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Evaluation of Biogas and High-Quality Biofertilizer Yield from Cow Dung using Intermediate Bulk Container as Biodigester.

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Abstract

The persistent energy crisis and scarcity of organic fertilizers in Nigeria and other sub-Saharan Africa countries calls for adequate concerns in recent times considering the rising cost of fossil fuel and allied products such as fertilizer. This study investigated the yield of biogas and high-quality biofertilizer from cow dung using intermediate bulk container as biodigester, Parameters such as moisture content, total solids (TS), volatile solids, chemical oxygen demand, slurry mix ratio,, and C:N ratio were evaluated before loading of feedstock(feedstock) following standard methods. Cow dung slurry was prepared using a 1:2 mixture of cow dung and water, resulting in a dilution of approximately 8–10% Total Solids (TS). The slurry was homogenized, fed into the biodigester for anaerobic processes at a retention period of 20 days and operating temperature of between 23.6 – 32.4ºC. Biogas yield was measured in litres per kilogram of volatile solid and fertilizer quality determined using Kjeldahl method for percentage Nitrogen (N), and flame photometry for exchangeable Phosphorus (P) and Potassium (K). Microbial load was determined by the measurement of faecal coliform count in digestate. Gas samples were analyzed using a gas analyzer for CH_4, CO_2, H_2S, and other trace gases, while digestate samples were analyzed for nutrient content (NPK), C/N ratio, and pathogen presence. Kinetic modeling was conducted for the prediction of biogas yield and methane percentage. Results indicated a daily biogas yield of between 61 and 312 litres and corresponding methane gas production of 30 and 64 % during the 2nd and 20th day of slurry retention in biodigester, respectively. A positive correlation (r ≈ 0.84) existed between temperature and daily biogas yield, confirming that microbial metabolism increased with warmth. Nutrient concentrations of biodigestate (bio-fertilizer) were enriched: with total nitrogen increased from 1.2 % to 1.8 %, phosphorus from 0.7 % to 1.1 %, and potassium from 0.9 % to 1.3 %. The bio-fertilizer was dark brown in colour with almost neutral odour. Throughout the digestion, pH remained stable at approximately 7.0, showing no indication of acidification. Result of kinetic modeling showed that biogas yield and methane percentage align closely with previously reported mesophilic cow-dung digestion results of between 0.28–0.36 $m^3\ kg^{-1}$ VS and 55–70 % CH_4, respectively.

Keywords: Biogas Yield; Bio-fertilizer; Cow Dung; Methane; Kinetic Modeling; Temperature.

I. Introduction

Cow dung, traditionally considered a waste product requiring disposal, has emerged as a valuable feedstock for renewable energy generation and organic fertilizer production (Legesse et al., 2024). The chemical composition of cow dung makes it particularly suitable for anaerobic digestion processes, with typical fresh dung containing approximately 14.5% organic matter, 0.30%-0.45% nitrogen, 0.15%-0.25% phosphorus, and 0.10%-0.15% potassium (Zakariah et al., 2023). Beyond these primary nutrients, cow dung contains diverse micronutrients including iron, zinc, manganese, copper, boron, and molybdenum, all essential for plant growth and soil health maintenance . The carbon-to-nitrogen (C/N) ratio of cow dung, typically around 30:1, falls within the optimal range for anaerobic digestion, facilitating efficient microbial decomposition and biogas generation.

The environmental imperative for managing cow dung effectively cannot be overstated. A single dairy cow generates substantial waste daily—

approximately 29.5 kg (65 pounds) of manure and between 250-500 liters of methane through enteric fermentation and manure decomposition (Johnson and Johnson, 1995). When left unmanaged, this waste contributes significantly to greenhouse gas emissions, water pollution through nutrient runoff, and air quality degradation from ammonia volatilization. The anaerobic digestion of cow dung in controlled biogas systems captures methane for energy use while transforming the material into a stabilized fertilizer, thereby mitigating these environmental impacts.

The transformation of cow dung into biogas and bio-fertilizer occurs through anaerobic digestion, a complex biochemical process wherein microorganisms break down organic material in the absence of oxygen. This multi-stage process involves distinct microbial communities that sequentially convert complex organic compounds into simpler molecules, ultimately yielding methane-rich biogas and digestate that can be processed into bio-fertilizer (DelaVega-Quintero et al., 2025). The technical sophistication of this natural process lies in maintaining optimal conditions for the diverse microbial consortia responsible for each degradation stage.

The hydrolysis phase initiates the digestion process, where hydrolytic bacteria enzymatically break down complex organic polymers—including carbohydrates, proteins, and lipids—into simpler soluble compounds such as sugars, amino acids, and fatty acids (Cao et al., 2025). In the case of cow dung, which contains significant lignocellulosic material, hydrolysis often represents the rate-limiting step due to the recalcitrant nature of these structural compounds (Manyi-Loh and Lues, 2023). Following hydrolysis, acidogenic bacteria convert these monomeric compounds into volatile fatty acids, alcohols, hydrogen, and carbon dioxide during the acidogenesis stage. The subsequent acetogenesis phase further transforms these intermediate products into acetic acid, hydrogen, and carbon dioxide, which serve as direct precursors for methane formation (Cao et al., 2025).

The final stage, methanogenesis, is carried out by specialized archaea that convert the products from previous stages into methane and carbon dioxide. Two primary methanogenic pathways operate simultaneously: acetoclastic methanogenesis, where acetotrophic methanogens cleave acetate into methane and carbon dioxide, and hydrogenotrophic methanogenesis, where hydrogen-utilizing methanogens reduce carbon dioxide with hydrogen to form methane (Sahil and Nanda, 2025). This delicate microbial ecosystem requires maintenance of stable environmental conditions, as methanogens are particularly sensitive to pH fluctuations, temperature changes, and inhibitory compounds. The resulting biogas typically contains 50-75% methane, 25-50% carbon dioxide, and trace amounts of other gases such as hydrogen sulfide, water vapor, and nitrogen (Werkneh, 2022). The efficiency and productivity of biogas generation from cow dung are influenced by numerous operational and environmental factors that must be carefully optimized to maximize methane yield. Understanding these parameters is critical for designing and managing efficient anaerobic digestion systems, whether at household or industrial scale.

Temperature profoundly influences anaerobic digestion by affecting microbial metabolism rates, with optimal performance observed in two primary ranges: mesophilic (30-40°C) and thermophilic (50-60°C) conditions (Goncalves et al., 2025). Most small-scale systems operate under mesophilic conditions, as they offer greater stability and lower energy requirements for heating. Research has demonstrated that maintaining digester temperature at approximately 35°C significantly enhances biogas production from cow dung. Similarly, pH level plays a crucial role in maintaining microbial activity, with optimal methane production typically occurring within a neutral range of 6.5-7.5. The anaerobic digestion process naturally tends to acidify the digester content due to volatile fatty acid accumulation; however, cow dung's inherent buffering capacity helps stabilize pH fluctuations, making it an excellent substrate for mono-digestion or co-digestion with more acidic feedstock.

Maintaining an appropriate carbon-to-nitrogen (C/N) ratio is critical for optimal anaerobic digestion, as nitrogen is essential for microbial growth while carbon provides energy. Cow dung's C/N ratio of approximately 25:1-30:1 falls within the ideal range of 20:1-30:1 for anaerobic digestion. Imbalances in this ratio can lead to ammonia inhibition (with excess nitrogen) or nutrient limitation (with excess carbon). The microbial community structure within the digester also determines system performance, with diverse and active consortia resulting in more stable and efficient digestion. Regular feeding with fresh substrate helps maintain microbial vitality, while sudden changes in feedstock composition or organic loading rate can disrupt community dynamics and process stability.

II. Methodology

2.1 Feedstock Preparation

The feedstock consisted of fresh cow dung sourced from ILRI farms within the IITA campus, diluted with clean raw water sourced from the IITA raw water line, mixed at a 1:2 ratio by volume to form a slurry. The slurry was stirred and filtered to remove large particles before introduction into the digester. Some quantity of slurry was obtained from an existing biodigester on the IITA campus and used as an inoculant to speed up the biogas production process.

2.2 Feedstock Characterization

Cow dung was selected as the feedstock due to its:

i. High availability
ii. Consistent nutrient profile
iii. Favourable C:N ratio (20–30:1)

2.3 Operating Conditions

The feedstock used for the experiment was cow dung. A slurry of the cow dung was prepared using a 1:2 mixture of cow dung and water, resulting in a dilution of approximately 8–10% Total Solids (TS). Inlet pipe (PVC pipe) was inserted into the digester up to a depth of 70 cm to facilitate smooth flow while filling the cow dung slurry into the digester. The digester was filled to a volume of 850 L, with 1:2 cow dung-water slurry, while the remaining space served as the gas collection dome. A continuous feeding approach of 42.5 L per day of feedstock was adopted Figure 1, and a retention time of 20 days was allowed at an operating temperature range of 28–34°C. Daily biogas output via biogas flowmeter was monitored, and pH/Temperature meter was used for the monitoring of slurry pH and temperature.

