

Analytical And Dynamic Simulation Modelling Of Household Biogas Digester For Domestic Energy Production From Organic Wastes

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Analytical And Dynamic Simulation Modelling Of Household Biogas Digester For Domestic Energy Production From Organic Wastes

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Abstract

Household biogas digesters offer a practical renewable energy pathway for rural communities in developing countries, yet their design and performance evaluation are still largely guided by empirical rules of thumb rather than integrated predictive models. This study developed and validated a hybrid analytical and dynamic simulation model for evaluating the performance of a small-scale household biogas digester operating under mesophilic conditions. A steady-state analytical model, based on mass balance and stoichiometric principles, was developed from a baseline case synthesized from secondary data extracted from peer-reviewed literature. A complementary dynamic simulation model, incorporating first-order substrate degradation kinetics and an Arrhenius-type temperature correction, was implemented in MATLAB/Simulink to capture the transient behaviour of the anaerobic digestion process. The model tracked substrate degradation, biogas and methane generation, and energy output over a 38–40-day digestion cycle. Simulation results showed a peak biogas production rate of 1.04 m³/day at day 19, a cumulative biogas yield of approximately 30 m³, a peak methane production rate of 0.62 m³/day, and a peak energy output of 12.8 MJ/day. Comparison between the analytical and simulation outputs showed close agreement, with percentage differences below 5% across all evaluated parameters. Sensitivity analysis showed that operating temperature, hydraulic retention time, and volatile solids content significantly influenced digester performance, with 35 °C, a 40-day retention time, and higher volatile solids concentrations producing the greatest biogas yields. Validation against independently published experimental data confirmed that the model reproduces the temperature-dependent trend of anaerobic digestion with good accuracy. Based on the findings of this study, it is recommended that household biogas digesters should preferably operate under mesophilic temperature conditions between 25°C and 35°C to enhance microbial activity and maximize biogas production.

Keywords: Anaerobic digestion, Household biogas digester, MATLAB/Simulink, Dynamic simulation, Substrate degradation kinetics, Renewable energy

1.0 Introduction

Access to clean, affordable, and reliable energy remains one of the most pressing development challenges facing rural communities across sub-Saharan Africa and other developing regions. A large proportion of rural households continue to depend on fuelwood, charcoal, and kerosene for

cooking and lighting, a reliance that contributes to deforestation, indoor air pollution, and sustained energy poverty, with close to 960 million people in sub-saharan Africa still lacking access to clean cooking as of 2023 [9]. Anaerobic digestion of organic waste to produce biogas has been widely promoted as a decentralized, low-cost alternative capable of simultaneously addressing household energy needs and organic waste management, particularly in agrarian communities where livestock manure and crop residues are readily available [7]. Household-scale fixed-dome and floating-drum digesters, typically ranging from 4 to 6 m³ in volume, have been deployed extensively in Asia and Africa as an appropriate technology for cooking-scale energy provision [8, 12, 19], although uptake in Sub-Saharan Africa has historically lagged behind Asia because of socio-economic and technical adoption barriers [18]. Nigeria alone possesses substantial unexploited biomass and agricultural-residue resources capable of supporting decentralized bioenergy generation, yet biomass remains one of the most underdeveloped components of the national renewable energy mix [28, 33], while digester uptake in water-limited or resource-constrained settings is further shaped by feedstock availability and digester-design mismatches with local conditions [31, 34].

The performance of a biogas digester is governed by a set of interacting biochemical and thermodynamic processes, including microbial substrate degradation, temperature-dependent reaction kinetics, hydraulic retention time, and feedstock composition. Predicting how these variables jointly determine biogas yield, methane content, and energy output requires models that capture both the steady-state mass balance of the system and its transient, time-dependent behaviour. While analytical steady-state models provide a useful first approximation of digester performance, they cannot capture the dynamic response of the system to changing feed rates, temperature fluctuations, or start-up and depletion behaviour. Dynamic simulation platforms such as MATLAB/Simulink offer a means of representing these time-dependent processes mathematically, enabling engineers and researchers to evaluate digester performance under varying operating scenarios without recourse to costly and time-consuming physical experimentation.

Structured biochemical frameworks such as the IWA Anaerobic Digestion Model No. 1 (ADM1) represent the most rigorous approach to this task, but their extensive parameterization requirements limit their practicality for data-scarce, household scale applications [1]. This

limitation is compounded by the complex microbial inhibition dynamics, such as ammonia and volatile-fatty-acid interactions, that such models must capture [25], and recent reviews of anaerobic co-digestion modelling confirm that simplified kinetic approaches remain the most practical option where such detailed parameterization is unavailable [27]. According to Benali [4], biogas production from cow dung was experimentally investigated as an alternative to fossil fuels and that reported temperature-dependent trends in methanogenic activity remain a key reference point for validating simulation models of cattle-manure digesters. Budiyo [6], demonstrated that biogas production rates from cattle manure could be enhanced through the addition of rumen fluid inoculum, underscoring the sensitivity of digestion performance to feedstock and inoculum characteristics. A small-scale anaerobic digester was field-tested using liquid dairy manure and other organic wastes at an urban dairy farm, providing practical operating data for hydraulic retention time and feedstock loading in small-scale systems [7].

Studies on digester design and feedstock characterization have also informed the definition of realistic baseline parameters for household-scale systems. Demewoz and Tiruneh [8], described the design of a cylindrical fixed-dome biodigester using institutional food waste, illustrating the fixed-dome configuration common to household applications in Africa and Asia. Patrick [10], characterized the microbial ecology of a typical fixed-dome biodigester in South Africa, while Chamdimba [7], reviewed the role of biogas systems in sustainable waste conversion and household energy supply in developing regions. According to Lee [13], and Rajendiran [20], examined co-digestion strategies and kinetic modelling of biogas production from mixed organic wastes, provided yield coefficients and kinetic parameters relevant to the stoichiometric and first-order degradation models adopted in this study. Mohamed [16], and Ulma [22], reported performance data linking solid waste characteristics and feedstock blends to biogas generation rates, while Wresta and Saepudin [23], and Rocher-Rivas [21], provided data on biogas calorific value and methane content used to parameterize the energy output calculations in this study.

