

Maximizing Biogas Output through Optimal Anaerobic Co-Digestion of Water Hyacinth and Cow Dung

Nweke James^{1*}, Emenike Wami², Awajogak Anthony Ujile³, T.O. Goodhead⁴

^{1,2,3,4}Department of Chemical and Petrochemical Engineering, Rivers State University, PMB 5080 Port-Harcourt, Nigeria.

Abstract — This study investigates biogas production from water hyacinth (*Eichhornia crassipes*) through anaerobic co-digestion with cow dung in order to enhance methane yield and process stability. Experiments were conducted in 18.9 L batch digesters operated at 75% working volume, an organic loading rate of $3.5 \text{ g VS L}^{-1} \text{ day}^{-1}$, and a hydraulic retention time of 70 days under mesophilic conditions (29–38 °C). Six feedstock configurations were evaluated, comprising mono-digestion of water hyacinth and five water hyacinth–cow dung co-digestion ratios. Mono-digestion of water hyacinth produced $42.3 \text{ L kg}^{-1} \text{ VS}$, while the optimal 2:1 water hyacinth–cow dung ratio achieved the highest cumulative biogas yield of $54.9 \text{ L kg}^{-1} \text{ VS}$, representing a 29.8% increase. Biogas upgrading using a three-stage purification system (ferric oxide, sodium hydroxide, and silica gel) increased methane concentration from 60.05% to 86.02%, yielding a calorific value of 31.46 MJ m^{-3} . Kinetic modelling based on coupled first-order hydrolysis and Monod microbial growth equations showed excellent agreement with experimental data ($R^2 = 0.984$, RMSE = 0.263 L). The results demonstrate that anaerobic co-digestion of water hyacinth with cow dung provides an efficient, environmentally sustainable pathway for renewable energy generation while simultaneously addressing aquatic weed management challenges.

Keywords— Anaerobic Co-Digestion, Biogas Production, Water Hyacinth, Cow Dung, Methane Yield, Biomass Optimization, Organic Waste Management, Renewable Energy, Digestion Efficiency, Bioenergy, Substrate Ratio, Sustainable Waste-to-Energy.

I. INTRODUCTION

The search for sustainable energy alternatives has intensified in recent decades due to the depletion of fossil fuel reserves, rising greenhouse gas emissions, and the increasing demand for reliable energy sources. Among the many biomass feedstocks investigated, aquatic plants have gained attention for their rapid growth rates and year-round availability. Water hyacinth (*Eichhornia crassipes*) is one of the most invasive aquatic weeds globally, with a remarkable growth potential producing up to 3.42 million offspring in 200 days (Nega et al., 2022). Its prolific reproduction disrupts aquatic ecosystems, blocks waterways, reduces biodiversity, and hampers fishing and navigation. In Nigeria and other tropical regions, its rapid spread across rivers and lakes has created significant ecological and socio-economic challenges, including reduced fish catches, increased water loss from evaporation, and breeding grounds for disease vectors (Villamagna & Murphy, 2010; Ndimele et al., 2011).

Beyond its ecological impact, water hyacinth contains a high proportion of volatile solids, making it a promising biofuel feedstock (Winardi et al., 2020; Ekong et al., 2023). Proximate analysis of water hyacinth revealed 43.08% moisture, 8% ash, 75.5% volatile solids, 6.24% fat, and a C/N ratio of 25.57, parameters which fall within the optimal range for efficient anaerobic digestion. These characteristics confirm its

suitability as a feedstock for biogas production, thereby making water hyacinth a strong candidate for renewable energy generation (Nweke et al., 2025). Several studies have explored its conversion to biogas through anaerobic digestion. For example, Singh et al (2013), Zahan et al (2019), reported methane yields of $0.21\text{--}0.24 \text{ m}^3/\text{kg VS}$ from water hyacinth under mesophilic conditions, while Adedeji et al (2022), Adebayo et al. (2012) highlighted the need for nutrient balancing to prevent process instability. However, mono-digestion of water hyacinth often encounters operational challenges, including nutrient imbalance, low buffering capacity, and unstable microbial activity, which can reduce methane yield and process efficiency. These limitations have hindered its large-scale application in biogas production despite its abundance and low or zero cost.