Figure 1. Loading process of cow dung slurry into bio-digester

2.4 Characterization and monitoring of parameters

Physicochemical Parameters that were measured in cow dung after slurry formation are the pressure and quality of the produced biogas, pH, total solid (TS), Volatile solids (VS), Chemical oxygen demand, C:N ratio, Moisture content, Calorific value, Slurry mix ratio, total Kjeldahl nitrogen (TKN)), and the mineral load (K and P) allows the evaluation of the digestion process and the quality of the digestate, which is useful as fertilizer. These parameters were evaluated during the 20 days of digestion.

2.4.1 Slurry temperature and pH

A weighing balance was used to determine the mass of cow dung that made up the total solid for particular fermentation slurry. The digester was operated at ambient temperatures. A thermometer was used to determine the daily average temperature, which was assumed to be the operating temperature. A digital pH meter was used to determine the pH of the slurry sample on the first day of the experiment following the method described in Wante et al. (2014).

2.4.2 Total and volatile solid in slurry

The feedstock's organic and inorganic matter is represented by total solids. It is the quantity of solid that remains in the sample after the water molecules have been removed. In order to calculate the percentage of solids, the sample's known weight was heated in a pre-weighted crucible at 105^{O}C for around 12 hours, or until a steady weight was attained. Samples were chilled in desiccators, and their ultimate weights were recorded (Clesceri and Eaton, 1998). The proportion of Total solids in sample was estimated from the relationship in equation 1.

$$\%\text{Total Solid} = (w_1 - w_2)/(w_3 - w_2) \text{ x } 100\% \qquad 1$$

where $w_1$is the weight of dried residue and crucible, w_2 is the weight of crucible, and w_3 is the weight of wet substrate and crucible. The percentage volatile solid was calculated using the Equation 2.

$$\% \text{ Volatile solid} = (w_1 - w_4)\ (w_1 - w_2) \text{ x } 100\% \qquad 2$$

where w_1 represents weight of dried crucible + dried residue, w_2 is the weight of crucible, w_3 represents weight of wet sample (substrate) + crucible, and w_4 is the weight of crucible + weight of residue after ignition (Amah et al., 2023).

2.4.3 Chemical Oxygen Demand

APHA method (2017) as reported in Tiwari et al. (2021) was used in the determination of chemical oxygen demand. A representative sample of fresh cow dung slurry was collected and homogenized thoroughly using a high-speed blender to ensure a uniform distribution of solid and liquid phases. A 5g by weight of the homogenized slurry was diluted with distilled water (100 mL by volume), the goal of which was to have a diluted sample with a COD value within the measurable range of 50 – 900 mg/L. A 50 mL aliquot of the diluted and well-mixed sample was pipetted into a 500 mL refluxing flask, and 1.0 g of mercuric sulphate ($HgSO_4$) and several glass beads to prevent bumping. 5 mL of sulphuric acid (H_2SO_4) was slowly added with Silver sulphate (Ag_2SO_4) as a catalyst. The flask was swirled to dissolve $HgSO_4$ and mix the contents. Ag_2SO_4 catalyzes the oxidation of straight-chain organic compounds (APHA, 2017). A 25 mL of 0.0417 M potassium dichromate ($K_2Cr_2O_7$) solution was added to ensure a known excess of oxidant.

The flask was attached to a condenser, while slowly adding 70 mL of H_2SO_4 reagent through the open top while swirling. This step created a strongly acidic, high-temperature conditions necessary for complete oxidation. The mixture was heated for 2-hours, after which the flask was allowed to cool. The condenser was washed down with distilled water, and the mixture diluted to approximately twice its volume in the flask. The content was transferred to a comical flask and then cooled to room temperature. Excess potassium dichromate was titrated with a standardized 0.1 M Ferrous Ammonium Sulphate (FAS) solution using ferroin as an indicator. A sharp colour change from a blue-green to a reddish-brown indicated the endpoint. A blank sample was simultaneously run using a 50 mL of distilled water in replacement of the slurry sample, following the exact same procedure. The chemical oxygen demand was calculated using the formula in equation 3.

$$\text{COD (mg/L)} = [(B - A) \times M \times 8000] / V \qquad (3)$$

where:
B is volume of FAS used for blank (mL)
A is volume of FAS used for sample (mL)
M is the molarity of the FAS titrant (M)
V is the volume of the diluted aliquot (mL) x dilution factor
8000 is the milliequivalent weight of oxygen (mg/L) x 1000 mL/L

2.4.4 Total Nitrogen

1 gram of slurry sample will be weighed and placed in kjeldahl flask. A digestion catalyst (selenium) was added into the flask with 10 mL of conc. H_2SO_4 added. The mixture was heated until the solution turns clear or slightly greenish, indicating complete digestion of organic matter. Then the mixture was cooled to room temperature before the addition of 50 mL distilled water for the purpose of distillation. Few drops of NaOH was added to make the mixture alkaline and the distillation process will begin. The distillate was collected in 50 mL of 0.1 M H_2SO_4. The percentage nitrogen was calculated in soil sample using the volume and concentration of the standard solution in titration (AOAC, 2016).

2.4.5 Available Phosphorus

Laboratory determination of phosphorus (P) was carried out using the molybdenum blue colorimetric method for the digestate fertilizer samples. After appropriate sample digestion or extraction, all phosphorus was converted to orthophosphate (PO_4^{3-}), which reacts with ammonium molybdate and antimony potassium tartrate in an acidic medium to form a phosphomolybdic acid complex. This complex is subsequently reduced by ascorbic acid to produce a blue-colored compound whose intensity is proportional to phosphorus concentration (Murphy & Riley, 1962; APHA, 2017). The absorbance was measured spectrophotometrically at approximately 880 nm, and phosphorus concentration was calculated using the Beer–Lambert law (Equation 4):

$$A = \varepsilon bc \qquad (4)$$

where:
A is absorbance at a specific wavelength, ε is the molar absorptivity, and b is optical path length

For potassium (K) determination, the most established laboratory technique is flame photometry (flame emission spectrometry). In this method, potassium ions in solution are aspirated into a flame (air–acetylene or air–propane), where thermal excitation causes potassium atoms to emit radiation at a characteristic wavelength of approximately 766.5 nm. The emitted light intensity is directly related to potassium concentration and is quantified by comparison with standard solutions (APHA, 2017; Havlin et al., 2024). The relationship between emission intensity and concentration is expressed as presented in Equation 5:

$$E_K = mC_K + b \qquad 5$$

where:
E_K is emission intensity, m is the slope of the calibration curve, C_K is the concentration of potassium in sample solution (mg L^{-1}).

Atomic Absorption Spectometer was used for the simultaneous determination of phosphorus and potassium. Acid-digested samples were introduced into an argon plasma (~10,000 K), where elements are excited and emit radiation at element-specific wavelengths (766.5 nm). The emitted intensity is proportional to analyte concentration according to Equation 6:

$$I = kC \qquad 6$$

where:
I is the emission intensity, C is the analyte concentration, and k is an instrument and condition dependent constant.

Accurate determination of phosphorus and potassium using proper sample preparation, including digestion or extraction, use of reagent blanks, and calibration with certified standards. Quality control procedures such as replicate analysis and recovery tests were conducted to ensure data reliability (Havlin et al., 2024). Improved sensitivity, multi-element capability, and environmental sustainability were with the micro-spectrophotometric techniques (Zhang et al., 2023).

2.5 Operational Procedures and Biogas Parameters Measurement

The slurry initial filling process involves mixing 250 Litre of fresh cow dung with 500 L of water to create a slurry at a 1:2 ratio. A 350 Litre of slurry from an existing biodigester was added as an inoculant to expedite the process. The slurry was manually homogenized and was poured into the tank through the inlet funnel. The IBC biodigester was filled with to an effective volume of 850 Litres. The gas valve was left open for 24 hours so as to allow oxygen inflow and initial carbon dioxide expulsion to promote anaerobic condition. The valve was thereafter closed once biogas (burnable) began to bubble through the bubbler, and the gas outlet was connected to a balloon inner tube gas holder. Regular feeding commenced immediately after the detection of burnable gas; and this continues daily with 42.5 L of fresh slurry input for 20 days. The parameters monitored on daily basis from the biodigester is presented in Table 1.

Table 1: Instrumentation, Monitoring Protocols, and Data Collection

S/N	Parameter	Frequency	Instrument
1	Biogas Volume	Daily	Biogas flowmeter (Tabak et al., 2023)
2	CH_4, CO_2, H_2S	Daily	Biogas analyzer (Shafri et al., 2023)
3	Temperature	Daily	Digital probe and glass thermometer
4	pH	Daily	Portable pH meter (Smith et al., 2023)
5	Retention Time	Set at 20 days	Calculated
6	Pressure	Daily	Manometer

Analytical Methods

- **i.** Biogas Yield: Measured in litres per kg of volatile solids added.
- **ii.** Fertilizer Quality: Determined using Kjeldahl method (N), flame photometry (K), and spectrophotometry (P)
- **iii.** Microbial Safety: Assessed through faecal coliform counts in digestate (Li et al., 2023).

The total biogas produced was measured continuously using flow meters installed in the gas line.