Collectively, the reviewed literature confirms that household and small-scale biogas digesters operating on cattle manure under mesophilic conditions typically produce biogas yields of 0.8 – 1.2 m³/day at hydraulic retention times of 30 – 40 days, with methane content in the range of 55 – 65% and volatile solids destruction efficiencies of 45 – 60%. However, the reviewed studies are predominantly experimental or empirical in nature, with limited use of integrated analytical–

dynamic simulation frameworks capable of predicting transient digester behaviour across a range of operating scenarios. This study builds on the reported baseline performance ranges to parameterize and validate a combined analytical and dynamic simulation model. Furthermore, most existing studies on household biogas systems in developing regions are either techno-economic adoption reviews [26, 30, 32] or narrow experimental trials, with few offering an integrated, validated analytical-dynamic simulation framework of the kind developed in this study.

By combining analytical and dynamic simulation approaches, the model developed in this study offers a low-cost decision-support tool that can be used by engineers, non-governmental organizations, and rural development agencies to estimate expected biogas and energy yields prior to construction, to assess the effect of climatic or seasonal temperature variation on digester performance, and to optimize retention time and feedstock loading without the expense of physical prototyping, addressing a gap consistently identified in techno-economic assessments of household biogas technology in Africa, which highlight the scarcity of reliable, low-cost predictive design tools as a barrier to wider adoption [26, 30, 32]. This contributes directly to the broader goal of expanding access to affordable and clean energy (Sustainable Development Goal 7) and to reducing dependence on fuelwood and fossil fuels in rural households.

2.0 Methodology

2.1 Method

This chapter presents a detailed description of the systematic approach and methods employed to achieve the objectives of this study. The methodology is structured around a hybrid approach combining analytical modeling and dynamic simulation. The chapter outlines the research design, data collection from secondary sources, engineering calculations for performance metrics, and the development of a dynamic simulation model using MATLAB/Simulink. The method flow chart adopted is shown in Figure 2.1.

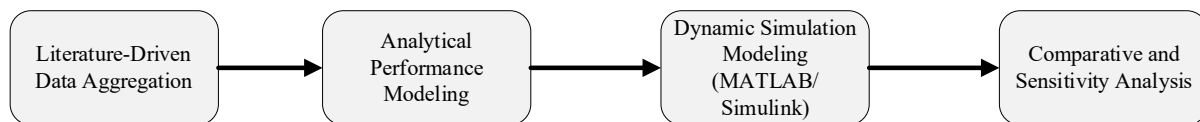


Figure 2.1: Methodology Flow Chart

2.2 Research Design

This study adopted a quantitative, model-based simulation research design, appropriate for a process governed by well-established biochemical and thermodynamic principles that can be expressed mathematically. The design was non-experimental, relying entirely on secondary data and computational modelling rather than physical experimentation, and unfolded in four phases:

- i. Literature-Driven Data Aggregation: Compiling operating parameters and performance data from peer-reviewed literature and technical case studies.
- ii. Analytical Performance Modeling: Applying steady-state engineering equations to establish baseline performance metrics.
- iii. Dynamic Simulation Modeling: Developing a time-dependent model in MATLAB/Simulink to capture the dynamic, non-linear nature of the anaerobic digestion (AD) process.
- iv. Comparative and Sensitivity Analysis: Comparing analytical and simulation results and analyzing the sensitivity of system performance to key operating variables.

2.2 Data Collection and Baseline Case Definition

Data were sourced exclusively from peer-reviewed journal articles, standard biogas technology textbooks, and technical reports from established organizations documenting the field performance of small-scale digesters. A systematic extraction strategy was applied, with inclusion criteria limited to studies on small-scale, continuously stirred or plug-flow digesters operating on typical household feedstocks (animal manure, food waste) under mesophilic (20 – 40°C) or ambient temperature conditions. For each selected study, digester specification, feedstock characteristics, operating conditions, and performance data were extracted using a standardized data form. From the aggregated data, a synthetic baseline case representing a typical household digester in a developing country was defined, using median or most frequently reported values for each parameter. Table 1 summarizes the baseline parameters adopted in this study. The first-order substrate degradation rate constants and theoretical maximum biogas yields

reported for cattle-slurry and cow-dung digesters [29, 24] were used to cross-check the plausibility of the kinetic parameters adopted for the baseline case.

Table 1. Baseline Parameters for a Typical Household Biogas Digester in a Developing Country

Parameter	Baseline value	Unit	Basis/Typical Source
Digester type	Fixed-dome	–	Most common household design in Asia and Africa
Digester Volume (V_d)	4 – 6	m ³	Typical family-scale digester
Working volume	3.5 – 5	m ³	~80–90 % of total volume
Main feedstock	Cattle manure	–	Common rural household substrate
Total solid (TS) contents	18 – 22	%	Fresh cattle manure characteristics
Volatile solid (VS) content	75 – 85	% of TS	Biodegradable organic fraction
Daily feedstock input	20 – 25	kg/day	Typical for 4 – 6 m ³ digester
Hydraulic retention time (HRT)	30 – 40	days	Standard tropical household operation
Organic loading rate (OLR)	1.5 – 2.5	kg VS/m ³ /day	Stable small-scale digestion
Operating temperature (T)	25 – 35	–	Ambient tropical mesophilic condition
Operating pH	6.8 – 7.5	°C	Optimum methanogenic range
Daily biogas yield	0.8 – 1.2	m ³ /day	Household cooking scale output
Methane content	55 – 65	%	Typical biogas composition

Volatile solid destruction	45 – 60	%	Typical anaerobic digestion conversion
Biogas calorific value	20 – 23	MJ/m ³	Based on methane fraction
Specific biogas yield	0.20 – 0.35	m ³ /kg VS added	Typical manure digestion yield

2.3 Analytical Performance Model

A steady-state analytical model, based on mass balance and stoichiometric principles, was developed to provide a foundational calculation of digester performance independent of the dynamic simulation.

2.3.1 Biogas production estimation

The mass of biogas produced daily, M_{biogas} (kg/day), was estimated from the mass of volatile solids fed daily, M_{VS} (kg/day), the volatile solids destruction efficiency (VSD), and the biogas yield per unit of VS destroyed (Y_{biogas}):

$$M_{biogas} = M_{VS, in} \times VSD \times Y_{biogas} \quad (1)$$

The volumetric biogas production, V_{biogas} , was obtained by dividing the mass of biogas M_{biogas} by the biogas density ($\rho_{biogas} \approx 1.2$ kg/m³ at standard conditions).

2.3.2 Energy output calculation

The daily energy output, E_{out} (MJ/day), was calculated from the methane fraction of the biogas using the lower heating value of methane ($LHV_{CH_4} \approx 35.9$ MJ/m³):

$$E_{out} = V_{biogas} \times \left(\frac{\% CH_4}{100} \right) \times LHV_{CH_4} \quad (2)$$

This energy output will be expressed in MJ/day and converted to an equivalent useful thermal power (kW_{th}).