One promising strategy to overcome these limitations is anaerobic co-digestion, in which water hyacinth is combined with other organic substrates to balance nutrient composition, improve microbial diversity, and enhance process stability. Cow dung, in particular, is rich in microbial inoculum and possesses strong buffering capacity, making it a suitable co-substrate for water hyacinth digestion (Yadvika et al., 2004; Mata-Alvarez et al., 2024). Previous studies have reported improved gas yield and stability when lignocellulosic biomass is co-digested with animal manure. For instance, Zhang et al (2022) achieved a 25–30% increase in methane yield when co-

digesting aquatic plants with pig manure, while Iqbal et al. (2014) demonstrated reduced start-up time and higher volatile solids reduction with similar feedstock combinations. Despite these findings, optimal mixing ratios and kinetic performance parameters for water hyacinth–cow dung systems remain insufficiently documented, particularly under the tropical climatic conditions of Nigeria.

From a chemical engineering perspective, anaerobic co-digestion represents a complex multiphase biochemical reactor system governed by mass balance, reaction kinetics, and thermodynamic constraints. Substrate hydrolysis, microbial growth, and methane formation are rate-limited by substrate availability, microbial affinity, and environmental conditions such as pH and temperature. Optimizing feedstock ratios directly influences volatile solids conversion efficiency, methane yield per unit mass of substrate, and overall energy recovery. Therefore, understanding the kinetic behavior and energy balance of water hyacinth–cow dung co-digestion systems is critical for reactor design, scale-up, and process optimization.

This study therefore aims to investigate biogas production from water hyacinth through anaerobic co-digestion with cow dung, focusing on yield optimization, process stability, and kinetic modelling. The scope of work includes analysis of water hyacinth, experimental evaluation of five feedstock ratios, and application of first-order and Monod-based kinetic models. These models were implemented in Python 3.11 using the Levenberg–Marquardt optimization algorithm to estimate kinetic parameters with high precision and accurately fit experimental data. The justification for this research lies in addressing two key challenges: providing a renewable energy pathway that contributes to energy security and environmental sustainability, and managing the ecological threat posed by uncontrolled water hyacinth proliferation in Nigerian waterways.



Fig: 1 Water Hyacinth Invasiveness

II. MATERIALS AND METHODS

1. Experimental Design

The study employed a Completely Randomized Design (CRD) with six treatments representing different mixing ratios of water hyacinth (WH) and cow dung (CD):

- T₁: 100% WH
- T₂: 1:1 (WH:CD)
- T₃: 2:1 (WH:CD)
- T₄: 1:2 (WH:CD)
- T₅: 1:3 (WH:CD)
- T₆: 3:1 (WH:CD)

Each treatment was replicated three times to provide adequate statistical power while optimizing material use. The CRD approach minimized bias and ensured uniform operating conditions across all digesters. Digesters were randomly assigned to treatment positions to eliminate systematic bias associated with spatial or operational variability.

All digesters were operated under identical environmental and operational conditions, including temperature range, and hydraulic retention time, ensuring that observed differences in performance were attributable solely to feedstock composition/mixing ratios.