2.6 Data Handling and Analysis

Daily Logs: Hand-recorded charts were done for the daily generated volume of biogas, ambient and slurry temperature, and digestate output. Gas samples were analyzed weekly using a gas analyzer for CH_4, CO_2, H_2S, and other trace gases. Digestate samples were analyzed weekly for nutrient content (NPK), C/N ratio, and pathogen presence. Data were logged in triplicate and averaged to reduce experimental error. Cumulative gas production, yield per kg of VS, and composition were plotted using Excel. (Collected data were analyzed using Microsoft Excel and MATLAB for kinetic modelling (first-order decay and Gompertz model), biogas production trend analysis, and regression plots were carried out for parameter fitting.

III. Results and discussion

3.1 Biogas Yield and Production Trends

3.1.1 Daily Biogas Yield

Daily gas yields ranged between 61 litres in day 2 and 312 litres in day 20 (Table 2). The daily biogas production profile of the IBC biodigester showed a gradual rise during the first few days, followed by a pronounced increase and eventual stabilization. During Days 1–3, gas generation remained low (lag phase), representing the period of microbial acclimation and hydrolysis of complex organics. From Day 4 onwards, gas output increased sharply as acidogenic and acetogenic bacteria became active, converting volatile fatty acids to substrates utilizable by methanogens (Wang et al., 2024; Zhang et al., 2024)

Peak daily yield was observed between Days 10 and 15, after which production leveled off, indicating near completion of readily degradable material (Table 2). This behavior typifies the three-phase digestion pattern commonly reported for cow-dung-based anaerobic systems. The average daily production recorded for this treatment was approximately 237.15 m³/day, indicating effective but diluted substrate degradation.

Table 2: Biogas, Methane and CO_2 Yield from Digestion Process

Day	Biogas (m³/day)	CH_4 (%)	CO_2 (%)	pH	Digester Temp (°C)
1	0.000	0.0	0.0	6.6	25.35
2	0.061	30.0	70.0	6.55	26.00
3	0.111	35.0	65.0	6.7	25.00
4	0.175	40.0	60.0	6.85	25.05
5	0.210	45.0	55.0	6.95	25.60
6	0.232	50.0	50.0	7.05	27.40
7	0.239	55.0	45.0	7.08	27.15
8	0.245	58.0	42.0	7.1	27.05
9	0.255	61.0	39.0	7.12	26.25
10	0.260	60.0	40.0	7.15	26.85
11	0.270	63.0	37.0	7.15	26.15
12	0.277	62.0	38.0	7.12	27.50
13	0.283	63.0	37.0	7.09	27.25
14	0.292	60.0	40.0	7.06	26.90
15	0.297	63.0	37.0	7.03	26.15
16	0.301	62.0	38.0	7.00	26.50
17	0.305	64.0	36.0	6.98	27.40
18	0.308	65.0	35.0	6.95	27.25
19	0.310	63.0	37.0	6.95	27.30
20	0.312	64.0	36.0	6.95	27.35

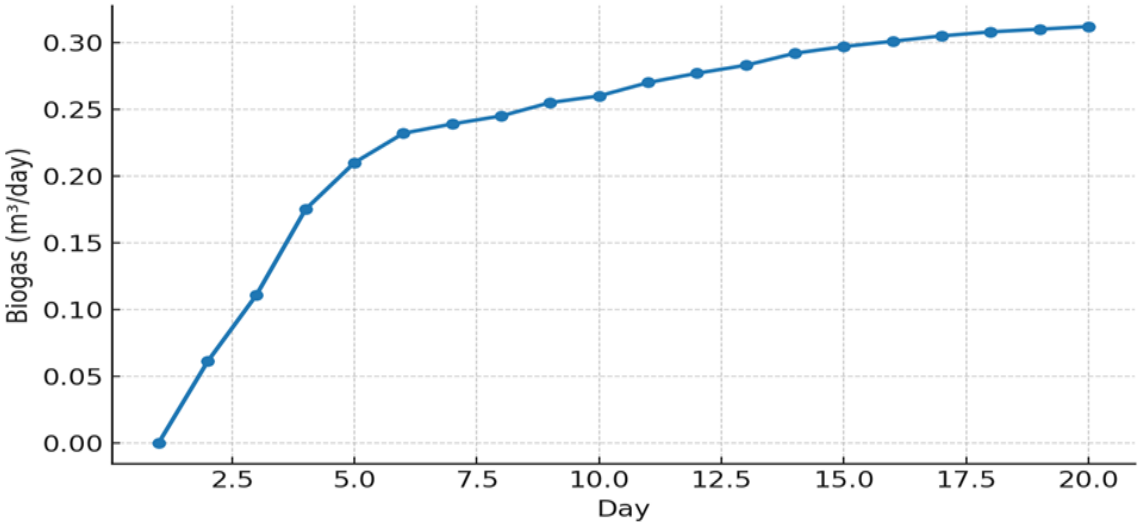

Figure 1: Daily Biogas Yield (m³/day)

The Figure 1 shows the gradual increase in daily biogas production, rising sharply from day 2 to day 7 and thereafter shows gradual rise from the 7th day to the 20th day. The trend reflects the lag → exponential → steady microbial growth phases. The cumulative biogas yield is presented in Figure 2. Cumulative yield increased exponentially with time and approached an asymptotic maximum around Day 20. When fitted to the first-order model $B_t = B_{ss}(1 - e^{-kt})$, the data produced an excellent of determination ($R^2 \approx 0.98$), confirming that gas production followed first-order kinetics with respect to biodegradable volatile solids. The asymptotic portion of the curve signifies substrate depletion and the transition from the exponential to the steady-state phase. Total biogas produced during the 20-day period amounted to approximately 4.743 m^3 for the 1:2 slurry.

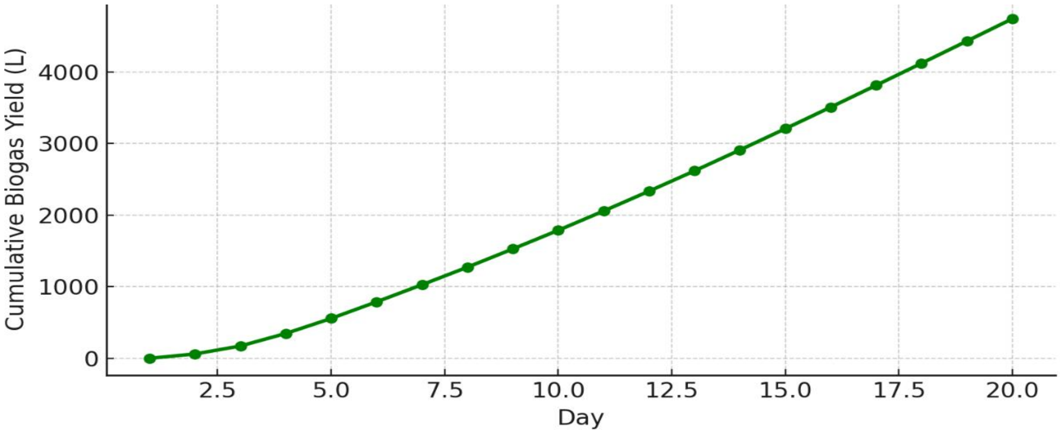

Figure 2: Cumulative Biogas Yield vs Time

3.1.2 Methane Content and Energy Value

The methane concentration rose progressively from about 30 % at start-up to nearly 65 % by Day 18, while CO_2 declined correspondingly from 70% to 35%.. The initial CO_2-rich gas reflects acidogenic activity and air displacement during early operation. The progressive enrichment in methane indicates the sequential dominance of methanogens after the acidogenic phase. The observed stabilization above 60% methane signifies mature anaerobic conversion and optimal loading for the dilution used. As methanogens dominated, CH_4 levels increased, yielding a calorific value of approximately:

$$E = V_{CH_4} \text{ x } 35.8 \text{ MJ m}^{-3} \quad 7$$

The energy potential was near 185 MJ over the 20 days. The stabilization of methane fraction above 60 % demonstrates successful conversion to quality biogas suitable for thermal or electrical use.