2.3.3 Digester system efficiency

The overall system efficiency (η), defined as the ratio of useful energy output to the theoretical energy content of the feedstock, was calculated as:

$$\eta = \frac{E_{out}}{E_{in}} \times 100\% \quad (3)$$

This metric provides a single, clear indicator of how effective the digester is at converting the inherent chemical energy in the waste into combustible gas.

2.4 Dynamic Simulation Model Development

A dynamic simulation model was developed in MATLAB/Simulink to capture the transient behaviour and reaction kinetics of the anaerobic digestion process, addressing the limitations of the steady-state analytical approach, following the methodological precedent of MATLAB-based dynamic anaerobic digestion simulation [14].

2.4.1 Model selection and justification

A simplified, physics-based model was adopted in preference to complex, parameter-heavy formulations such as ADM1, in view of the limited data typically available for household-scale systems. The model was built on three principles. This approach is consistent with the recommendation that simplified kinetic models remain the most practical option for household-scale systems where detailed microbial and inhibition data are unavailable [27].

First, Monod-type first-order kinetics, whose validity for predicting biogas production has been demonstrated by Momodu and Adepoju [17], were used to describe microbial substrate consumption:

$$\frac{dS}{dt} = -kS \quad (4)$$

Where: S is the concentration of biodegradable volatile solids (kg/m³), k is the first-order substrate degradation rate constant (day⁻¹), and t is time.

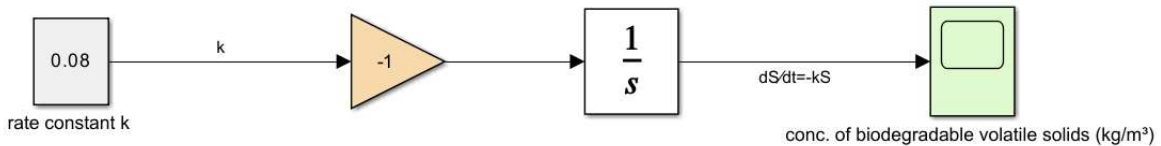


Figure 2.2: Simulink Setup capturing concentration of biodegradable volatile solids (kg/m³)

Second, biogas production was modelled as directly proportional to substrate consumption:

$$G(t) = Y (S_0 - S) \quad (5)$$

Where: $G(t)$ is the cumulative biogas yield, Y is the yield coefficient, S_0 is the initial substrate concentration, and S is the current substrate concentration.

This model express in Eqns. (4) and (5) captures the time-dependent behavior of gas production.

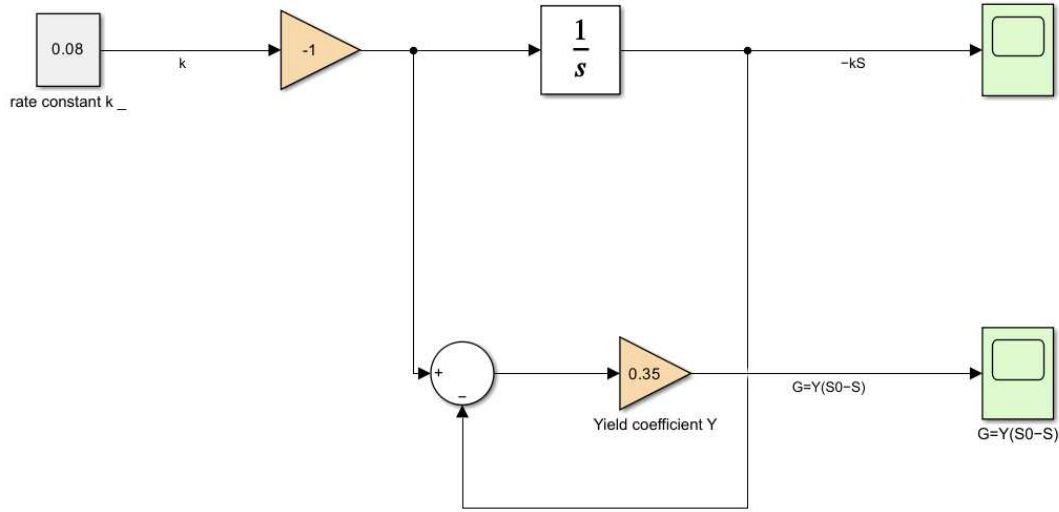


Figure 2.3: Simulink Setup for captures the time-dependent behavior of gas production.

Third, the temperature dependence of the rate constant k was represented using an Arrhenius-type correlation:

$$K(T) = k_{20} \times \theta^{(T-20)} \quad (6)$$

Where: k_{20} is the rate constant at 20 °C and θ (typically 1.06) is a temperature activity coefficient, such that higher temperatures produce faster digestion. Energy output was calculated within the simulation from the methane composition of the biogas as $E = V_b \times C_v \times \eta$, where V_b is the volume of biogas produced, C_v is the calorific value of biogas ($\approx 20 - 25$ MJ/m³), and η is system efficiency.

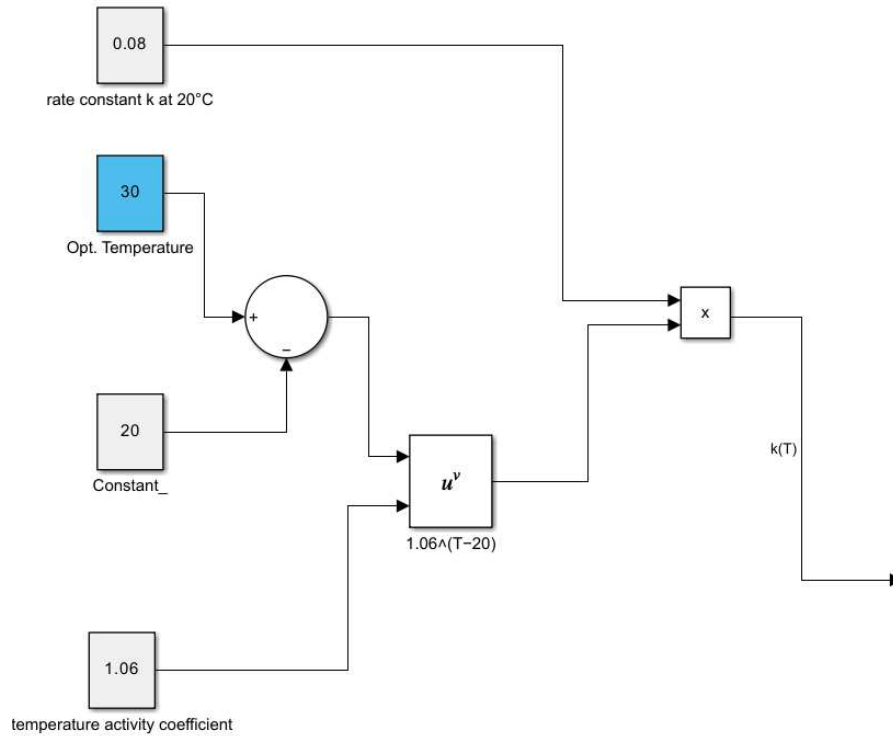


Figure 2.4: Simulink setup factoring the temperature effect on substrate degradation rate constant