2. Materials Preparation

Fresh water hyacinth (*Eichhornia crassipes*) was harvested from Oxbow Lake, Yenagoa, Bayelsa State. The biomass was washed to remove debris, chopped into 2–3 cm pieces, and ground at 1500 rpm to increase surface area for microbial hydrolysis, (see figure 2). Cow dung was sourced from the Rumuokoro cattle slaughterhouse, Port Harcourt. Substrates were blended with water at a 1:2 substrate-to-water ratio to maintain adequate moisture for microbial activity. The initial slurry pH (6.2) was below the optimal methanogenic range (6.5–7.8), which could inhibit microbial activity. To correct this, wood ash derived from mahogany was applied as a natural alkaline buffer owing to its high content of carbonates, potassium, and calcium compounds. A measured addition of 6 g of wood ash raised the slurry pH to 6.8, which was within the favorable range for methanogenesis. Beyond pH correction, the incorporation of wood ash also functioned as a stabilizing agent by neutralizing excess volatile fatty acids and mitigating the accumulation of free ammonia, thereby creating a more conducive environment for methanogenic microorganisms.



Plate 2 Fresh Water Hyacinth Chopped and Grinded

3. Treatment Loading

Each digester was charged with a total slurry mass of 14.1 kg. Feedstock quantities were calculated according to the treatment ratios (Table 1).

Table 1. Feedstock distribution for each treatment

Treatment	WH (kg)	CD (kg)	Water (kg)	Total (kg)
100% WH	4.70	0.00	9.40	14.10
1:1	2.35	2.35	9.40	14.10
2:1	3.13	1.57	9.40	14.10
1:2	1.57	3.13	9.40	14.10
1:3	1.18	3.52	9.40	14.10
3:1	3.52	1.18	9.40	14.10

4. Digester Configuration and Operation

The experimental units consisted of an anaerobic digesters with a total volume of 18.9 L and a working capacity of 75%. Each digester was sealed to maintain anaerobic conditions and fitted with a gas outlet connected to the purification and storage system.

Operating parameters were maintained as follows:

- Temperature: 29–38 °C (mesophilic range), monitored continuously with integrated digital thermometers.
- pH: 6.5–7.2, adjusted periodically to maintain stability.
- Hydraulic Retention Time (HRT): 70 days.

- Mixing: Manual agitation twice daily to minimize scum formation and enhance contact between microbes and substrate.

The complete system consisted of: (see figure 3)

- Primary digester tank – for slurry degradation and gas generation.
- Gas purification train – a three-stage system designed to reduce CO₂, H₂S, and water vapor.
- Gas storage unit – calibrated storage cylinder equipped with airtight valves for collection of upgraded biogas.



Figure 3: Process Flow Diagram

5. Gas Collection and Purification

The process flow (Figure 3) illustrates the experimental setup, where the digester tanks were charged with their respective slurry mixtures and hermetically sealed to maintain anaerobic conditions. During digestion, microbial activity converted the organic substrates into biogas, which was directed through a three-stage purification train (ferric oxide, calcium oxide, and silica gel) for the sequential removal of hydrogen sulfide, carbon dioxide, and moisture. The purified, methane-rich gas was subsequently collected and transferred into the storage for downstream utilization.

The three-stage purification line include:

- Stage 1: Reduction of acidic gases (mainly CO₂).
- Stage 2: Removal of hydrogen sulfide (H₂S).
- Stage 3: Drying to eliminate residual water vapor.

This sequential purification process enhanced gas quality, increasing methane concentration. Biogas was passed through the purification train at an average flow rate of 0.8–1.0 L min⁻¹. Chemical media were regenerated or replaced every 10–12 days to maintain removal efficiency.

6. Substrate and Digestate Characterization

The water hyacinth–cow dung substrate and the resulting digestate from the 2:1 co-digestion treatment were analyzed to evaluate substrate degradation and digestion efficiency. Table 2 summarizes the proximate composition, carbon content, and estimated COD and BOD values before and after 70 days of anaerobic digestion.