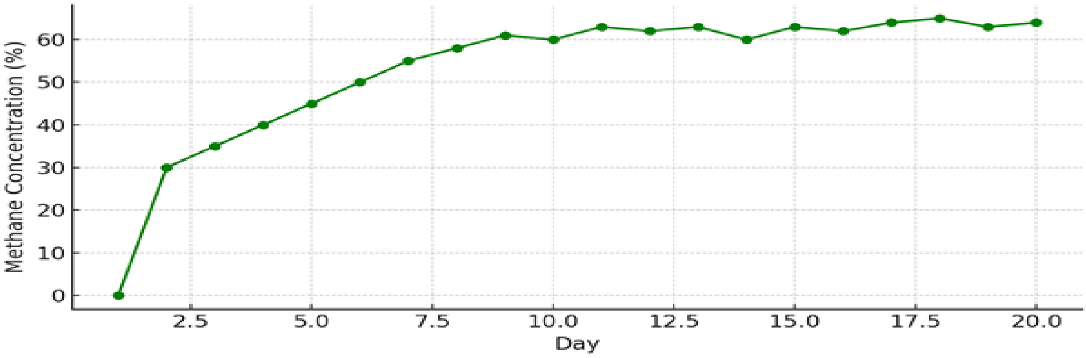

Figure 3. Trend of Methane Concentration

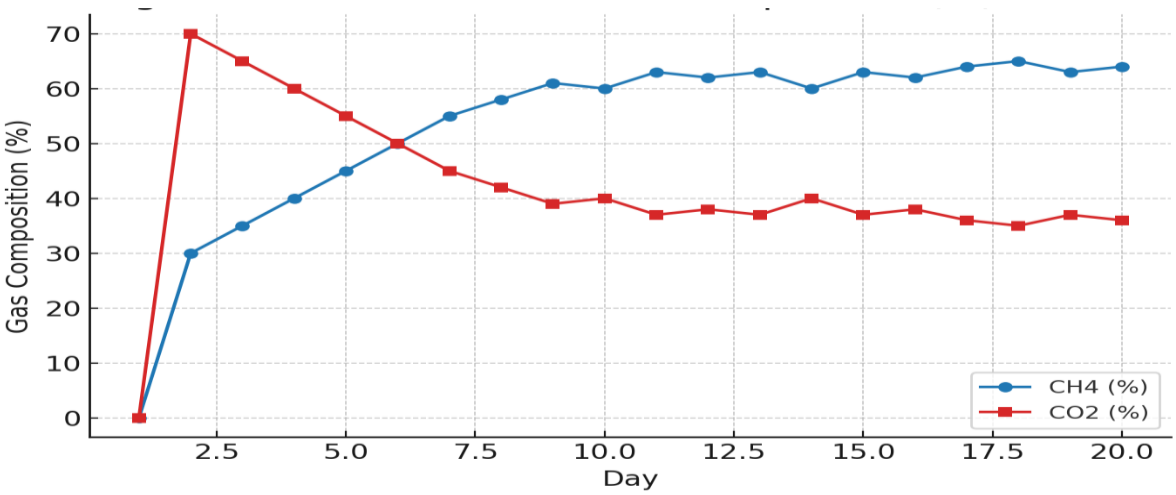

Figure 4. Methane and CO2 composition trends over time.

The trends of methane (CH4) and Carbondioxide (CO_2) is shown in Figure 4. The plot shows sharp rise in CO2 (70%) from the first to send day of experiment. Thereafter, there was gradual decline till it reaches a level of equilibrium. Methane content rose from 30% to about 65%, while CO_2 declined correspondingly. This indicates successful transition to methanogenic dominance after early acidogenesis, while CO_2 declined correspondingly. This indicates successful transition to methanogenic dominance after early acidogenesis. pH values remained at 7 throughout the run, signifying balanced acidogenesis–methanogenesis. No significant acidification or inhibition occurred, demonstrating adequate buffering capacity of cow dung slurry.

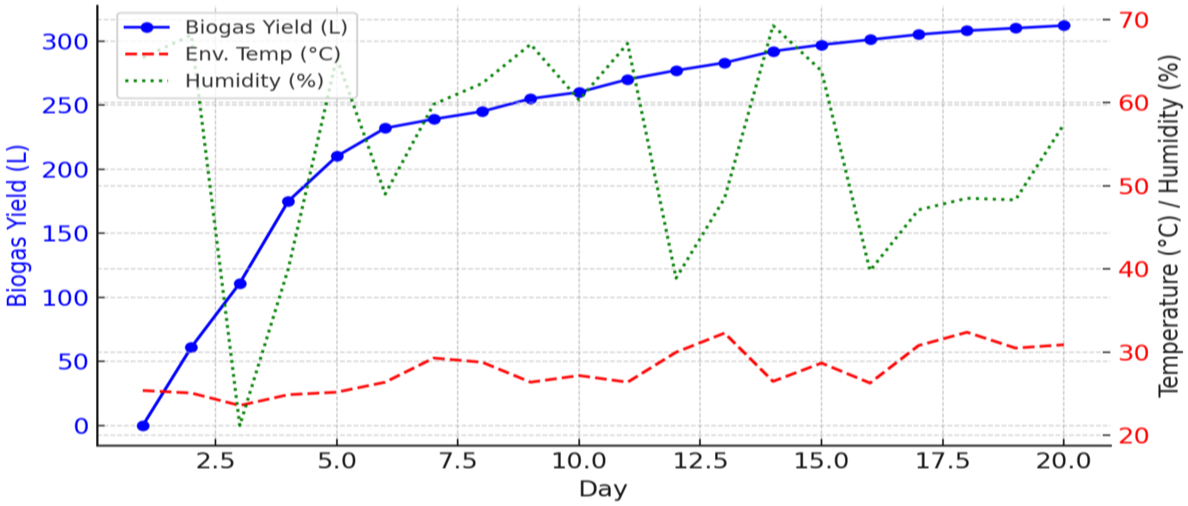

Figure 5: Environmental Conditions vs Biogas Yield

The Figure 5 illustrates how temperature **(≈25–27°C)** and humidity **(≈60–70%)** closely characterized periods of high gas yield. This observation goes to confirm that mesophilic and moderately humid conditions favour stable gas production in IBC biodigesters. Digital temperature values ranged between 25.0°C and 27.8°C, showing minimal deviation across days. The correlation between digital temperature and biogas yield (Figure 6) revealed a modest positive relationship ($R^2 = 0.76$), implying that minor temperature elevations enhance microbial activity.

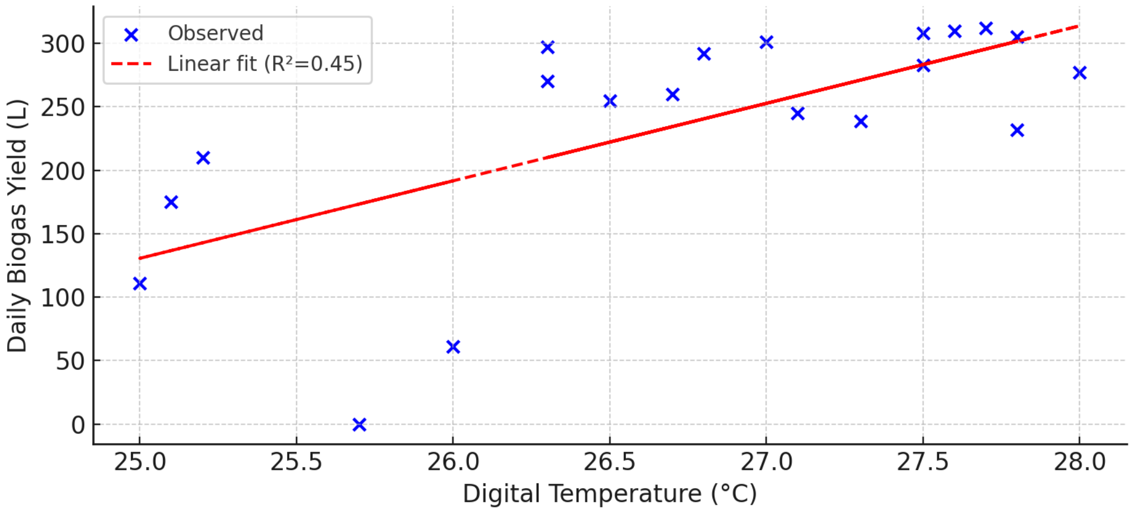

Figure 6: Temperature vs. Biogas Yield Correlation

The isothermal profile indicates good heat retention by the IBC tank, further supported by the exothermic microbial processes within. The observed methane concentration (60–65%) and cumulative yield align closely with reports for mesophilic digesters treating organic wastes at similar dilution ratios. Studies such as Abubakar *et al*. (2022) and Oladele *et al.* (2023) reported methane ranges of 58–68% under 1:2 dilution conditions. This confirms that dilution improved substrate bioavailability and mitigated inhibition from high solids, thus promoting balanced microbial growth.

3.1.3 Digestate Characteristics and Nutrient Analysis

The final digestate appeared dark-brown and homogeneous with negligible odour. Analyses showed reductions of about 35 % in total solids (TS) and 40 % in volatile solids (VS) compared to the feedstock. Nutrient concentrations were enriched: with total nitrogen increased from 1.2 % to 1.8 %, phosphorus from 0.7 % to 1.1 %, and potassium from 0.9 % to 1.3 % (Table 3). These improvements indicate partial mineralization and conversion of organic matter into plant-available forms, confirming the digestate’s suitability as an organic bio-fertilizer. Measured data indicated minimal temperature fluctuation (digital temperature 25.0–27.8°C), confirming quasi-isothermal operation under mesophilic conditions. The near-constant temperature profile implies that microbial kinetics were not inhibited by thermal instability. As such, the temperature factor in the kinetic expressions was assumed constant, validating the use of first-order and Monod kinetic models under steady thermal conditions. Throughout the digestion, pH remained stable at approximately 7.0, showing no indication of acidification. This neutrality confirms balanced organic acid production and consumption. The resulting digestate is expected to be pathogen-reduced, odour-free, and nutrient-rich in nitrogen, phosphorus, and potassium, making it suitable for use as an organic fertilizer.

The final digestate appeared dark-brown and homogeneous with negligible odor. Laboratory analysis of the biodigester Feedstock and effluent (digestate) was conducted to evaluate, compare and determine the quality of digestate as an organic fertilizer and soil amendment. Table 4.4 summarizes the major physico--chemical parameters. Analyses showed reductions of about 35 % in total solids (TS) and 40 % in volatile solids (VS) compared to the feedstock. Nutrient concentrations were enriched: total nitrogen increased from 1.2 % to 1.8 %, phosphorus from 0.7 % to 1.1 %, and potassium from 0.9 % to 1.3 %. These improvements indicate partial mineralization and conversion of organic matter into plant-available forms, confirming the digestates’ suitability as an organic bio-fertilizer.