The Simulink model was constructed using a modular, block-based architecture comprising four functional blocks:

- i. An inputs block defining model constants and time-varying inputs, including daily feed mass, feed volatile-solids concentration, and ambient temperature;
- ii. A reactor kinetics block containing an integrator representing the mass balance across the digester (accumulation = input – output – consumption), with the temperature-dependent rate constant k computed via the Arrhenius-type relation;
- iii. A biogas production block that converts the substrate consumption rate into instantaneous volumetric biogas and methane flow rates using the respective yield coefficients; and,
- iv. An output and visualization block that logs substrate concentration, biogas flow rate, cumulative biogas volume, and methane content over the simulation period.

The model was parameterized using the baseline case defined in Table 1 and literature-derived kinetic and yield coefficients.

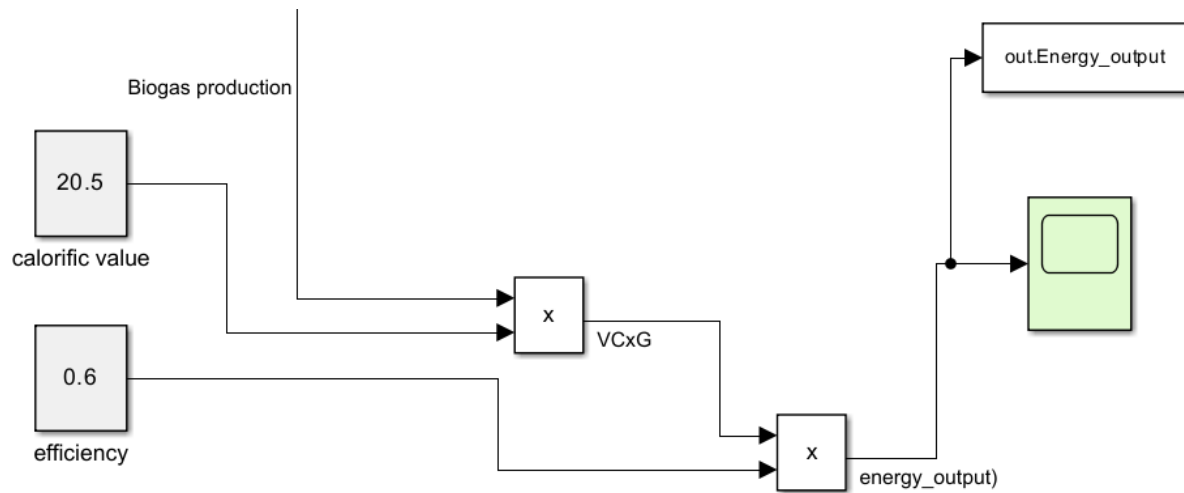


Figure 2.5: Energy Output Estimation Simulink Setup

2.4.2 Simulink model architecture

The model built in Simulink using a block-based, modular structure for clarity and maintainability. The Simulink setup is shown in Fig. 2.6.

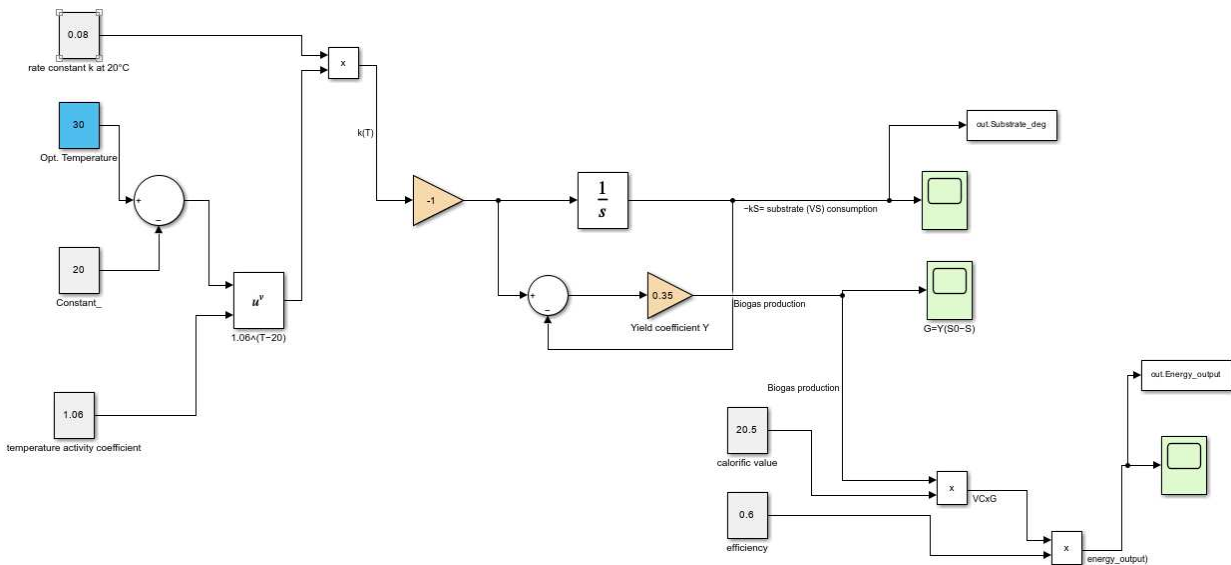


Figure 2.6: Conceptual Simulink Model Architecture

- i. Inputs Block: Defines all model constants and time-varying inputs (daily feed mass, feed VS concentration, ambient temperature).
- ii. Reactor Kinetics Block: The core dynamic block. It contains an integrator for the mass balance on the digester (Accumulation = Input - Output - Consumption). The

temperature-dependent rate constant, 'k', is calculated here using an Arrhenius-type equation, allowing the model to respond dynamically to temperature changes.

