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Research Article

Modeling and Analysis of Biogas Production from Cow Manure: Simulation Study Using SuperPro Designer and Performance Evaluation

Riski Gunawan Nasution[1,*], Ryoshi Meijisa Reigi Putra[1], Yoga Fernanda Syaputra[2], Khairul Akli[1], Dedy Rahmad[3]

[1]Department of Chemical Engineering, ATI Padang Polytechnic, Padang, Indonesia
[2]Department of Chemical Engineering, Bung Hatta University, Padang, Indonesia
[3]Phytochemistry Engineering, ATI Padang Polytechnic, Padang, Indonesia

Abstract

This study presents a steady-state simulation model for biogas production using cow manure as the feedstock, implemented in SuperPro Designer (Version 10). The main goal is to assess process performance under defined operating conditions: mesophilic temperature (37 ℃), pH 7, and a hydraulic retention time of 30 days. The manure composition on a dry basis was set as 18.0% protein, 24.0% fat, and 58.0% carbohydrates, mixed with water at a 1:1 ratio to produce 1000 kg/h of feed slurry (wet basis: 8.7% carbohydrates, 2.7% protein, 3.6% fat, and 85% water). The simulation includes thirteen stoichiometric biochemical reactions representing hydrolysis, acidogenesis, acetogenesis, and methanogenesis within a continuous anaerobic digester. Results show a biogas production rate of 25.42 kg/h, composed of methane (76.45%), carbon dioxide (22.19%), hydrogen sulfide (0.60%), and hydrogen (0.74%). The methane yield reached 0.388 Nm^3 CH_4 per kg of volatile solids added, with a volatile solids destruction rate of 45.2%. A sensitivity analysis identifies carbohydrate conversion as the most influential parameter on methane yield, which varies from 0.372 to 0.404 Nm^3/kg VS under a ±20% change. Comparisons with previous simulation studies confirm that the results are within acceptable ranges reported in the literature, supporting the model's usefulness as a conceptual design tool. This model provides a preliminary framework for designing biogas processes from bovine manure, while acknowledging that experimental validation, kinetic modeling, and uncertainty analysis are necessary before practical application.

Keywords

Biogas, Cow Manure, SuperPro Designer, Steady-State Simulation, Methane, Anaerobic Digestion, Mass Balance, Sensitivity Analysis

*Correspondence: Riski Gunawan Nasution (mhdriski200408@gmail.com)

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1. Introduction

Biogas, generated through the anaerobic decomposition of organic matter by microorganisms, consists primarily of methane (CH_4) and carbon dioxide (CO_2) [17]. Feedstocks with a methane content exceeding 50% possess considerable combustible energy value, making biogas a viable renewable energy carrier. The optimal carbon-to-nitrogen (C/N) ratio for efficient biogas production generally ranges from 20:1 to 40:1 [1].

As a renewable energy source, biogas offers a dual benefit: mitigating energy crises and addressing climate change. Cow manure is a particularly promising feedstock due to its widespread availability, high organic content, and the environmental co-benefits of its utilization. Conversion of cow manure to biogas simultaneously reduces environmental pollution and provides an alternative energy source for domestic, industrial, and power generation applications [1].

The biochemical process of biogas formation encompasses four sequential stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis[11]. Operational parameters—including temperature (optimally 37 ℃ for mesophilic conditions), neutral pH, hydraulic retention time (HRT of 30 days), and an appropriate C/N ratio—are critical determinants of process efficiency[18].

Direct experimentation to evaluate diverse operational scenarios is frequently costly and time-intensive. Computer simulation tools, such as SuperPro Designer, enable virtual modeling of biogas processes, parameter sensitivity testing, and result prediction as a prerequisite to experimental research. Such simulations can conserve resources and assist in identifying feasible operational ranges warranting further experimental investigation [2, 14].

SuperPro Designer has been applied across various biotechnological process modeling contexts, including biogas production[30]. Zhang et al. [34] demonstrated that simulation software can effectively analyze operational variables—including temperature, pH, and HRT—within the context of methane production. Nevertheless, validation of simulation outputs against experimental data remains necessary to confirm model accuracy.

Despite the considerable body of literature on biogas simulation, significant limitations persist in modeling approaches based on cow manure that comprehensively address local feedstock characteristics, element-balanced stoichiometry, and rigorous mass closure. Prior studies frequently neglect elemental consistency in reaction formulation or employ oversimplified conversion assumptions. This study addresses these gaps by developing a detailed, stoichiometrically consistent steady-state simulation model for biogas production from cow manure, emphasizing mass balance closure and sensitivity analysis.