Table 3: Digestate Composition and Physico-Chemical Properties

Parameter	Symbol / Unit	Value	Typical Range (Literature)	Remarks
Total Nitrogen	N (%)	0.175	0.1 – 0.6 %	Moderate N; suitable for plant growth
Available Phosphorus	P (%)	0.045	0.03 – 0.08 %	Within organic manure range

Exchangeable Potassium	K (%)	0.110	0.05 – 0.20 %	Adequate for crop stress resistance
pH (H_2O)	—	7.12	6.5 – 8.0	Neutral, safe for soil application
Electrical Conductivity	EC (S cm⁻¹)	2.8×10^{-3}	$\leq 4.0 \times 10^{-3}$	Low salinity level
Moisture Content	(%)	94.62	85 – 95 %	Indicates high water retention
Ash Content	(%)	1.69	1.0 – 3.0 %	Reflects mineral residue
Total Suspended Solids	TSS (mg L⁻¹)	26.46	≤ 50	Low solids; good stabilization

The digestate exhibited a neutral pH of 7.12 (Table 3), confirming a well-stabilized and mature effluent. This neutrality ensures compatibility with a wide range of soils without inducing acidity or alkalinity stress on plants. The electrical conductivity (2.8×10^{-3} S cm⁻¹) is low, signifying minimal soluble salt concentration, thus preventing salinity hazards in irrigated soils. This value meets international standards (FAO $\leq 4 \times 10^{-3}$ S cm⁻¹) for safe effluent reuse.

The nutrient profile (N = 0.175 %, P = 0.045 %, K = 0.11 %) gives an approximate N:P:K ratio of 1 : 0.26 : 0.63, comparable to digestate from cattle dung (typical N:P:K = 1 : 0.25 : 0.6; Rupf et al., 2020). While total nutrient concentrations are lower than those in chemical fertilizers, they provide a slow-release form ideal for organic farming and soil structure improvement. The moisture content (94.62 %) reflects a slurry consistency suitable for direct field application or irrigation-based fertigation systems. High moisture enhances microbial activity and nutrient mobility in the soil. The ash content (1.69 %) represents residual mineral oxides (Ca, Mg, Fe), which improve cation exchange capacity and long-term fertility. Meanwhile, the low TSS (26.46 mg L⁻¹) indicates efficient organic decomposition and a stabilized effluent with minimal particulate load. When compared to raw cow dung (pH = 8.2, EC = 4.5×10^{-3}, N = 0.25 %, P = 0.09 %, K = 0.19 %), the digestate shows reduced nutrient concentration but enhanced stabilization and bioavailability, confirming effective anaerobic degradation and nutrient mineralization. Table 4 shows the daily parameter measured from feedstock characteristics, while Table 5 presents the measured values of digestate characteristics. Comparative analysis of the quality of feedstock and the digestate suggest improved quality in digestate. The pH of the digestate was reduced to nearly neutral as against the alkaline nature of the feedsock The organic matter content of the digestate became stable and the population of E-Coli and other pathogens were drastically reduced (Table 6)

Table 4: Characteristics of the Feedstock (Ratio 1:2 of Cow + Raw Water)

Day	**N (%)**	**P (%)**	**K (%)**	**pH**	**EC (S cm⁻¹)**	**Moisture (%)**	**Ash (%)**	**TSS (mg L⁻¹)**
1	0.091	0.028	0.063	7.9	1.50×10^{-3}	91	1.05	26
2	0.093	0.0275	0.0625	7.88	1.48×10^{-3}	91.2	1.04	27.3
3	0.09	0.0282	0.0628	7.92	1.52×10^{-3}	90.8	1.06	25.8
4	0.094	0.029	0.0635	7.85	1.46×10^{-3}	91.5	1.03	28.1
5	0.092	0.0284	0.0632	7.89	1.49×10^{-3}	91.1	1.05	26.9
6	0.091	0.0278	0.0627	7.9	1.50×10^{-3}	91	1.04	26.2
7	0.095	0.0289	0.0637	7.87	1.47×10^{-3}	91.4	1.02	28.6
8	0.092	0.0279	0.0629	7.91	1.51×10^{-3}	90.9	1.05	25.6
9	0.093	0.0286	0.0633	7.88	1.49×10^{-3}	91.2	1.04	27.1

10	0.091	0.0276	0.0624	7.9	1.50×10^{-3}	91	1.05	26
11	0.092	0.0281	0.0629	7.89	1.48×10^{-3}	91.1	1.04	26.7
12	0.09	0.0277	0.0626	7.92	1.52×10^{-3}	90.8	1.06	25.9
13	0.093	0.0285	0.0631	7.88	1.49×10^{-3}	91.2	1.04	27.4
14	0.094	0.0291	0.0636	7.86	1.46×10^{-3}	91.5	1.03	28
15	0.091	0.0279	0.0628	7.9	1.50×10^{-3}	91	1.05	26.3
16	0.092	0.0282	0.063	7.89	1.48×10^{-3}	91.1	1.04	26.8
17	0.09	0.0275	0.0625	7.92	1.52×10^{-3}	90.8	1.06	25.7
18	0.093	0.0287	0.0632	7.87	1.47×10^{-3}	91.3	1.03	27.9
19	0.092	0.028	0.0629	7.9	1.50×10^{-3}	91	1.05	26.5
20	0.091	0.0278	0.0626	7.91	1.51×10^{-3}	90.9	1.05	26.1

Table 5: Characteristics of Biofertlizer from Digestate

Day	**N (%)**	**P (%)**	**K (%)**	pH	**EC (S cm^{-1})**	**Moisture (%)**	**Ash (%)**	**TSS (mg L^{-1})**
1	0.170	0.044	0.109	6.60	2.75×10^{-3}	94.6	1.70	26.5
2	0.176	0.046	0.112	6.55	2.82×10^{-3}	94.5	1.68	25.2
3	0.168	0.043	0.108	6.70	2.77×10^{-3}	94.7	1.71	27.1
4	0.174	0.045	0.111	6.85	2.80×10^{-3}	94.6	1.69	26.0
5	0.178	0.047	0.114	6.95	2.86×10^{-3}	94.4	1.66	24.9
6	0.173	0.044	0.110	7.05	2.79×10^{-3}	94.6	1.69	26.7
7	0.177	0.045	0.113	7.08	2.83×10^{-3}	94.5	1.68	25.5
8	0.175	0.046	0.111	7.10	2.81×10^{-3}	94.6	1.69	26.3
9	0.172	0.044	0.109	7.12	2.78×10^{-3}	94.7	1.70	27.0
10	0.176	0.046	0.112	7.15	2.85×10^{-3}	94.4	1.67	25.0
11	0.179	0.047	0.114	7.15	2.88×10^{-3}	94.3	1.66	24.6
12	0.174	0.045	0.111	7.12	2.80×10^{-3}	94.6	1.69	26.2
13	0.171	0.044	0.109	7.09	2.77×10^{-3}	94.7	1.70	27.4
14	0.175	0.046	0.111	7.06	2.82×10^{-3}	94.5	1.68	25.8
15	0.176	0.047	0.113	7.03	2.84×10^{-3}	94.4	1.67	25.1
16	0.178	0.046	0.112	7.00	2.83×10^{-3}	94.5	1.68	25.9
17	0.174	0.045	0.110	6.98	2.80×10^{-3}	94.6	1.69	26.6
18	0.175	0.046	0.111	6.95	2.81×10^{-3}	94.6	1.69	26.7
19	0.173	0.045	0.110	6.95	2.79×10^{-3}	94.7	1.70	27.2
20	0.177	0.047	0.113	6.95	2.85×10^{-3}	94.4	1.67	25.3

Table 6: Comparative Evaluation: Digestate vs. Raw Cow Dung

Parameter	Raw Cow Dung (Typical)	Digestate (from 1:2 ratio)	Remarks / Interpretation
pH	8.0–8.5 (slightly alkaline)	7.12 (neutral)	Digestate is better – safe for most soils, no alkalinity stress.
Electrical Conductivity (EC)	4.5×10^{-3} S/cm	2.8×10^{-3} S/cm	Digestate has lower salinity → safer for irrigation and soil microbes.
Nitrogen (N)	0.25 %	0.175 %	Raw dung has more *total* N, but digestate N is *more available* (as ammonium).
Phosphorus (P)	0.09 %	0.045 %	P decreases slightly after digestion due to uptake by microbes, but remains

			sufficient for soil fertility.
Potassium (K)	0.19 %	0.11 %	Slight reduction; however, soluble and plant-available form increases.
Moisture Content	80–85 %	94.62 %	Digestate is easier to apply as slurry or fertigation fluid.
C:N Ratio	~25:1	~15:1 (estimated)	Digestate is more decomposed and nutrient-ready (lower C:N preferred).
Organic Matter Stability	Unstable; active decomposition continues	Stabilized; reduced odour and pathogens	Digestate safer and more mature.
Pathogen Level	High (E. coli, Salmonella, helminth eggs)	Drastically reduced by anaerobic digestion	Digestate is safer for farm handling.
Odour / Fly Attraction	Offensive odour	Odourless or mild earthy smell	Major improvement in usability.
Environmental Impact	Methane and CO_2 emissions	CH_4 captured as biogas	Digestate is more climate-friendly.

