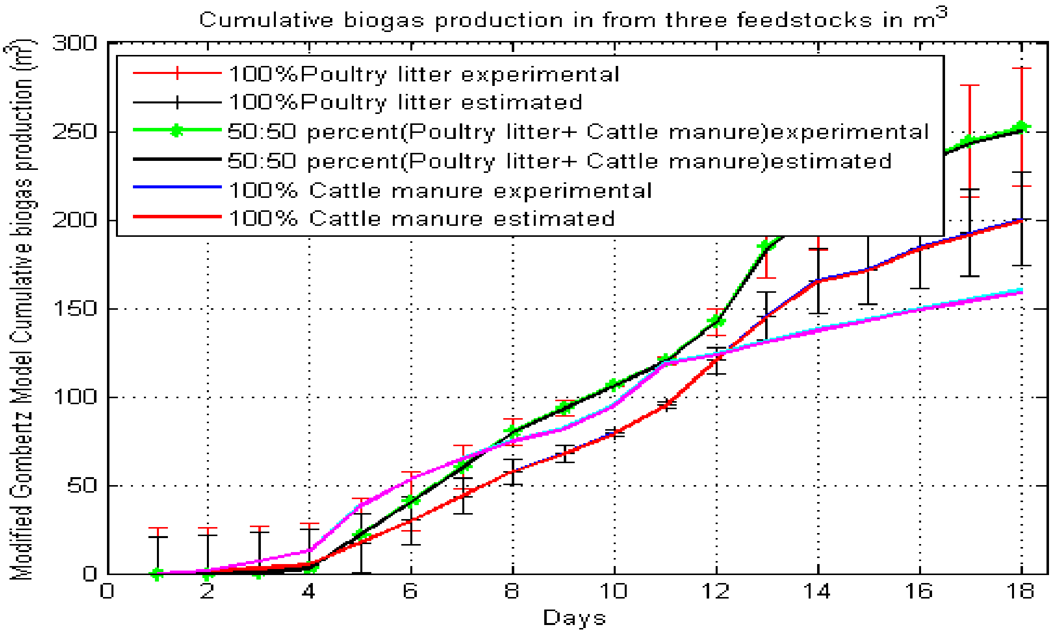

Figure 12 : Cumulative biogas production in the Modified Gompertz model from three feedstocks in m^3

Source: Experiment results from the Ministry of Water & Energy Laboratory Center

Table 13: Bio gas generated by the Modified Gompertz Model

Gas generated		**100% poultry Litter**	**50%Poultry to Litter:50% cattle manure**	**100%cattle manure**
Experimental biogas in Liters		252.018	200.288	159.736
First-order kinetics	Estimated Biogas BFoK(L)	81.46	56.58	61.66
	K per day	1.269	0.847	0.7908
	R^2	0.2414	0.4464	0.4658
	RMSE	82.81	43.64	42.87
Modified Gompertz model	Biogas (B_{MGM})(m^3)	385	296.4	181.5
	U_m(m^3)	24.07	19.3	16.44
	λ in days	4.387	4.706	2.39
	R^2	0.9932	0.9954	0.9934
	RMSE	8.108	5.302	4.936

3.12.1. Overview of Biogas Production:

According to Figure 12 and Table 13, **the** Biogas production experimentally: 100% poultry litter produced the most biogas (252.018 L), followed by 50:50 cattle manure and poultry litter mix (200.288 L), and 100% cattle manure produced the least (159.736 L). This suggests that poultry litter works better than cattle manure when it comes to producing biogas(Shindell et al., 2024).

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e-ISSN: 2468-4376
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3.12.2. Analysis of the First Order Kinetics (BFoK) Model:

Estimated Biogas (BFoK): The first-order kinetics model estimated biogas production was lower than the experimental results, especially for the 100% poultry litter (81.46 L), suggesting that the model may understate the biogas potential. K values: The kinetic rate constants (K) show how quickly biogas was produced; the highest K value was recorded for 100% poultry litter (1.269 per day), indicating a quicker degradation process than the other mixtures (Khadka et al., 2022)

R2 Values: All treatments had comparatively low R2 values (0.2414 to 0.4658), suggesting that the first-order kinetics model does not well describe the experimental data. This implies that the dynamics of biogas production in these substrates might not be well described by first-order kinetics

RMSE: The first-order kinetics model does not fit the experimental data well, as evidenced particularly by 100% poultry litter (82.81) at high Root Mean Square Error (RMSE) values.

3.12.3. Analysis of the Modified Gompertz Model (BMGM):

Estimates of biogas production were higher for the Modified Gompertz model than for the first-order kinetics model; the highest estimate is also for 100% poultry litter (385 m^3). This is more in line with what has been observed in experiments.

- Um Values: The maximum biogas production potential (Um) was also larger across all treatments compared to BFoK, demonstrating that this model was more optimistic about the potential of these substrates for biogas generation(Kelif et al., 2024b).

λ Values: The lag time (λ) is relatively short for all substrates, indicating that biogas production starts rapidly following substrate addition. 100 % cattle manure had the least lag time (2.39 days), indicating a quicker rate of degradation in this mixture(Lee et al., 2019).

R^2 Values: The experimental data were fit quite well was fits by the Modified Gompertz model, as evidenced by the much higher R^2 values (0.9932 to 0.9954). This implies that the Gompertz model outperforms the first-order kinetics model in capturing the dynamics of biogas production.

RMSE: The Modified Gompertz model exhibits superior predictive performance, as seen by much lower RMSE values compared to the first-order kinetics model.

CONCLUSION

100% Poultry Litter (PL): Mean daily generation: 0.3991 mL/g VS, total yield: 7.1835 mL/g VS, and conclusion: higher organic content results in superior biogas generation.

50:50 Cattle Manure + Poultry Litter (CM + PL): Performance is mediocre, and average daily production is 0.338 mL/g VS; however, there are some synergistic effects when compared to cattle manure alone.

Among the feedstocks examined, 100% cattle manure (CM) produced the least amount of biogas, with a total yield of 4.7087 mL/g VS and a mean daily production of 0.2969 mL/g VS.

Important Points to Note: As is common with anaerobic digestion, methane and carbon dioxide make up the majority of the biogas composition. The large range of methane content suggests variability based on feedstock and digestion techniques.

Methane generation requires a pH of about 7.27, which also improves microbial activity and the general quality of biogas. Lastly, because of its higher organic content and ideal pH for anaerobic digestion, poultry litter routinely produces more biogas than bovine manure.

Although not as efficient as 100% poultry litter, the 50:50 blend of bovine manure and poultry litter yields more biogas than pure cattle manure and has better pH stability.

Compared to first-order kinetics, the Modified Gompertz model predicts biogas production from mixed manure types more accurately, indicating the possibility of enhancing biogas output by comprehending feedstock mixing effects.

Acknowledgment:

Superior appreciation goes to Jimma University and the Jimma Institute of Technology Center of Excellence for their partial funding, which is thankfully recognized.

Authors Contributors:

Teka Fida, Venkata Ramayya Ancha, and Abebe Nigussie Nigatu were involved in article writing and participated in analysis and editing. All writers read and approved the final draft of the manuscript. TF will be responsible. Co-writers/authors gave their final approval for the version that would be published, agreed to the journal to which the article would be submitted, approved & responsible for all parts of this work.

Declaration:

Writer role statement. Data accessibility statements: The data has been used confidentially.

Declaration of Interest Statement:

The authors state no conflict of interest.

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