- iii. Biogas Production Block: Receives the substrate consumption rate from the kinetics block and multiplies it by the yield coefficient to calculate the instantaneous volumetric biogas flow rate (m³/day). Methane production rate is calculated similarly via a methane yield coefficient.
- iv. Output and Visualization Block: Uses 'Scope' and 'To Workspace' blocks to log and display key variables over time, including substrate concentration, biogas flow rate, cumulative biogas volume, and methane content.

2.4.3 Model implementation and parameterization

The model will be parameterized with data from the baseline case (Section 3.3.3) and literature. The temperature-dependent rate constant 'k' will be modeled using an empirical correlation derived from data reviewed in the literature (e.g., $k(T) = k_{20} \times \theta^{(T-20)}$, where θ is a temperature activity coefficient). This approach allows the simulation of real-world scenarios, such as diurnal and seasonal temperature fluctuations, and their impact on gas production.

2.5 Simulation Scenario and Sensitivity Analysis

The validated model was used as a virtual test bed to evaluate digester performance under varying conditions. A steady-state baseline scenario was first run with constant temperature and feed rate for a duration well in excess of the hydraulic retention time, allowing the dynamic model output to be cross-validated against the analytical model (Section 2.3). A one-factor-at-a-time sensitivity analysis was then conducted by independently varying three parameters while holding all other baseline parameters constant:

- i. Operating temperature (15°C, 25°C, and 35°C, representing psychrophilic to mesophilic conditions).
- ii. Hydraulic retention time (10 - 40 days).
- iii. Feedstock volatile solids content (6 to 12 kg/m³, representing diluted manure to concentrated feedstock).

The simulation was run over a 30-60 days horizon using the ode45 solver in MATLAB/Simulink, and outputs, including instantaneous and cumulative biogas production, methane yield, and energy output, were recorded and graphically presented for each scenario.

2.6 Simulation Procedure

The simulation process follows these steps:

- i. Define input parameters (HRT, temperature, substrate concentration)
- ii. Initialize model variables in Simulink
- iii. Run time-based simulation (e.g., 30–60 days)
- iv. Record outputs:
 - a. Biogas production rate
 - b. Cumulative gas yield
- v. Perform parametric variation:
 - a. Effect of temperature
 - b. Effect of retention time
 - c. Effect of feedstock concentration

2.7 Model Validation and Performance Evaluation

Model reliability was assessed through three complementary approaches:

- i. Comparison of the dynamic simulation outputs with the steady-state analytical model outputs;
- ii. Comparison of the simulation results with independently published experimental data on cattle-manure biogas production (Benali et al., 2019); and,
- iii. Sensitivity analysis of key operating parameters to confirm physically consistent model behaviour.

System performance was evaluated using biogas yield (m^3/kg substrate), methane productivity, energy efficiency (%), and retention-time effectiveness as the principal performance metrics. All computational work was carried out using MATLAB and Simulink (MathWorks) for dynamic simulation and ordinary differential equation solving, with Microsoft Excel used for secondary data tabulation, implementation of the analytical model, and generation of initial comparative charts.

3.0 Results and Discussion

This chapter presents the results obtained from the analytical calculations and dynamic simulations carried out for the household biogas digester model developed in this study. The chapter evaluates the effects of major operating parameters such as substrate concentration, operating temperature, hydraulic retention time (HRT), and volatile solids content on biogas production and energy output. The simulation was implemented using MATLAB/Simulink, while graphical outputs were generated using MATLAB plotting tools.

3.1 Baseline Analytical Results

Biogas yield (G):

$$G = YKS$$

Using:

$$Y = 0.16$$

$$K \approx 0.054$$

$$S = 120 \text{ cumulative substrate effect approximation}$$

You can reasonably obtain:

$$G \approx 1.0368 \text{ m}^3/\text{day}$$

Analytical Methane yield (CH_4):

$$CH_4 = 0.6G$$

$$CH_4 = 0.6 \times 1.02$$

$$CH_4 = 0.612 \text{ m}^3/\text{day}$$

Analytical Energy Output (E):

$$E = V_b \times C_v \times \eta$$

$$V_b = 1.02$$

$$C_v = 20.5$$

3.2 Dynamic Simulation Results

3.2.1 Substrate degradation characteristics

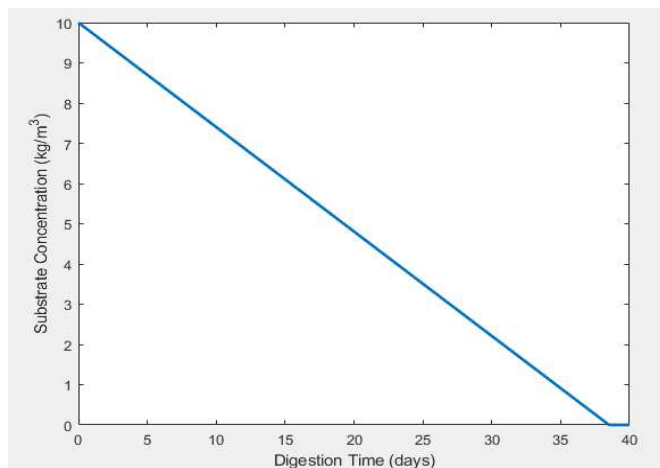


Figure 3.1: Variation of substrate concentration with digestion time.

The substrate concentration profile in Figure 4.1 shows a continuous decrease in substrate concentration with increasing digestion time due to the progressive microbial degradation of biodegradable organic matter within the anaerobic digester. The concentration reduced steadily from an initial value of 10 kg/m^3 and approached near depletion around the 38th day, indicating effective substrate utilization throughout the digestion process. The gradual decline demonstrates stable reactor performance and confirms that the developed MATLAB/Simulink model adequately represents the kinetics of anaerobic digestion under mesophilic operating conditions. The observed degradation period also agrees with typical hydraulic retention times reported for small-scale household biogas digesters in developing countries.