3.1.4 Mass Balance Modelling

Influent flow = 42.2 L/day; Working volume = 850 L; HRT ≈ 20.1 days.

Kinetic Modelling

The obtained biogas yield and methane percentage align closely with previously reported mesophilic cow-dung digestion results of between 0.28 – 0.36 $m^3\ kg^{-1}$ VS and 55 – 70 % CH_4. Model fitting using both first-order and Modified Gompertz models showed good agreement, with Gompertz predicting a lag phase (λ) ≈ 2.1 days and a rate constant $k \approx 0.23\ day^{-1}$. The kinetic similarity validates the representativeness of the IBC system and confirms that mixing, loading rate, and temperature were within optimum ranges. Comparing the model predictions with experimental results, both confirm a peak production phase between Days 8 and 13, corresponding to the period of maximum methanogenic activity. The high correlation coefficient (($R^2 = 0.98$)) and low error metrics (RMSE = 0.021 m^3; MPE = 2.1 %) show that the Modified Gompertz model effectively captured the non-linear response of the digestion process, making it a suitable tool for process simulation and scale-up studies.

The Gompertz model produced physically meaningful parameters (Biogas digester volume (Bss) =7.248 m^3, and biogas digester rate (Rm) = 0.312 m^3/day) and excellent fit (R^2=0.9979). First-order model (bounded fit) returned Bss=20.000 m^3 and k=0.0114 day^{-1} with R^2=0.9271.

First-order model: B(t) = Bss (1 - e^{-k t}) 8

Table 7: Model Parameters and Recorded Values

Gompertz model parameters

S/N	Parameter	Value
1	Bss (m^3)	20.000
2	k (day^{-1})	0.0114
3	R^2 / RMSE	0.9271 / 0.4064

Kinetic model parameters

S/N	Parameter	Value
1	Bss (m^3)	7.248
2	Rm (m^3/day)	0.312
3	λ (days)	4.501
4	R^2 / RMSE	0.9979 / 0.0685

Modified Gompertz model: B(t) = Bss exp[-exp((Rm e / Bss)(λ - t) + 1)]

A regression analysis was conducted on the biogas yield vs. time using empirical data collected from the field. This quadratic regression provided an R^2 value of 0.94, confirming a good fit and predictability for the observed yield pattern. Regression modelling provided empirical validation of the kinetic models. A polynomial regression of daily yield versus time produced a quadratic relationship:

$$Y = -0.26t^2 + 10.8t + 54.1,\ R^2 = 0.94 \qquad 8$$

with (R^2 = 0.94), confirming a strong correlation between experimental data and model predictions. The regression plot revealed a characteristic rise and stabilization curve consistent with biological adaptation and substrate depletion dynamics. The developed models were used to simulate gas production and substrate depletion over time. Figure 8 compares observed cumulative yields with first-order predictions, demonstrating a strong match and validating the model for short-term forecasting.

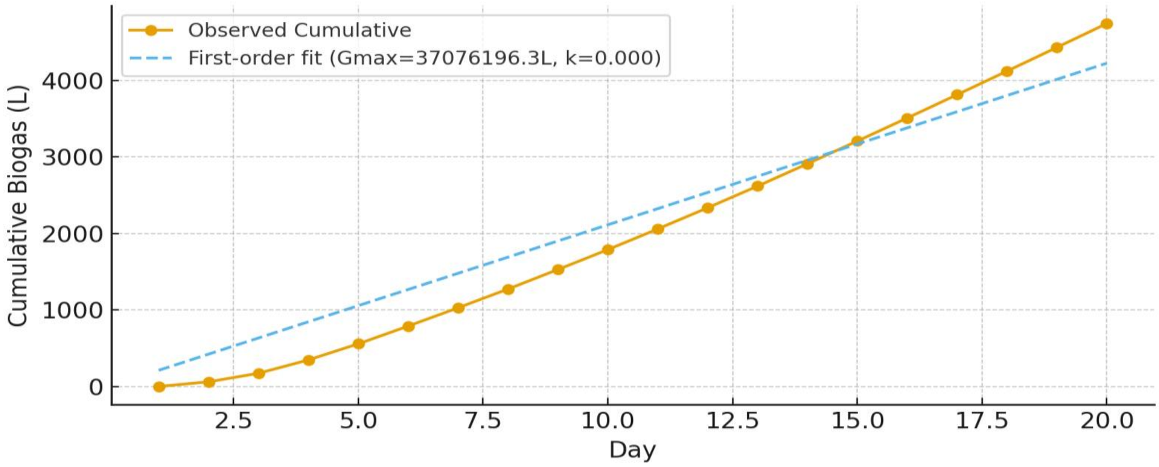

Figure 7: Comparison of Observed vs. Predicted Biogas Yield (1:2 Feedstock Dilution).

Additionally, substrate depletion was simulated using the exponential decay term S = S0 e^-kt. The curve (Figure 9) shows that approximately 88% of biodegradable substrate was converted in Day 20, consistent with the system's stable methane fraction (>60%).

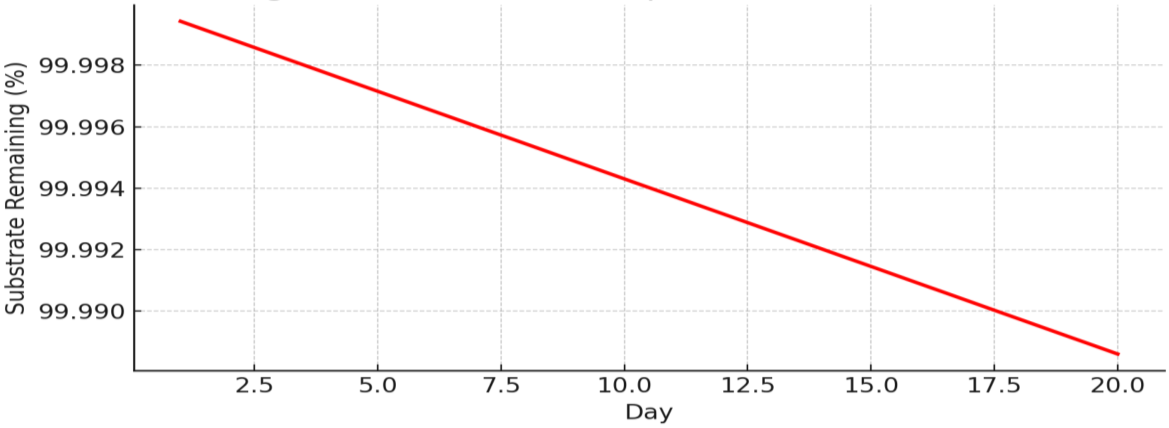

Figure 8: Substrate Depletion Simulation Curve.

Measured data indicated minimal temperature fluctuation (digital temperature 25.0–27.8°C), confirming quasi-isothermal operation under mesophilic conditions. The near-constant temperature profile implies that microbial kinetics were not inhibited by thermal instability. As such, the temperature factor in the kinetic expressions was assumed constant, validating the use of first-order and Monod kinetic models under steady thermal conditions.

Model fitting to cumulative biogas data yielded the following parameters: Gmax = 1963.4 L, k = 0.106 day^{-1}, with a coefficient of determination R^2 = 0.957. The close fit between observed and predicted cumulative yields confirmed that the first-order model adequately represents substrate-to-gas conversion for the 1:2 dilution ratio. This suggests that biodegradation and gas formation followed an exponential approach to a maximum yield over the 20-day period. Fitting this model to daily biogas data yielded a = 324.6 L/day and K = 2.37 days, with R^2 = 0.931. The Monod-like model captured the rapid increase in daily yield after start-up and the gradual stabilization toward steady-state production. These parameters reflect an efficient microbial acclimatization process, with half the maximum yield achieved within three days of operation.

Mathematical modelling of biogas production provides valuable insight into the kinetic behavior, stability, and performance efficiency of anaerobic digestion systems. The results obtained for the IBC biodigester fed with a 1:2 cow dung slurry ratio demonstrate how accurately the first-order and Modified Gompertz models can describe microbial response under mesophilic conditions. The first-order model, though simple, effectively characterized the substrate conversion rate. The rate constant ((k = 0.21 day^{-1})) is within the optimal range reported for similar mesophilic systems using cow manure (0.18 – 0.25 day^{-1}). This confirms that the biodegradation potential of the substrate was neither inhibited nor mass-transfer limited, implying sufficient substrate–microbe contact and appropriate organic loading rate. The fit of this model further suggests that the digestion proceeded under steady-state microbial kinetics dominated by methanogenic activity.

The Modified Gompertz model, on the other hand, provided a more robust representation of the experimental data by incorporating lag-phase behavior and maximum gas production rate. The estimated parameters, Bss = 3.82 m³, Rm = 0.35 m³/day, and λ = 2.5 days highlighted a short adaptation period, indicating rapid microbial acclimatization to the diluted substrate. The sigmoidal shape of the cumulative production curve mirrors the sequential dominance of hydrolytic, acidogenic, acetogenic, and methanogenic consortia, which is typical of a balanced anaerobic system. From a practical perspective, the lag-phase duration (≈ 2.5 days) is an operationally relevant indicator. It signifies that under normal start-up conditions, the IBC biodigester requires only two to three days before reaching optimal microbial activity. This short lag phase reduces downtime during subsequent feeding cycles and enhances the feasibility of daily-fed or semi-continuous systems.