Table 2: Characterization of Water Hyacinth–Cow Dung Sample Before Digestion and After 70 Days of Anaerobic Digestion

Parameter	Initial Value	Digestate Value
Moisture (%)	43.08 ± 1.5	65.12 ± 1.5
Total Solids, TS (%)	56.92	34.88
Volatile Solids, VS (%)	75.52 ± 2.0	6.12 ± 1.0
Ash (%)	8.00 ± 0.5	19.45 ± 0.8
Carbon (%)	41.21 ± 2.0	12.50 ± 1.0
COD (mg L ⁻¹)	871	~260
BOD (mg L ⁻¹)	610	~120

The 69.38% reduction in VS and 28.71% reduction in carbon content indicate effective conversion of biodegradable matter into biogas. TS decreased by 22.04%, while ash content increased due to preferential degradation of organic fractions. COD and BOD removals of approximately 70% and 80%, respectively, demonstrate digestate stabilization and a significant reduction in organic load.

III. RESULTS AND DISCUSSION

1. Cumulative Biogas Yield

The anaerobic digestion of water hyacinth (WH) and cow dung (CD), either as sole substrates or in co-digestion ratios, was monitored for 70 days. Cumulative yields varied significantly across treatments as shown on table 3 and figure 4.

The results indicate that co-digestion consistently outperformed mono-digestion, with the 2:1 and 1:1 ratio delivering the highest yields, underscoring the importance of balancing carbon-rich WH with nitrogen-rich CD for optimal microbial activity

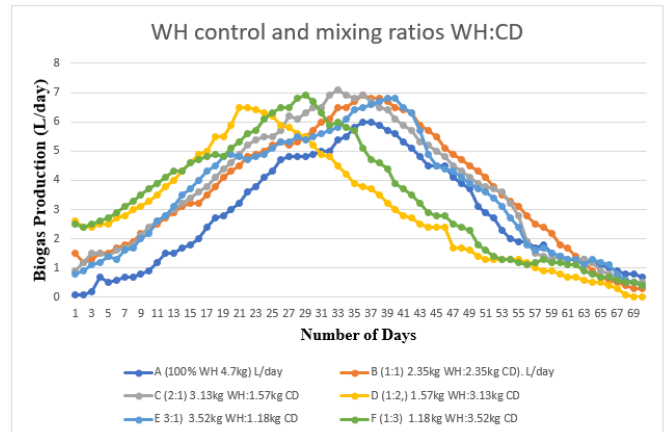


Figure 4: Combined Biogas Yield over 70 days

Table3: Cumulative Biogas Production

Ratio	Cumulative Yield (L)	L/kg of Substrate	% Increase over Control
Control (A)	198.78	42.3	Baseline (0%)
1:1 (B)	257.9	54.9	29.8%
2:1 (C)	258.1	54.9	29.8%
1:2 (D)	210.4	44.8	5.9%
3:1 (E)	247.8	52.7	24.6%
1:3 (F)	237.5	50.5	19.4%
100% CD	230.6	49.06	

2. Biogas Production Trends

Daily biogas production patterns across all treatments exhibited four distinct phases, as illustrated in Figure 4 and table 3.

Lag Phase (Days 0–5): During the initial acclimatization period, gas production remained minimal across all treatments. This was attributed to the time required for microbial consortia to adapt to the substrates, initiate hydrolysis, and establish syntrophic interactions. As shown in Figure 4, the production curves remained nearly flat, confirming the slow onset of digestion.

Log Phase (Days 7–25): A sharp increase in gas production was observed in this period, particularly in the co-digestion treatments. This trend, evident in Figures 4, can be ascribed to intensified hydrolytic and acidogenic activities that enhanced substrate breakdown and methanogenesis. The co-digestion of water hyacinth with cow dung (WH:CD) exhibited notably higher gas yields compared to the mono-digestion of water hyacinth. This finding highlights the synergistic effects of co-substrate addition in improving biodegradability and microbial activity.

Peak Phase (Days 25–35): The highest daily gas yields were attained during this phase. As shown in Figure 4, the 2:1 WH:CD treatment achieved the maximum production rate (7.1L/day) among all configurations, indicating that this ratio provided the most favorable balance of nutrients and microbial activity. The peak observed across treatments corresponds with the optimal stabilization of methanogenic populations and efficient conversion of volatile fatty acids (VFAs) to methane.

