Biogas Plant Optimization: Gas Composition-Energy Relationship and Sustainable Practices

Arjin Ata[1*], Seyhmus Tumur[1], and Angsana Chuporn[3]

[1] Department of Civil Engineering, Dicle University, Diyarbakir, Turkey; arjinata@gmail.com
[3] Kyung Hee University, Korea; jaey3030@gmail.com

Abstract. The optimization of biogas production facilities represents a critical component in advancing sustainable energy strategies globally. This study investigates the relationships between biogas composition and electricity generation through comprehensive analysis of 10 months of operational data (August 2023 - June 2024) from a full-scale biogas plant. Data encompassing hourly measurements of methane (CH_4), carbon dioxide (CO_2), and oxygen (O_2) concentrations, alongside active energy generation values, were systematically analyzed. Monthly averages revealed CH_4 concentrations ranging from 44.20% to 54.45%, CO_2 from 33.49% to 38.34%, and power output from 3.25 to 5.30 MW. Statistical analysis demonstrated weak correlations between gas composition and electrical output ($r = -0.15$ for CH_4, $p > 0.05$), suggesting that operational parameters significantly influence performance beyond compositional factors. Descriptive statistics indicated mean CH_4 concentration of 48.12 ± 2.85%, CO_2 of 35.34 ± 1.43%, and average power generation of 4.43 ± 0.79 MW. This study proposes eight evidence-based optimization strategies encompassing substrate management, process monitoring, additive integration, emission control, and advanced technologies, with potential to increase energy efficiency by 10-30%. The findings underscore the necessity of holistic operational optimization rather than sole reliance on gas composition for enhancing biogas plant performance and advancing bioenergy sustainability objectives.

Keywords: Biogas Optimization, Methane Production, Power Production and Process

1 Introduction

Global energy transition towards renewable sources has positioned biogas production as a cornerstone technology for sustainable development and circular economy implementation. Biogas, generated through anaerobic digestion of organic matter, typically comprises 50-70% methane (CH_4), 30-50% carbon dioxide (CO_2), and trace amounts of other gases including oxygen (O_2), hydrogen sulfide (H_2S), and nitrogen. The calorific value of biogas directly correlates with methane concentration, making compositional optimization critical for energy efficiency in combined heat and power (CHP) systems [1-6].

R. Rzayev et al. (eds.), *Proceedings of the International Conference on Current Problems in Engineering and Applied Sciences (ICCPEAS 2025)*, Advances in Engineering Research 299,
https://doi.org/10.2991/978-94-6239-668-5_57

The anaerobic digestion process involves four sequential biological phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each phase requires specific microbial populations and environmental conditions, with methanogenesis representing the rate-limiting step for methane production. Process efficiency depends on multiple interacting parameters including temperature, pH, hydraulic retention time (HRT), organic loading rate (OLR), and carbon-to-nitrogen (C:N) ratio [6-9].

Despite extensive theoretical understanding, the translation of compositional relationships into operational performance remains challenging in full-scale facilities. This study addresses this gap by analyzing real operational data from a biogas plant to examine the practical relationships between gas composition and electricity generation, while proposing evidence-based optimization strategies grounded in both empirical data and contemporary literature [10-14].

The research objectives are threefold: (1) to quantify the statistical relationships between biogas composition parameters and electrical output, (2) to identify operational factors influencing plant performance, and (3) to develop comprehensive optimization recommendations based on integration of empirical findings and global best practices.

2 Materials and Methods

2.1 Study Site and Data Collection

This study analyzed operational data from a full-scale biogas plant equipped with combined heat and power generation systems. The facility operates under mesophilic conditions with continuous feeding systems. Data collection spanned 10 months from August 2023 to June 2024, excluding November 2023 due to data availability constraints.

2.2 Data Acquisition and Parameters

Hourly measurements were obtained from fixed gas analyzers monitoring CH_4, CO_2, and O_2 concentrations (reported in percentage). Active electrical energy generation was recorded from meter readings in megawatt-hours (MWh). For each month, 22-24 hourly readings were collected and processed.

2.3 Data Processing and Statistical Analysis

Monthly averages were calculated for all parameters. Power output normalization was performed using the formula:

$$\text{Average Power (MW)} = \frac{\text{Total Energy (MWh)}}{\text{Days} \times 24}$$

Statistical analyses included:

- Descriptive statistics (mean, standard deviation, minimum, maximum, range)

- Pearson correlation coefficients between gas concentrations and power output
- Linear regression modeling to assess predictive relationships
- Significance testing with $\alpha = 0.05$ threshold

All analyses were performed using Python statistical libraries including NumPy, Pandas, and SciPy.

2.4 Literature Review Methodology

A comprehensive literature review was conducted to identify optimization strategies and best practices. Search terms included "biogas optimization," "methane production enhancement," "anaerobic digestion parameters," "HRT biogas," "OLR biogas," and "C:N ratio optimization." Sources encompassed peer-reviewed journals, technical reports, and international energy agency publications [15-17].

3 Results

3.1 Gas Composition Trends

Monthly average gas composition exhibited temporal variations throughout the study period. Table 1 presents the complete monthly dataset for all measured parameters.