The model is subsequently benchmarked against published literature to assess its internal consistency, with explicit acknowledgment that such benchmarking does not constitute experimental validation. It is anticipated that this simulation will serve as a conceptual foundation for further technical analysis, particularly in regions with high livestock farming potential. Practical implementation, however, would necessitate further experimental validation, economic analysis, and lifecycle assessment.

2. Materials and Methods

2.1. Feedstock Composition and Input Data

Cow manure was used as the primary feedstock in this simulation. The dry-basis composition—protein (18.0%), fat (24.0%), and carbohydrates (58.0%)—was derived from Chuenchart et al. [10]. For stoichiometric modeling and kinetic calculations, protein was represented as $C_5H_7NO_2$, fat as $C_{57}H_{104}O_6$, and carbohydrates as $C_6H_{10}O_5$.

Operational conditions were set to mesophilic temperature (37 ℃) at atmospheric pressure (1 atm) with an HRT of 30 days. The feed was a slurry at a 1:1 (manure: water) dilution ratio, with a base feed flow rate of 1000 kg/h. Modeling was executed using SuperPro Designer Version 10 [15], employing the NRTL thermodynamic method for the liquid phase and the Ideal Gas equation of state for the gas phase. All simulations were run under steady-state conditions.

2.2. Simulation Procedure

The simulation was conducted in several stages within SuperPro Designer. First, the process model was constructed by representing the biogas production flow using standard unit operations: a feed tank (liquid drum), a mixer, an anaerobic digester, and a centrifugal pump. All parameters defined in Section 2.1 were entered into the model. Steady-state simulation was executed to generate complete mass and energy balances. Results were then analyzed to identify the operational parameters most significantly influencing biogas yield and quality. Finally, the model was subjected to a consistency check against published simulation studies.

2.3. Mode of Operation

The simulation was configured in continuous (steady-state) mode, consistent with the operational characteristics of commercially-scale anaerobic digesters that operate continuously. In this mode, mass and energy flows are assumed to remain constant over time, obviating the need for scheduling calculations between unit operations. Continuous mode was selected at the project initialization stage within SuperPro Designer v10.

2.4. Component Definition

Chemical components involved in the process were defined in SuperPro Designer as either pure components or stock mixtures. The built-in database (v10) provides an extensive library; however, specific compounds required for modeling cow manure degradation—such as Cystine as a protein hydrolysis proxy—were not available in the standard database. These components were therefore added manually as pure components, with physical and chemical properties (molecular formula, molecular weight, density, boiling point) defined from authoritative literature sources (PubChem, SciFinder).

The cow manure feed was represented as a custom stock mixture with composition derived from Chuenchart et al. [10], as detailed in Table 1.

Table 1. *Dry-Basis Composition of Cow Manure as Stock Mixture Input.*

Component	Percentage (Dry Basis)	Chemical Formula (Simulation)
Protein	18.0%	$C_5H_7NO_2$
Fat	24.0%	$C_{57}H_{104}O_6$
Carbohydrate	58.0%	$C_6H_{10}O_5$
Total	100.0%	—

Source: Chuenchart et al [10].

2.5. Unit Operations

Table 2. *Unit Operations Used in the Simulation.*

Equipment Name	Code	Function
Anaerobic Digester	AD-101	Main reactor for anaerobic reactions (13 stoichiometric reactions)
Mixer	MX-101	Blends cow manure with water at 1:1 ratio
Feed Tank (Liquid Drum)	LD-101	Stores feed slurry and pre-heats to 37 ℃
Centrifugal Pump	PM-101	Transfers slurry from feed tank to anaerobic reactor

2.6. Stoichiometric Reaction Network

The anaerobic digestion process was modeled using 13 stoichiometric reactions representing the four degradation stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Reactions were formulated based on Wahyudi & Jelita [33] with mass coefficients verified for elemental balance closure, as detailed in Table 3.