Decline Phase (Days 35–70): A gradual reduction in gas production was observed after Day 35. This decline was due to substrate depletion and the persistence of recalcitrant lignocellulosic fractions of water hyacinth, which resisted microbial breakdown. The decreasing trend also reflects the natural exhaustion of readily biodegradable organic matter, leaving behind materials with limited bioconversion potential. Overall, the temporal production trends demonstrate that co-digestion strategies significantly improved both the rate and magnitude of biogas yield compared to mono-digestion. The identified four-phase pattern is consistent with typical anaerobic digestion dynamics reported in previous studies.

3.. Multistage Biogas Purification Performance

Biogas from the optimized 2:1 water hyacinth–cow dung ratio was purified through a three-stage system: Fe_2O_3 (H_2S removal), NaOH (CO_2 scrubbing), and silica gel (moisture control).

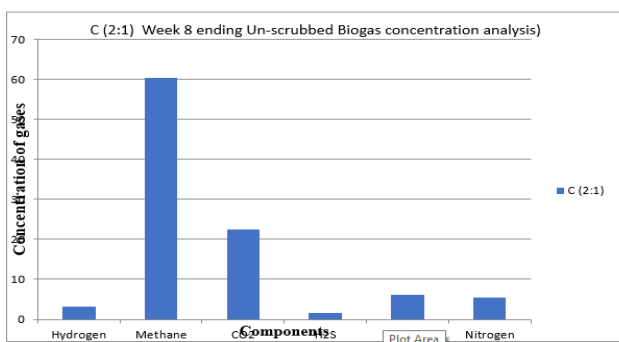


Figure 5: Unscrubbed Gas

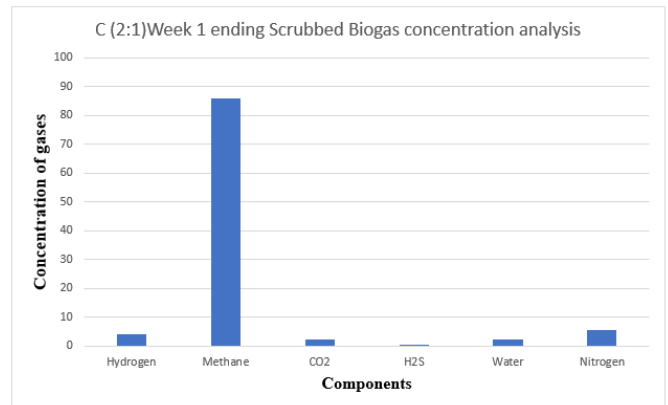


Figure 6: Scrubbed Gas

As shown in Figures 5 and 6, methane content increased from 60.5% to 86.02% (+25.5%), primarily due to CO_2 reduction from 22.5% to 2.2%. This enrichment significantly improved the calorific value of the gas.

H_2S decreased sharply from 1.63% to 0.05%, mitigating corrosion and sulfur emissions, while H_2O dropped from 6.2% to 2.2%, ensuring better storage stability and cleaner combustion. Minor changes were observed in H_2 (3.1–4.1%) and N_2 (5.5–5.4%), confirming the selectivity of the process. Overall, the multistage system upgraded raw biogas into a high-quality fuel with improved purity, energy potential, and process compatibility.

4. Flame Confirmation Test and Applications

Combustion of the purified biogas produced a stable and intense blue flame, confirming the high methane content and superior combustion characteristics of the gas. The observed flame quality is indicative of efficient energy release and suitability for thermal and power generation applications.

The treated gas is suitable for domestic cooking, small-scale heating, and CHP applications, with reduced CO_2 and H_2S minimizing equipment degradation and emissions. This demonstrates the potential of multistage purification to deliver cleaner, high-calorific-value biogas for sustainable energy use.

5. Optimized Biogas Production Model

Figures 7 present the model validation curves, comparing the experimental biogas production data with the predictions obtained from the developed kinetic framework. The close alignment between the observed and simulated values confirms the reliability of the model in representing the anaerobic digestion process.