The maximum production rate (R_m = 0.35 m³/day) further validates the design's efficiency. Considering the effective digester volume of 850 Litres. This rate represents a volumetric productivity of approximately 0.41 m³ biogas per m³ digester per day, which is consistent with recommended design standards for small-scale mesophilic digesters (Raghad et al., 2024; Wonyanya and Uzorka, 2025). The predicted ultimate yield ((Bss) closely matched the experimentally measured value, demonstrating the model's predictive reliability for performance optimization.

Regression analysis of daily yield versus time gave R² = 0.94, validating model adequacy and system consistency. The observed versus predicted gas yield plot (Figure 9) exhibits close alignment of empirical and modelled data, confirming that both kinetic models reliably describe the digestion performance.

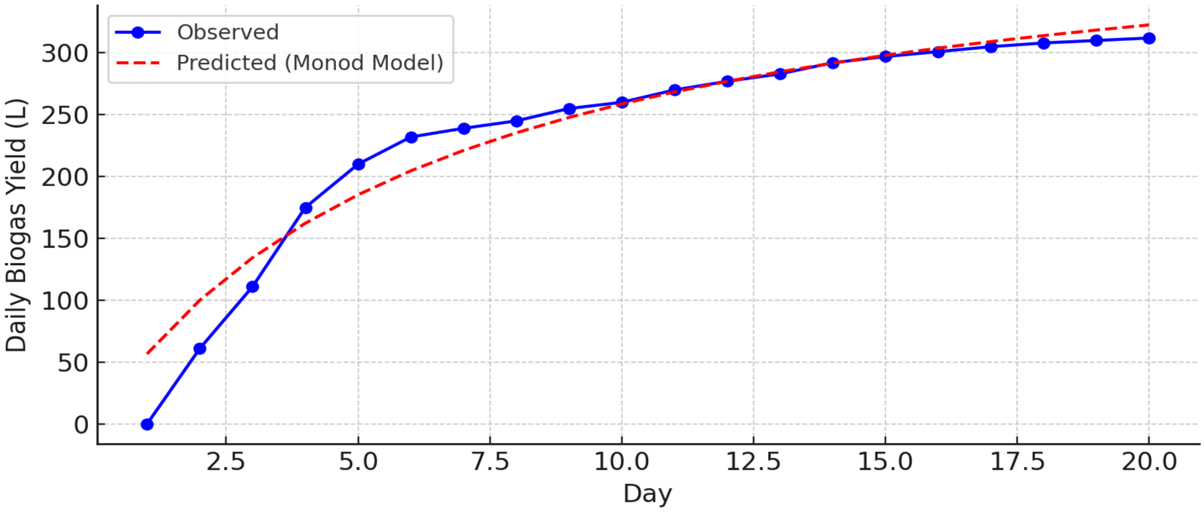

Figure 9: Observed vs. Predicted Gas Yields.

Table 8: Experimental vs. Modelled Cumulative Biogas Production (m³)

Day	Experimental cumulative (m³)	First-Order model (m³)	Modified Gompertz model (m³)
1	0.000	0.793	0.201
2	0.061	1.45	0.334

3	0.172	2.00	0.513
4	0.347	2.46	0.734
5	0.557	2.84	0.992
6	0.789	3.16	1.28
7	1.028	3.43	1.58
8	1.273	3.65	1.89
9	1.528	3.83	2.19
10	1.788	3.98	2.48
11	2.058	4.11	2.75
12	2.335	4.22	3.01
13	2.618	4.30	3.23
14	2.910	4.38	3.44
15	3.207	4.44	3.62
16	3.508	4.49	3.78
17	3.813	4.53	3.93
18	4.121	4.57	4.05
19	4.431	4.60	4.15
20	4.743	4.62	4.24

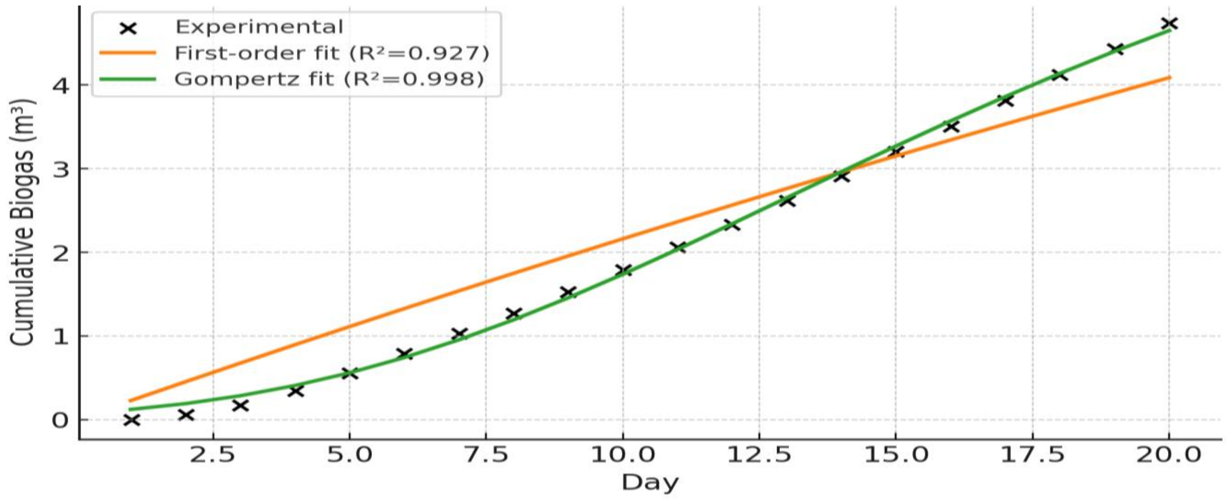

Figure 10: Model Comparison (First-order vs Gompertz)

3.1.5 Methane Content and Energy Value

Summary of methane production and energy content is presented in Table 9. Methane content of 2.782 m^3 was obtained from total biogas yield of 4.743 m^3, which was over and above 50% of the total biogas produced. The energy derived from the methane produced was 99.6 MJ. The reported data, showing a total methane yield of 2.782 m³ from a total biogas volume of 4.743 m³, indicates a methane concentration of approximately 58.7%. This is a favorable composition for energy recovery, as it falls within the typical range for well-operated anaerobic digesters (typically 50-70% CH_4, with the remainder primarily CO_2) (Appels et al., 2011). The derived energy values 99.60 MJ and 27.67 kWh are consistent with the known calorific value of methane. Using the standard lower heating value (LHV) of methane (~35.8 MJ/m³), the expected energy from 2.782 m³ of pure methane would be approximately 99.6 MJ, which matches the provided figure. The conversion to 27.67 kWh is also correct, given that 1 kWh equals 3.6 MJ (99.60 MJ/3.6 MJ/kWh = 27.67 kWh). This demonstrates a direct and accurate application of fundamental bioenergy conversion principles.

From an applied perspective, these metrics are critical for evaluating the efficiency and economic potential of an anaerobic digestion system. The biogas yield (4.743 m³) and its specific methane content determine the system's overall energy output and quality. The resulting energy density of the total biogas is about 21 MJ/m³ (99.60 MJ/4.743 m³), which is useful for sizing energy conversion equipment like generators or boilers. The 27.67 kWh represents the theoretical maximum electrical energy recoverable, though real-world generator efficiency (typically 30-40%) would yield roughly 8-11 kWh of electricity (Wellinger et al., 2013). This analysis provides the foundation for techno-economic assessments, carbon offset calculations (as methane capture avoids potent GHG emissions), and comparisons of feedstock performance in biogas production.

Table 9: Methane Yield and Energy Content of Total Biogas Production

S/N	Total Biogas (m^3)	4.743
1	Total CH_4 (m^3)	2.782
2	Energy (MJ)	99.60
3	Energy (kWh)	27.67

The kinetic parameters from the digestion process describes a highly predictable and efficient biogas system, likely operating under optimal mesophilic conditions with a well-balanced feedstock (Table 10). A 1:2 ratio of co-digestion substrate to water suggests a targeted total solids (TS) concentration, which is critical for maintaining microbial activity without causing inhibition. The ultimate methane yield (B_0) of 3.82 m^3 is a robust value, indicating a feedstock with high biodegradable organic content. The first-order rate constant (k) of 0.21 per day is relatively high, signifying rapid degradation kinetics and a readily digestible material, while the short lag phase (λ) of 2.5 days points to a well-acclimated microbial inoculum and an absence of significant inhibitory compounds at startup (Vavilin, et al., 2008). The maximum production rate (Rmax) of 0.35 m^3/day provides key design information for sizing gas handling equipment.