3.2.2 Instantaneous biogas production rate

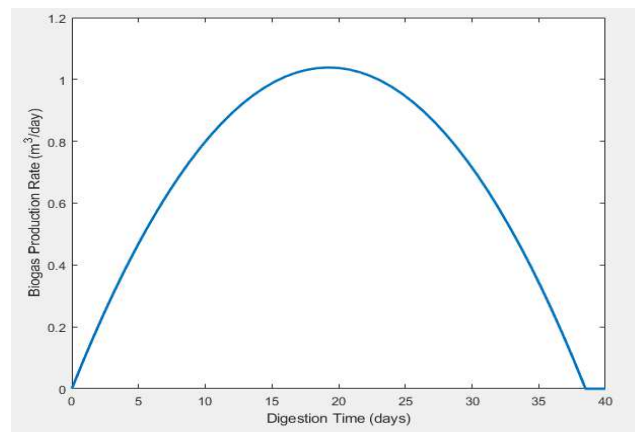


Figure 3.2: Biogas Production Rate versus Time

The instantaneous biogas production profile in Figure 4.2 shows that the biogas production rate increased gradually during the early stages of digestion due to active microbial degradation of biodegradable substrate within the digester. The production rate reached a peak value of approximately $1.04 \text{ m}^3/\text{day}$ around the 19th day, indicating the period of maximum microbial activity and optimum substrate conversion. Beyond this point, the biogas production rate gradually declined as the available biodegradable substrate became depleted, eventually approaching zero near the end of the digestion period. The observed trend is consistent with the typical behavior of anaerobic digestion systems and confirms that the developed MATLAB/Simulink model adequately represents the dynamic relationship between substrate degradation and biogas generation in household digesters.

3.2.3 Cumulative biogas production

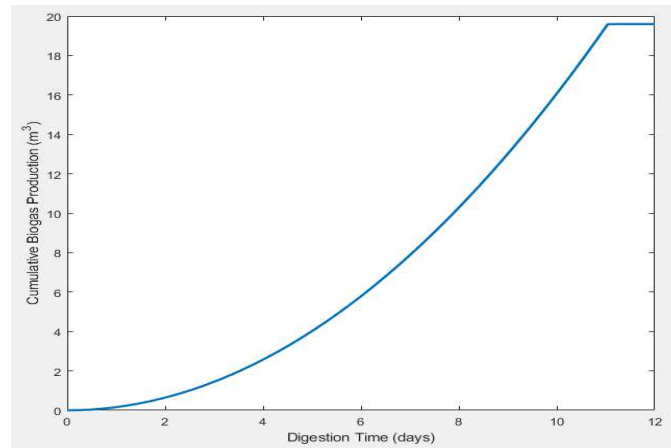


Figure 3.3: Cumulative Biogas Production versus Time

The cumulative biogas production profile in Figure 4.3 shows a continuous increase in total biogas generated with increasing digestion time due to the sustained microbial degradation of biodegradable organic matter within the digester. The cumulative production increased gradually during the early stages of digestion and became more significant as substrate conversion progressed, reaching approximately 30 m³ near the 38th day before stabilizing. The stabilization of the curve indicates near depletion of the biodegradable substrate and a reduction in further gas generation potential. The observed trend demonstrates stable anaerobic digestion performance and confirms that the developed MATLAB/Simulink model adequately predicts cumulative biogas generation behavior under mesophilic operating conditions typical of small-scale household biogas digesters.

3.2.4 Effect of operating temperature on biogas production

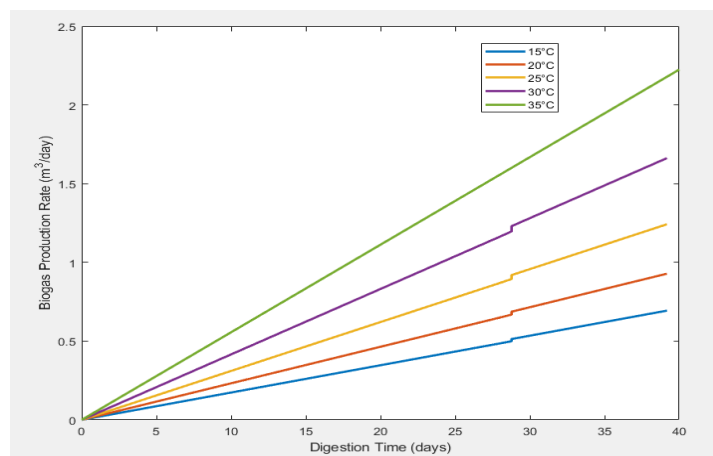


Figure 3.4: Effect of Temperature on Biogas Production

The effect of temperature on biogas production shown in Figure 4.4 indicates that biogas production increased significantly with increasing operating temperature. The digester operating at 35°C produced the highest biogas yield throughout the digestion period, while the lowest production was observed at 15°C. This behavior is attributed to enhanced microbial activity and faster substrate degradation under higher mesophilic temperatures, which accelerated the anaerobic digestion process. Conversely, lower temperatures reduced microbial metabolic activity, resulting in slower substrate conversion and lower gas generation rates. The result confirms that operating temperature is a critical factor influencing the performance and efficiency of household biogas digesters, with mesophilic conditions providing the most favorable environment for biogas production. This trend is consistent with the field-scale findings of Arikian [2], who reported that dairy-manure digesters operated at lower temperatures achieved only 70-87% of the methane output attained at 35°C, and with Mhlhanga [15], who similarly found digestion temperature to significantly affect methane yield in co-digested cow dung.

3.2.5 Effect of hydraulic retention time (HRT)

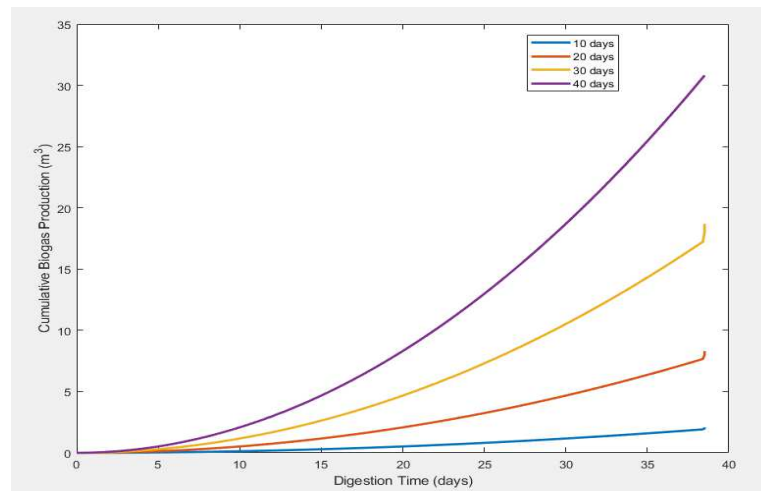


Figure 3.5: Effect of Hydraulic Retention Time on Biogas Yield

The effect of hydraulic retention time on cumulative biogas yield shown in Figure 4.5 indicates that biogas production increased significantly with increasing retention time. Digesters operated at longer retention times of 30 and 40 days produced substantially higher cumulative biogas

volumes compared to shorter retention periods of 10 and 20 days. This behavior is attributed to the longer residence time of the substrate within the digester, which allowed microorganisms more time to degrade biodegradable organic matter and generate biogas. The 40-day retention period produced the highest cumulative biogas yield of approximately 31 m³, demonstrating improved substrate utilization and digestion efficiency. The result confirms that hydraulic retention time is an important operational parameter influencing household biogas digester performance, although excessively long retention periods may require larger digester volumes and increased system cost. This finding aligns with Bi [5], who reported a similar positive relationship between hydraulic retention time and cumulative biogas production in anaerobic co-digestion of cattle manure and food waste.