The biogas production kinetics were described using a coupled formulation of first-order substrate degradation and Monod-

type microbial growth, both of which are standard approaches in anaerobic digestion modelling. Parameter estimation and curve fitting were carried out using the Levenberg–Marquardt nonlinear least-squares optimization algorithm implemented in Python 3.11, ensuring robust convergence and minimization of residual error.

Levenberg–Marquardt Update Equation:

$$\theta_{k+1} = \theta_k - (J^T J + \lambda I)^{-1} J^T (y_{\text{pred}} - y_{\text{exp}})$$

Where:

θ are the parameters ($k_h, Y, \mu_{\text{max}}, K_s, k_d$)

J is the Jacobian matrix of partial derivatives,

λ is a damping factor, I is the identity matrix,

y_{pred} and y_{exp} are predicted and observed biogas yields respectively. $S(\theta)$ (the letter “S”) represents the **objective function**, i.e., the **sum of squared errors (residuals)** between the experimental data and the model predictions.

Objective Function

$$\text{Minimize } S(\theta) = \sum_{i=1}^n [V_{\text{expi}} - V_{\text{gas}}(t_i; \theta)]^2$$

Where:

$V_{\text{exp},i} V_i$: Experimental biogas volume

$V_{\text{gas}}(t_i)$: Model-predicted volume

Table 4: Kinetic Parameters

Parameter	Symbol	Value	Unit	Description
Hydrolysis rate constant	k_h	0.0913	day ⁻¹	Rate of substrate decomposition
Yield coefficient	Y	8.8795	L/g	Gas produced per gram of substrate
Maximum growth rate	μ_{max}	0.0744	day ⁻¹	Maximum specific microbial growth
Half-saturation constant	K_s	0.0245	g/L	Substrate concentration at half μ_{max}
Decay constant	k_d	0.0362	day ⁻¹	Microbial mortality and deactivation

Trials: The optimizer internally iterated over hundreds of evaluations until convergence was achieved. Python implements this internally via `scipy.optimize.curve_fit`:

The optimized kinetic parameters derived from this fitting are summarized in Table 3

The hydrolysis rate constant (see table 4) ($k_h = 0.0913 \text{ day}^{-1}$) indicates efficient breakdown of water hyacinth’s lignocellulosic matrix, which is typically a limiting step in biogas production. The yield coefficient ($Y = 8.8795 \text{ L/g}$) reflects a favorable conversion efficiency, confirming that water hyacinth, when co-digested with cow dung, is a promising substrate for methane-rich biogas production.

The low half-saturation constant ($K_s = 0.0245 \text{ g/L}$) suggests that the microbial community has a strong substrate affinity, enabling effective substrate utilization even at low concentrations. This feature is particularly advantageous in maintaining stable digestion during the late phases of biogas production, when easily degradable organics are depleted.

The maximum microbial growth rate ($\mu_{\text{max}} = 0.0744 \text{ day}^{-1}$) is consistent with reported values for anaerobic consortia, demonstrating balanced hydrolytic and methanogenic activities. Meanwhile, the decay constant ($k_d = 0.0362 \text{ day}^{-1}$) reflects typical microbial washout and inactivation rates, indicating that the model realistically incorporates microbial population dynamics.

Overall, the kinetic modeling results demonstrate that co-digestion of water hyacinth with cow dung provides a synergistic environment that enhances hydrolysis, optimizes microbial growth, and sustains high methane yields. The close fit between predicted and experimental values validate the applicability of the developed model for simulating biogas production trends under varying substrate ratios. Such a model offers valuable predictive capacity for scaling up digester design, optimizing operational parameters, and evaluating long-term system stability.