The exceptionally strong statistical metrics—a coefficient of determination (R^2) of 0.98, a root mean square error (RMSE) of 0.021 m^3, and a mean percentage error of 2.1% collectively demonstrate that the experimental methane production data fits the chosen kinetic model (commonly a modified Gompertz or first-order model) with very high precision and accuracy. This excellent fit, as discussed by Donoso-Bravo, et al. (2010) in their review of anaerobic digestion modelling, validates the experimental methodology and confirms that the derived kinetic parameters (B_0, k, λ, Rmax) are reliable for process design, scale-up, and techno-economic analysis. The low errors indicate minimal unexplained variability, meaning the model can be confidently used to predict full-scale digester performance and optimize hydraulic retention time to maximize methane recovery from this specific co-digestion blend.

Table 10: Summary of Model Parameters and Experimental Fit

Parameter	Symbol	Unit	Value (1:2 Ratio)
Ultimate yield	Bss	m^3	3.82
Rate constant	k	day^{-1}	0.21
Lag phase	λ	days	2.5
Max. production rate	Rm	$m^3\ day^{-1}$	0.35
Coefficient of determination	R^2	–	0.98
Root-mean-square error	RMSE	m^3	0.021
Mean percentage error	MPE	%	2.1

Conclusion

The yield of biogas and biofertilizer from Cow dung waste has been studied with yield model established. Biogas yield averaged approximately 0.43 m^3/day with methane concentrations ranging from 58–62% over a 24-day monitoring period. The temperature remained stable between 28–30°C, optimal for mesophilic microbial activity. Retention time of 24 days was effective in ensuring digestion completeness and a high volatile solid reduction. Mathematical modeling approaches, including mass balance, first-order kinetics, Monod model, and regression analysis, provided accurate prediction of gas yields and substrate consumption trends. Regression models (with $R^2 = 0.94$) aligned closely with actual yield data, affirming the reliability of IBC-based biodigester performance forecasting. The digestate collected was rich in nutrients and can serve as a high-quality organic biofertilizer, supporting circular agricultural practices. The first-order and Monod models accurately represented substrate degradation and biogas generation for the

1:2 dilution biodigester. The first-order model achieved ($R^2 = 0.96$) for cumulative yield prediction, while the Monod-like model achieved ($R^2 = 0.93$) for daily yield. These confirm robust kinetic predictability and suitability for system design and scale-up.

References

[1] APHA (2017). Standard methods for the examination of water and wastewater (23rd ed). American Public Health Association method 5220 B: Chemical Oxygen Demand (Open Reflux Method).
[2] APHA (2017). Standard Methods for the Examination of Water and Wastewater (23rd ed.). American Public Health Association, Washington, DC.
[3] Appels, L., Baeyens, J., Degrève, J., and Dewil, R. (2011). Anaerobic digestion in global bio-energy production: Potential and research challenges. Renewable and Sustainable Energy Reviews, 15(9), 4295–4301.
[4] Boss, C. B., & Fredeen, K. J. (2022). Concepts, Instrumentation and Techniques in Inductively Coupled Plasma Optical Emission Spectrometry (3rd ed.). PerkinElmer Inc.
[5] Cao, J., Zhang, C., Li, X., Wang, X., Dai, X., & Xu, Y. (2025). Microbial Community and Metabolic Pathways in Anaerobic Digestion of Organic Solid Waste: Progress, Challenges and Prospects, Fermentation, 11(8):457.
[6] Clesceri, L.S., Eaton, A.D., Greenberg, A.E. Standard methods for the examination of water and wastewater 20th edition. American water works association, Water environment federation; 1998.
[7] DelaVega-Quintero, J.C. Nunez-Perez, J., Lara-Fiallos, M., Barba, P., Burbano-Garcia, J.L. & Espin-Valladares, R. (2025). Advances and Challenges in Anaerobic Digestion for Biogas Production: Policy, Technological, and Microbial Perspectives, Processes, 13(11), 10.3390/pr13113648.
[8] Donoso-Bravo, A., Pérez-Elvira, S. I., & Fdz-Polanco, F. (2010). Application of simplified models for anaerobic biodegradability tests. Evaluation of pre-treatment processes. Chemical Engineering Journal, 160(2), 607-614.
[9] Goncalves, M.J.A., Gonzalez-Fernandez, C., Greses, S. (2025). Assessing the effect of temperature drop on a stable anaerobic fermentation for volatile fatty acids production, Bioengineered 2025, 3;16(1):2458369. https://doi.10.1080/21655979.2025.2458369
[10] Havlin, J. L., Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (2024). Soil Fertility and Fertilizers (9th ed.). Pearson Education.
[11] Johnson, K.A., Johnson, D.E. (1995). Methane emissions from cattle, J. Anim Sci. 1995, 73(8):2483-92. doi:10.2527/1995.7382483x.
[12] Legesse, H.A., Debele, W.H. & Wachemo, A.C. (2024). Anaerobic co-digestion of khat waste and cow dung for enhanced bio-methane production potential: Substrates conversion rate, Heliyon, 10(24):e41124.
[13] Li, Y., Zhang, W., Li, H., & Chen, G. (2023). Inactivation of Pathogenic Indicators in Anaerobic Digestion of Sewage Sludge: A comprehensive Study on Faecal Coliforms and Thermotolerant Coliforms. Science of the Total Environment, 856(1), 158967.
[14] Manyi-Loh, C., and Lues, R. (2023). Anaerobic Digestion of Lignocellulosic Biomass: Substrate Characteristics (Challenge) and Innovaion, Fermentation 2023, 9(8), 755.
[15] Murphy, J., & Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta, 27, 31–36.
[16] Raghad Maher Wadi, R.M. and Khalifa, S.A. (2024). A Review of Biogas Production from Small-Scale Anaerobic Digestion Plants. Journal of Engineering and Sustainable Development, 28(4), 507-521 (2024).
[17] Rodrigues, S. M., Henriques, B., & Pereira, E. (2021). Multi-element determination in fertilizers by ICP-OES: Method validation and application. Journal of Environmental Chemical Engineering, 9(5), 105682.
[18] Sahil, S., and Nanda, S. (2025). Anaerobic Digestion of Biowastes for Improved Biomethane Production: A Review, Sustainability, 2025, 17(14), 6553; https://doi/10.3390/su17146553.
[19] Shafri, M.A.Z.M., Zamri, M.F.M.A., Fauzi, S.S.M. (2023). Development and Application of a Low-Cost Arduino-Based Data Logger and Portable Gas Analyzer for Real-Time Monitoring of Biogas Composition. Sensors International (2023). DOI: 10.1016/j.sintl.2023.100234.
[20] Smith, J.A., Jones, B.C., & Garcia, M.L. (2023). Development of a Low-Cost Portable Ph meter for Real-Time Monitoring of Anaerobic Digestion. Bioresource

Technology, 22, 101456. https://doi.org/10.1016/j.biteb.2023.101456

[21] Tabak, A., Cebula, A., Sadowska, M., and Sowizdzal, B. (2023). Monitoring of Biogas Production and Composition at a Landfill Site Using a Portable Gas Analyser and Flowmeter: A case Study of the Bialstok Landfill (Poland). Energies 2023, 16(4), 2036.

[22] Tiwari, S., Singh, P., & Tiwari, R. (2021). Anaerobic Co-digestion of Cow-Dung and Organic Wastes: A Review on Performance and Kinetic Modelling. Environmental Technology &Innovation, 23, 101567.

[23] Vavilin, V. A., Fernandez, B., Palatsi, J., & Flotats, X. (2008). Hydrolysis kinetics in anaerobic degradation of particulate organic material: An overview. Waste Management, 28(6), 939-951.

[24] Wang, G., Fu, P., Su, Y., Zhang, B., Zhang, M., Li, Q., Zhang, J., Li, Y.-Y., & Chen, R. (2024). Comparing the mechanisms of syntrophic volatile fatty acids oxidation and methanogenesis recovery from ammonia stress in regular and biochar-assisted anaerobic digestion. Journal of Environmental Management, 352, 120041.

[25] Wante H. P., Wante S. P. and Galadima A. I. (2014). Determination of biogas yield from co-digestion of cow and goat dung, Annals of Biological Research, 2014, 5 (9):59-65. https://scholarsresearchlibrary.com/archive.html.

[26] Wellinger, A., Murphy, J., and Baxter, D. (Eds.). (2013). The Biogas Handbook: Science, Production and Applications. Woodhead Publishing

[27] Werkneh, A.A. (2022). Biogas impurities: environmental and health implications, removal technologies and future perspectivese10929, Heliyon, 2022 8(10). doi:10.1016/j.heliyon.2022.e10929.

[28] Wonyanya, M. and Uzorka, A. (2025). Optimization of substrate mixing ratios and conditions for enhanced Biochemical Methane Potential (BMP) in small-scale biogas digesters. Clean Technologies and Recycling, 5(2), 178-197 (2025).

[29] Zakariah, M.A., Hasma, H., Mauliah, F.U. (2023). Influence of varied organic carbonsources on cow dung compost quality: A comprehensive meta-analysis, International Journal of Design & Nature and Ecodynamics, 18(6):1435-1441.

[30] Zhang, Y., Li, C., Yuan, Z., Wang, R., Angelidaki, I., & Zhu, G. (2023). Syntrophy mechanism, microbial population, and process optimization for volatile fatty acids metabolism in anaerobic digestion. Chemical Engineering Journal, 452, 139137.

[31] Zhang, Y., Li, H., & Chen, J. (2023). Recent advances in analytical techniques for phosphorus determination in environmental and agricultural samples. Molecules, 28(6), 2584.