Table 3. *Anaerobic Digestion Reactions with Mass Coefficients.*

No.	Reaction Stage	Reactant	Mass Coef.	Product	Mass Coef.
1	Carbohydrate Hydrolysis	Carbohydrates + Water	147.6	Glucose	295.2
2	Fat Hydrolysis	Fats	147.6	Glycerol + Oleic Acid	36.85 / 110.75
3	Protein Hydrolysis	Protein	147.6	Cystine	147.6
4	Cystine Acidogenesis	Cystine	164.16	Lactic Acid + Propionic Acid	90.08 / 74.08
5	Oleic Acid Acidogenesis	Oleic Acid	194.2	Acetic + Butyric + Ethanol	60.04 / 88.11 /

No.	Reaction Stage	Reactant	Mass Coef.	Product	Mass Coef.
					46.05
6	Glucose Acidogenesis	Glucose	106.12	Acetic Acid + Ethanol	60.05 / 46.07
7	Glycerol Acidogenesis	Glycerol	74.08	Propionic Acid	74.08
8	Ethanol Acetogenesis	Ethyl Alcohol	62.07	Acetic Acid + Hydrogen	60.05 / 2.02
9	Lactic Acid Acetogenesis	Lactic Acid	90.08	Acetic Acid + CO_2 + H_2	60.05 / 28.01 / 2.02
10	Butyric Acid Acetogenesis	Butyric Acid	88.11	Acetic Acid + CO_2	60.05 / 28.05
11	Propionic Acid Acetogenesis	Propionic Acid	74.08	Acetic Acid + CO_2 + H_2	60.05 / 12.01 / 2.02
12	Acetic Acid Methanogenesis	Acetic Acid	60.05	CO_2 + Methane	30.00 / 30.05
13	CO_2 Methanogenesis	CO_2 + H_2	44.01 / 2.11	Methane + Water	28.01 / 18.02

Source: Wahyudi & Jelita [33]

2.7. Assumptions and Model Limitations

This simulation was constructed on several foundational assumptions. First, the process operates under steady-state conditions, implying no time-dependent parameter variation. Second, anaerobic biochemical reactions are modeled using stoichiometric approaches with fixed conversion rates based on literature data, thereby abstracting actual reaction kinetics and microbial community dynamics.

Third, the solubility of gas-phase components (CO_2, H_2S, CH_4) in the liquid phase was estimated using empirical coefficients rather than rigorous thermodynamic equilibrium models. Fourth, inhibitory mechanisms—such as those induced by ammonia accumulation, volatile fatty acids (VFAs), or heavy metal concentrations—were not incorporated. Fifth, feedstock composition was assumed constant and homogeneous, excluding natural variability observed in real substrates.

These assumptions imply that the model functions primarily as a conceptual estimation and comparative tool, providing general trends and order-of-magnitude process descriptions, rather than a predictive simulator for real operational conditions.

3. Results

Biogas formation in the anaerobic reactor results from a series of complex biochemical processes performed by microorganisms under anoxic conditions. The process flow diagram for the simulation is schematically described as follows: cow manure feedstock (carbohydrates, proteins, fats, and water at wet-basis proportions of 8.7%, 2.7%, 3.6%, and 85%, respectively) is first mixed with water in a 1:1 ratio through the mixer (MX-101). The resulting slurry is preheated to 37 ℃ in the feed tank (LD-101) and pumped into the anaerobic digester (AD-101), which operates under mesophilic conditions (37 ℃, 1 atm). The digester processes 13 reactions and produces two output streams: an overhead gas stream (biogas) and a bottom liquid stream (digestate), the latter of which may be further valorized as a soil amendment or fertilizing product [24].

The Methanobacterium species responsible for methanogenesis develop optimally at mesophilic temperatures, making 37 ℃ a critical operational parameter for efficient methane production [6].

The complete mass balance for base-case operating conditions is presented in Table 4.

Table 4*. Complete Mass Balance for Base-Case Operating Conditions.*

Stream	Component	Flow Rate (kg/h)	Mass Fraction	Note
Input	Cow Manure	500	0.500	—
	Water	500	0.500	—
	Total Input	1000	1.000	—
Biogas Output	Methane (CH_4)	19.43	0.7645	76.45%
	Carbon Dioxide (CO_2)	5.64	0.2219	22.19%

Stream	Component	Flow Rate (kg/h)	Mass Fraction	Note
	Hydrogen Sulfide (H_2S)	0.15	0.0060	0.60%
	Hydrogen (H_2)	0.19	0.0074	0.74%
	Total Biogas	25.42	0.0254 (of feed)	—
Digestate Output	Water	920.15	0.9443	—
	Solids	54.43	0.0557	—
	Total Digestate	974.58	0.9746 (of feed)	—

The mass balance demonstrates closure: 1000 kg/h feed produces 25.42 kg/h biogas and 974.58 kg/h digestate, totaling 1000 kg/h. The feed slurry consists of cow manure and water at a 1:1 ratio, yielding an organic content of 1.35% protein, 1.8% fat, 4.35% carbohydrates, and 92.5% water on a wet basis.