6.. Experimental vs Predicted Biogas Yield

The figure 7 below shows the validated biogas curve. The experimental biogas yield obtained was 258.1L, representing the actual volume of gas generated under the study’s operating conditions. This result was in close agreement with the predicted yield of 259.4L, which was computed using a Python-based simulation algorithm developed specifically for this research to model microbial kinetics and substrate degradation.

The model's predictive performance was quantitatively validated using statistical indices:

Coefficient of Determination (R^2): 0.984
Root Mean Square Error (RMSE): 0.263

The high R^2 value indicates an excellent correlation between the experimental and predicted datasets, suggesting that the model successfully captured the biogas production dynamics. The low RMSE further confirms minimal deviation, highlighting the robustness of the model in describing the fermentation process. see figure 7

This close alignment between experimental and predicted results demonstrates that the developed model is not only accurate but also reliable for forecasting biogas yields in similar co-digestion systems. Such validation enhances its potential applicability in scaling up biodigester designs and optimizing substrate ratios for improved energy recovery.

7.. Model Performance

The obtained R^2 value (0.984) exceeds those reported in similar anaerobic digestion kinetic studies (typically 0.90–0.96), indicating superior predictive accuracy of the developed model.

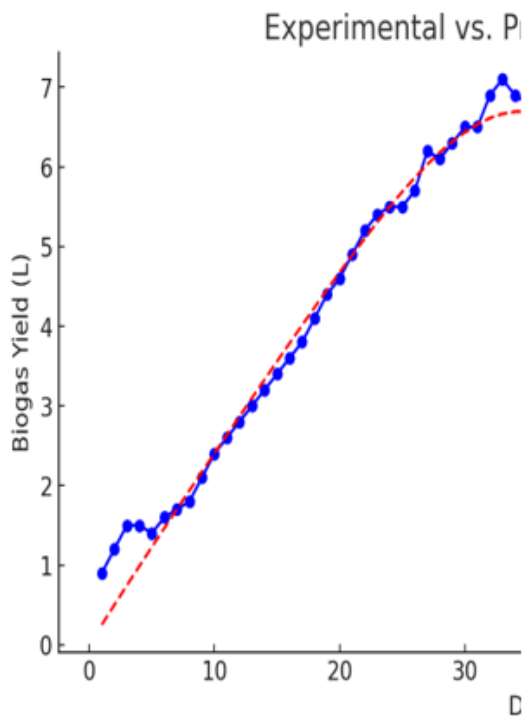


Figure 7: Validated Biogas curve

8. Combined ANOVA for Biogas Yield Across Treatments

Daily biogas production data were time-averaged for each digester prior to statistical analysis to avoid pseudo-replication. Consequently, the ANOVA reflects replicate-level mean yields rather than daily measurements.

The ANOVA (Table 5) indicates marginally significant differences in mean biogas yield across treatments ($F_{cal} = 2.312 > F_{crit} = 2.236, p < 0.05$). This confirms that co-digestion ratios influenced the production performance, validating substrate mixing as a key factor in process optimization

Replicate-level. ANOVA (see table 5) revealed no significant within-treatment differences ($p > 0.05$ in all cases), confirming consistency and reproducibility of biogas yields across replicates.

The major statistical variations were attributed to substrate mixing ratios rather than replicate error, highlighting the robustness of the experimental design. Although the p-value (0.043) indicates statistical significance at the 95% confidence level, the result is marginal. This suggests that substrate ratio influences biogas yield, but further large-scale trials are recommended to strengthen statistical confidence.

Table 5: ANOVA Result

Source of Variation	SS	df	MS	F	P-value	F-critical (0.05)
Between Groups	44.930	5	8.986	2.312	0.043	2.236
Within Groups	1609.441	414	3.888	—	—	—
Total	1654.372	419	—	—	—	—

9.. Reproducibility and Trends in 2:1 WH-CD Co-Digestion

Figure 8 below shows the daily biogas yield for the 2:1 water hyacinth–cow dung treatment expressed as mean $\pm$ standard deviation ($n = 3$). Error bars represent variability among replicate digesters. The data show that biogas production increased steadily during the initial and log phases, peaking around days 30–40 at approximately 6–6.5 L/day. The small error bars throughout most of the digestion period indicate high reproducibility and minimal experimental variation among replicates. Slightly larger deviations observed during the decline phase (days 50–70) reflect minor differences in microbial activity as the substrate became limited. Overall, the

error-bar analysis confirms the reliability of the co-digestion process and indicates that variations in daily biogas yield are attributable primarily to substrate kinetics rather than operational inconsistencies.