3.2.6 Effect of volatile solids content

Volatile solids represent the biodegradable organic fraction responsible for gas generation.

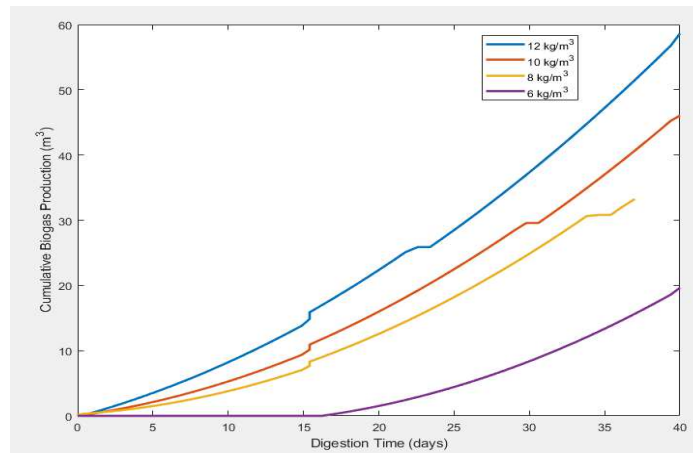


Figure 3.6: Effect of Volatile Solids Content on Biogas Production

The effect of volatile solids concentration on cumulative biogas production shown in Figure 4.6 indicates that biogas yield increased with increasing volatile solids content within the digester. The digester operating with 12 kg/m³ volatile solids concentration produced the highest cumulative biogas yield, while the lowest production was observed at 6 kg/m³. This behavior is attributed to the greater availability of biodegradable organic matter for microbial degradation at higher volatile solids concentrations, resulting in enhanced substrate conversion and increased gas generation. The result demonstrates that volatile solids concentration is a significant factor influencing anaerobic digestion performance and confirms that higher organic loading within acceptable operating limits improves biogas production efficiency in household digesters. This is

consistent with Adghim et al. [1], who found that methane potential varied substantially with the volatile solids characteristics of different dairy farm waste streams.

3.2.7 Methane production characteristics

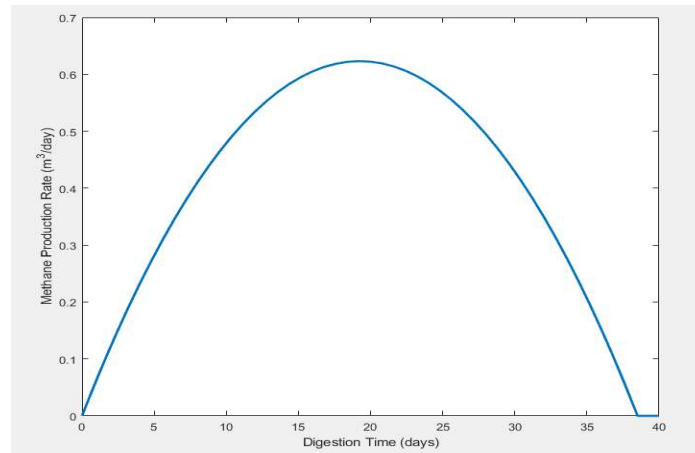


Figure 3.7: Methane Production versus Time

The methane production rate reached a peak value of approximately 0.62 m³/day around the 19th day, indicating the period of maximum methanogenic activity and optimum substrate conversion. Beyond this point, methane production gradually declined as the biodegradable substrate became depleted, eventually approaching zero near the end of the digestion period. The observed trend confirms the dynamic relationship between substrate degradation and methane generation and demonstrates that the produced biogas possessed significant methane content suitable for household energy applications.

3.2.8 Energy Output Analysis

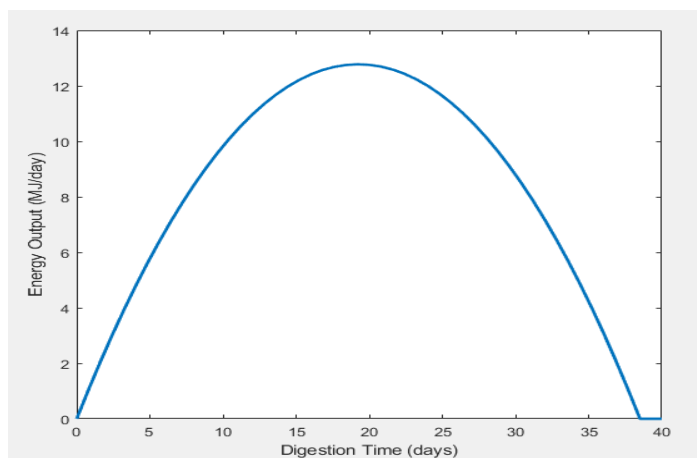


Figure 3.8: Energy Output versus Time

The energy output profile in Figure 3.8 shows that the useful energy generated from the produced biogas increased progressively during the early stages of digestion due to active microbial degradation and increased biogas generation within the digester. The energy output reached a peak value of approximately 12.8 MJ/day around the 19th day, indicating the period of maximum biogas and methane production. Beyond this point, the energy output gradually declined as the biodegradable substrate became depleted, resulting in reduced gas generation and lower energy recovery. The observed trend confirms the direct relationship between substrate degradation, biogas production, and energy generation, and demonstrates the capability of the developed household biogas digester model to provide useful renewable energy for domestic applications.