Key performance metrics derived from the simulation:

***Table 5**. Methane Performance.*

Performance Metric	Value
Methane Yield	0.388 Nm^3 CH_4/kg VS added
VS Destruction Rate	45.2%
Biogas Production Rate	0.508 Nm^3/kg VS added
Methane Content in Biogas	76.45% (mass basis)
H_2S Content	0.60% (requires desulfurization unit)

Simulation results indicate that methane (CH_4) dominates biogas composition at 76.45%, followed by carbon dioxide (22.19%), hydrogen sulfide (0.60%), and hydrogen (0.74%). The methane yield of 0.388 Nm^3/kg VS falls within the expected range for mesophilic anaerobic digestion of cow manure. A methane content exceeding 70% theoretically approaches specifications for energy applications; however, the 0.60% H_2S content underscores the necessity of a desulfurization unit in any practical system, given H_2S's corrosive nature and environmental toxicity.

The VS destruction rate of 45.2% indicates that approximately half of the volatile solids in the feed are converted to biogas, with the remainder retained in the digestate. This conversion rate is consistent with the characteristics of cow manure, which contains lignocellulosic fractions that are resistant to biological degradation under standard mesophilic conditions [7].

4. Discussion

The simulation results provide several insights when interpreted against the broader anaerobic digestion literature. The methane content obtained (76.45% by mass) lies at the upper end of the range typically reported for mesophilic digestion of livestock manure, which commonly falls between 50% and 70% CH_4 [16, 32]. This relatively high methane fraction can be attributed to the carbohydrate-rich composition assumed for the feedstock and to the fixed stoichiometric conversion efficiencies applied in the reaction network, which do not account for the partial hydrolysis and incomplete conversion typically observed under real operating conditions. The result should therefore be interpreted as an upper-bound conceptual estimate rather than a value expected to be reproduced exactly in a physical digester.

When compared with prior SuperPro Designer-based studies, the methane yield of 0.388 Nm^3 CH_4/kg VS obtained in this work is broadly consistent with the value reported by Harun et al. [12] for food waste digestion and with the process optimization results of Zhang et al. [34] for agricultural waste, both of which report yields in the 0.3–0.45 Nm^3/kg VS range typical of mesophilic systems[25]. This agreement supports the internal consistency of the stoichiometric framework developed in this study; however, food waste and general agricultural waste differ substantially from cow manure in fiber content and biodegradability, so the comparison should be regarded as a plausibility check rather than a validation of predictive accuracy for manure-specific systems.

The moderate volatile solids (VS) destruction rate of 45.2% reinforces this interpretation. Cow manure contains substantial lignocellulosic fractions—cellulose, hemicellulose, and lignin—that resist microbial hydrolysis under standard mesophilic conditions [23, 26]. Because the present model applies fixed conversion coefficients rather than kinetic expressions that explicitly capture hydrolysis rate limitations, the simulated VS destruction may not fully reflect the retention-time-dependent behavior observed experimentally, where destruction efficiency often plateaus well before the nominal 30-day HRT is reached.

The sensitivity analysis identifying carbohydrate conversion as the most influential parameter on methane yield is consistent with findings from other stoichiometric and kinetic anaerobic digestion models, in which carbohydrate fractions typically hydrolyze fastest and contribute disproportionately to biogas generation [21]. This finding carries a direct practical implication: pretreatment strategies aimed at enhancing carbohydrate accessibility, such as mechanical or thermal pretreatment[20, 29], are likely to yield a greater improvement in methane production than equivalent efforts targeting protein or fat degradation, a pattern also reported by Alkhraisat [4] and by Negahban et al. [27] in organic-loading and feeding-rate studies on cow manure digestion.

The hydrogen sulfide content of 0.60%, while numerically small, carries disproportionate practical significance because H_2S is corrosive to metal equipment and toxic to microorganisms and personnel at elevated concentrations. This finding aligns with the broader literature on biogas desulfurization, which consistently identifies H_2S removal as a necessary downstream unit operation regardless of the digester substrate [9]. Coupling the present model with a biological or chemical desulfurization step, as discussed by Amrouche et al. [5] for agricultural biogas systems, would therefore be a logical extension for any subsequent techno-economic evaluation of this process.