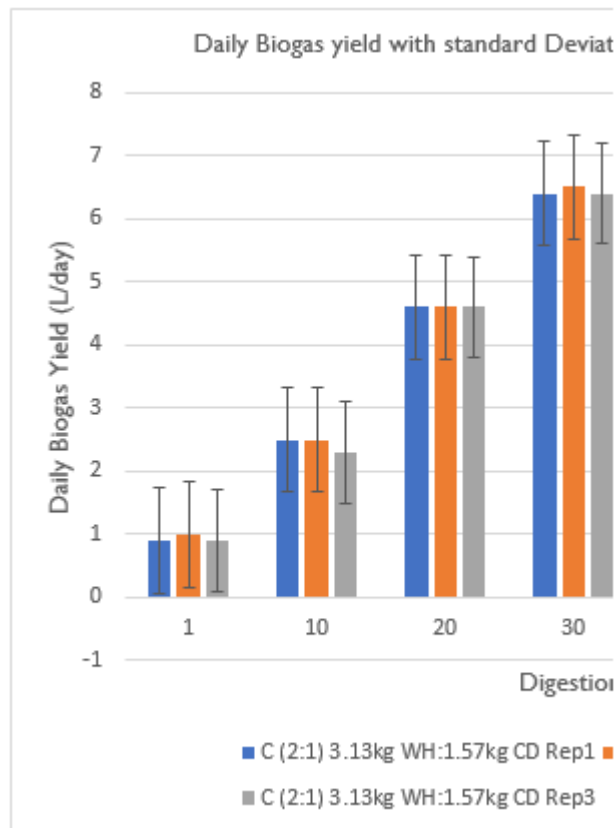


Figure 8: Daily Biogas yield with standard deviation (2:1 water Hyacinth: Cow dung)

10. Energy Balance

Based on the measured calorific value (31.46 MJ m^{-3}) and cumulative biogas yield, the optimized system achieved an estimated energy recovery of 1.72 MJ kg^{-1} VS added, confirming efficient conversion of organic matter into usable energy.

IV. CONCLUSION

This study demonstrated that anaerobic co-digestion of water hyacinth and cow dung at an optimized 2:1 ratio increased biogas yield by 29.8% relative to mono-digestion, achieving a methane purity of 86.02% and a calorific value of 31.46 MJ m^{-3} . The integration of wood ash effectively stabilized digester

pH and enhanced microbial activity, contributing to improved process performance. Kinetic modelling yielded a high predictive accuracy ($R^2 = 0.984$), confirming the suitability of the developed model for reactor design and scale-up. Beyond technical performance, the process offers strong potential for sustainable energy generation, aquatic weed control, and climate change mitigation, directly supporting Sustainable Development Goal 7 (Affordable and Clean Energy).

The kinetic parameters obtained in this study provide valuable data for the design, scaling-up, and optimization of bioreactors, making the process more sustainable and technically feasible for large-scale application.

Overall, these findings confirm that the strategic co-digestion of water hyacinth with cow dung, coupled with the use of wood ash as a natural alkalinity booster, offers a reliable pathway for renewable energy production, effective aquatic weed management, and climate change mitigation through reduced dependence on fossil fuels.

It is recommended that future research should focus on designing and fabricating a household-scale biogas cylinder with an integrated diaphragm/rotary compressor and pressure gauge. The system should ensure efficient gas flow, safety, and reliability through household trials

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