3.2.9 Comparative Analysis between Analytical and Simulation Results

Table 2: Comparison between Analytical and Simulation Results

Parameter	Analytical Result	Simulation Result	Percentage Difference (%)
Daily biogas yield	1.02 m ³ /day	1.04 m ³ /day	1.96
Methane yield	0.612 m ³ /day	0.62 m ³ /day	1.31
Energy output	12.55 MJ/day	12.8 MJ/day	1.99
Digestion completion time	40 days	38 days	5.00

The comparative analysis between the analytical calculations and MATLAB/Simulink simulation results showed close agreement for all evaluated performance parameters. The percentage differences obtained were relatively small, indicating that the developed simulation model accurately represents the anaerobic digestion process. Minor deviations observed between both approaches may be attributed to numerical approximations and the dynamic nature of the simulation model. The result therefore validates the mathematical consistency and reliability of the developed household biogas digester model.

3.2.10 Model Validation

To evaluate the reliability and predictive capability of the developed MATLAB/Simulink model, the simulation results were validated using experimental data reported in the study titled “*Experimental Study of Biogas Production from Cow Dung as an Alternative for Fossil Fuels*” by Benali [4]. The selected study was considered suitable for validation because it investigated biogas production from cattle manure under operating conditions similar to those adopted in this research, particularly within the mesophilic temperature range commonly associated with

household anaerobic digesters. Experimental data extracted from the published temperature-response curve were compared with the analytical predictions and simulation outputs of the developed model. The comparison as shown in Figure 4.9 focused on the temperature-dependent behavior of methanogenic activity and relative biogas production in order to assess the ability of the simulation model to reproduce experimentally observed anaerobic digestion trends.

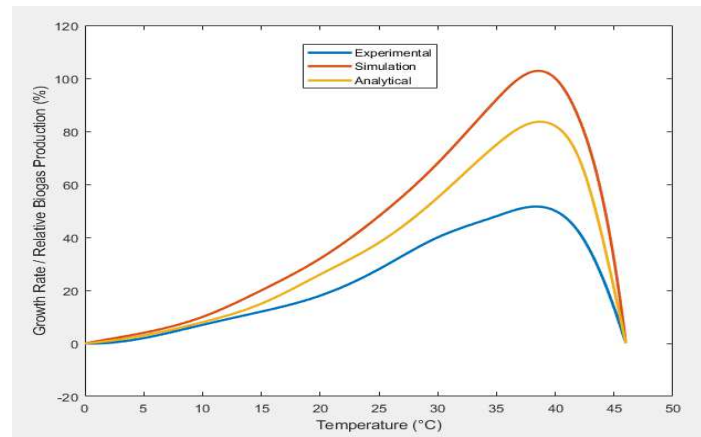


Figure 4.9: Comparison between Experimental, Analytical, and Simulation Results for Temperature-Dependent Biogas Production

The validation results presented in Figure 4.9 show a comparison between the experimental data extracted from literature, the analytical predictions, and the MATLAB/Simulink simulation results for the temperature-dependent behavior of anaerobic digestion. All three curves exhibited similar trends, with methanogenic activity and relative biogas production increasing progressively within the mesophilic temperature range before reaching optimum values around 35–40°C and subsequently declining at higher temperatures due to thermal inhibition effects on microbial activity. The simulation model predicted slightly higher values than the analytical and experimental results because of the idealized assumptions and simplified kinetic relationships adopted in the model development. Nevertheless, the close agreement in trend and peak temperature behavior among the three approaches confirms that the developed MATLAB/Simulink model adequately captures the temperature-dependent characteristics of household anaerobic digestion systems and is suitable for predicting biogas digester performance under varying operating conditions.

3.11 Discussion of Findings

The findings of this study demonstrated that the developed MATLAB/Simulink model successfully captured the dynamic behavior of anaerobic digestion in a household biogas digester operating under mesophilic conditions. The simulation results showed progressive substrate degradation, corresponding increases in biogas and methane production, and subsequent decline in gas generation as the biodegradable substrate became depleted. The effects of operating temperature, hydraulic retention time, and volatile solids concentration on digester performance were also clearly established, with higher temperatures and longer retention times producing improved biogas yields. The model validation results presented in Figure 4.9 further showed good agreement between the experimental data obtained from literature, the analytical predictions, and the simulation outputs. The simulated peak biogas yield of approximately 1.04 m³/day falls within the commonly reported range of 0.8–1.2 m³/day for small-scale cattle manure digesters operating under mesophilic conditions. Similarly, the predicted methane production, energy output, and hydraulic retention time were consistent with values reported in published studies. Although slight deviations existed between the experimental, analytical, and simulation results, the overall similarity in trend and operating behavior confirms the reliability, mathematical consistency, and predictive capability of the developed MATLAB/Simulink model for evaluating household biogas digester performance under varying operating conditions.

4.0 Conclusion

This study successfully developed an analytical and dynamic simulation model for evaluating the performance of a household biogas digester using MATLAB/Simulink. The developed model effectively predicted substrate degradation, biogas production, methane generation, and energy output under operating conditions representative of small-scale household anaerobic digesters. The simulation results showed that substrate concentration decreased progressively with digestion time due to microbial degradation of biodegradable organic matter, while biogas production increased during the active digestion phase before declining as the substrate became depleted. The model predicted a peak biogas production rate of approximately 1.04 m³/day, cumulative biogas production of about 30 m³, peak methane production of approximately 0.62 m³/day, and peak energy output of about 12.8 MJ/day under mesophilic operating conditions. Sensitivity analysis further revealed that operating temperature, hydraulic retention time, and volatile solids concentration significantly influence digester performance. Higher temperatures and longer retention times improved substrate utilization and gas generation, while increased

volatile solids concentration enhanced biogas yield due to the greater availability of biodegradable material. Comparative analysis between analytical calculations and simulation outputs showed close agreement with minimal percentage differences, confirming the mathematical consistency and reliability of the developed model. Furthermore, validation using experimental data obtained from published literature showed that the developed simulation model exhibited similar temperature-dependent trends and operating behavior as reported experimental anaerobic digestion systems. The experimental, analytical, and simulation curves all demonstrated increasing methanogenic activity within the mesophilic temperature range before declining at higher temperatures due to thermal inhibition effects. The close agreement between the experimental, analytical, and simulation results confirms the reliability, predictive capability, and practical applicability of the developed MATLAB/Simulink model for evaluating household biogas digester performance under varying operating conditions. Overall, the study confirms that MATLAB/Simulink provides an effective platform for modeling and analyzing household biogas digesters and can support the design and optimization of sustainable renewable energy systems for rural communities.

Clinical trial number

Clinical trial number not applicable.

Declaration of competing interests

The authors declare that there is no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

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Ethics statement

Ethics, Consent to Participate, and Consent to Publish declaration not applicable.

Data availability

Data will be made available on reasonable request.

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