From a modeling perspective, the steady-state, fixed-stoichiometry approach adopted here trades predictive fidelity for computational simplicity and interpretability. More advanced frameworks, such as the Anaerobic Digestion Model No. 1 (ADM1) and its various modifications, explicitly incorporate microbial growth kinetics, inhibition terms, and dynamic mass transfer, and are generally considered more representative of transient reactor behavior [3, 13]. The present model should accordingly be regarded as a conceptual, first-order design tool suitable for preliminary mass balance estimation and parameter screening, rather than as a substitute for kinetic or dynamic simulation when detailed process control or scale-up decisions are required.

Benchmarking against Wahyudi and Jelita [33], from whom the stoichiometric reaction network was adapted, and against the independent SuperPro Designer studies discussed above, indicates that the present results are internally consistent and fall within literature-reported ranges. This consistency, however, reflects agreement in modeling assumptions and stoichiometric structure rather than agreement with the experimentally measured performance of an operating digester, and it should not be interpreted as experimental validation.

Future work building on this model should prioritize three directions. First, experimental validation using locally sourced cow manure under controlled laboratory- or pilot-scale conditions would allow the fixed conversion coefficients to be calibrated against measured data. Second, replacing the stoichiometric reaction network with a kinetic or ADM1-based formulation would enable the model to capture time-dependent behavior, inhibition effects, and the influence of operational upsets. Third, integrating the mass balance results with techno-economic analysis and life cycle assessment, as demonstrated for related manure-based digestion systems [31, 19], would extend the present conceptual framework toward a decision-support tool capable of informing investment and design choices for biogas facilities in livestock-intensive regions.

5. Conclusions

This steady-state simulation study successfully developed a conceptual model for biogas production from cow manure using SuperPro Designer, incorporating a stoichiometrically consistent 13-reaction anaerobic digestion network. The primary conclusions are as follows:

The simulation produced a biogas composition of 76.45% CH_4, 22.19% CO_2, 0.60% H_2S, and 0.74% H_2 under base-case operating conditions (37 ℃, pH 7, HRT 30 days, 1:1 dilution). A methane yield of 0.388 Nm^3 CH_4/kg VS and a VS destruction rate of 45.2% were obtained. Sensitivity analysis identified carbohydrate conversion as the most critical model parameter.

Consistency checks against Harun et al. [12] and Wahyudi & Jelita [33] confirm that simulation outputs fall within acceptable ranges relative to comparable studies, supporting the model's conceptual validity. However, differences in substrate type, temperature, and model assumptions preclude direct quantitative comparison or claims of model superiority.

The primary contribution of this work is a mass-balanced, sensitivity-analyzed conceptual simulation framework for preliminary biogas process design from cow manure. The model identifies carbohydrate conversion and H_2S content as critical parameters warranting attention in both experimental and engineering design phases.

Key limitations include the steady-state assumption, fixed stoichiometric conversion rates, and the absence of inhibitory mechanisms. Practical application requires rigorous experimental validation using actual feedstocks, dynamic or semi-mechanistic modeling, and integration with techno-economic analysis (TEA) and lifecycle assessment (LCA). Future research should also focus on validating the model with laboratory-scale digesters using local cow manure, incorporating pre-treatment effect modeling, and extending the framework to co-digestion scenarios[8, 22, 28].

Abbreviations

CH_4	Methane
CO_2	Carbon Dioxide
H_2S	Hydrogen Sulfide
H_2	Hydrogen
HRT	Hydraulic Retention Time
VS	Volatile Solids
OLR	Organic Loading Rate
C/N	Carbon-to-Nitrogen Ratio
VFA	Volatile Fatty Acids
TEA	Techno-Economic Analysis
LCA	Life Cycle Assessment
NRTL	Non-Random Two-Liquid (thermodynamic model)
NFE	Nitrogen-Free Extract

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Author Contributions

Riski Gunawan Nasution: Conceptualization, Formal Analysis, Methodology, Conceptualization, Resources

Yoga Fernanda Syaputra: Data curation, Investigation, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Riski Gunawan Nasution is a student at the Department of Chemical Engineering, Renewable Energy Bioprocess Engineering Technology, Politeknik ATI Padang, Padang 25171, Indonesia. His research interests include renewable energy systems, biogas process engineering, process simulation, and anaerobic digestion technology.