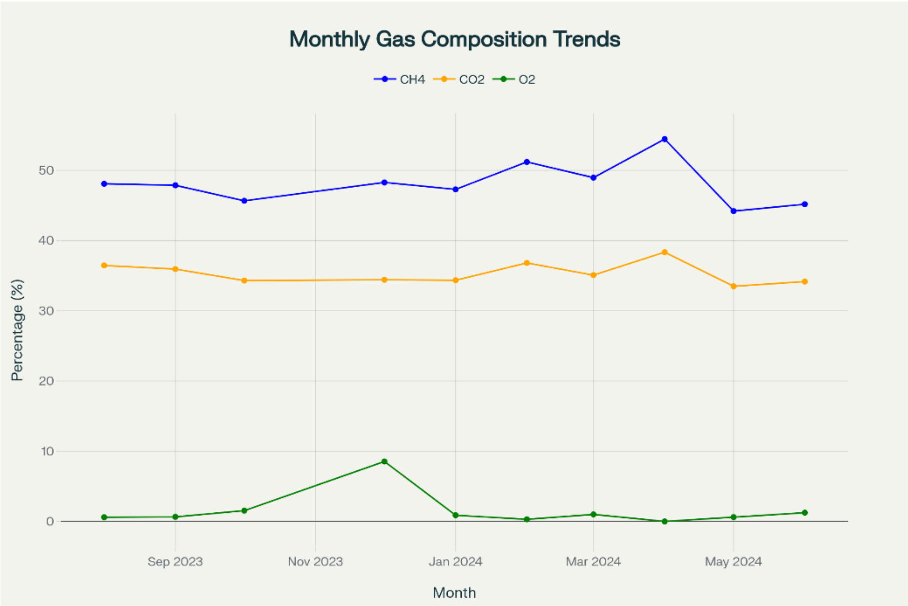

Fig. 1. Monthly gas composition trends

Table 1. Monthly average gas composition and power generation

Month	CH_4 (%)	CO_2 (%)	O_2 (%)	Power (MW)
2023-08	48.08	36.46	0.61	3.65
2023-09	47.87	35.94	0.67	3.25
2023-10	45.67	34.31	1.55	3.80
2023-12	48.28	34.42	8.55	3.60
2024-01	47.29	34.35	0.90	5.00
2024-02	51.19	36.81	0.32	5.30
2024-03	48.96	35.08	1.02	5.30
2024-04	54.45	38.34	0.01	4.00
2024-05	44.20	33.49	0.63	5.20
2024-06	45.18	34.16	1.26	5.20

Methane concentration peaked in April 2024 (54.45%) and reached its minimum in May 2024 (44.20%), representing a 10.25 percentage point range. Carbon dioxide levels fluctuated between 33.49% and 38.34%, with lower variability compared to methane. Notably, oxygen concentration in December 2023 exhibited an anomalous spike to 8.55%, indicating potential aerobic intrusion during that period.

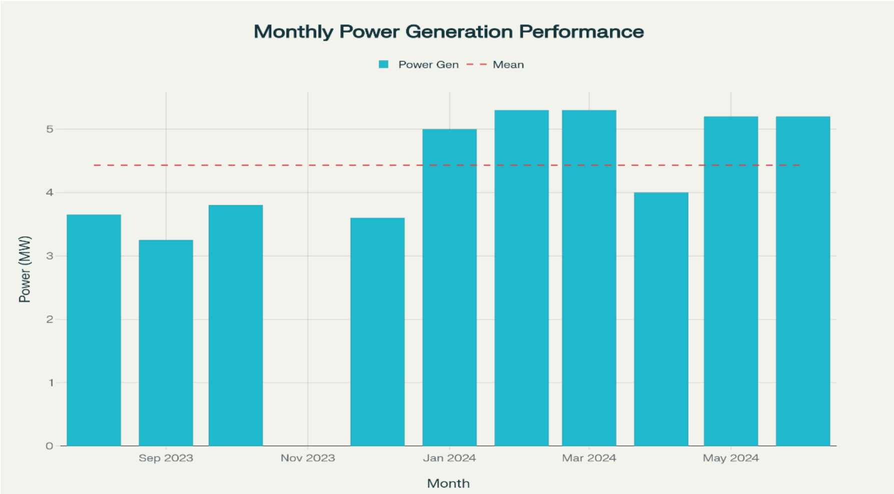

Fig. 2. Monthly electrical power generation

3.2 Descriptive Statistics

Comprehensive descriptive statistics for all measured parameters are presented in Table 2.

Table 2: Descriptive statistics of measured parameters

Parameter	**Unit**	**Mean**	**Std Dev**	**Min**	**Max**	**Range**
Methane (CH_4)	%	48.12	2.85	44.20	54.45	10.25
Carbon Dioxide (CO_2)	%	35.34	1.43	33.49	38.34	4.85
Oxygen (O_2)	%	1.55	2.37	0.01	8.55	8.54
Power Output	MW	4.43	0.79	3.25	5.30	2.05

The mean methane concentration (48.12%) fell below the typical range reported in literature (50-70%), suggesting potential for optimization. The high standard deviation for oxygen (2.37%) relative to its mean (1.55%) indicates substantial variability, likely attributable to the December 2023 anomaly.

3.3 Statistical Relationships

Correlation analysis between gas composition parameters and power generation revealed weak to negligible relationships, as detailed in Table 3.

Table 3. Statistical analysis of gas-power relationships

Parameter	**Correlation (r)**	**P-value**	**R^2**	**Regression Equation**
CH_4	-0.1479	0.6834	0.0219	Power = -0.0412×CH_4 + 6.4136
CO_2	-0.2896	0.4170	0.0839	Power = -0.1603×CO_2 + 10.0963
O_2	-0.3304	0.3512	0.1091	Power = -0.1106×O_2 + 4.6015

All correlations failed to achieve statistical significance ($p > 0.05$), with R^2 values ranging from 0.0219 to 0.1091. The negative correlation coefficients, while weak, suggest that periods of higher gas concentrations did not necessarily coincide with increased power output. This counterintuitive finding indicates that operational factors beyond gas composition exert dominant influence on energy generation efficiency.

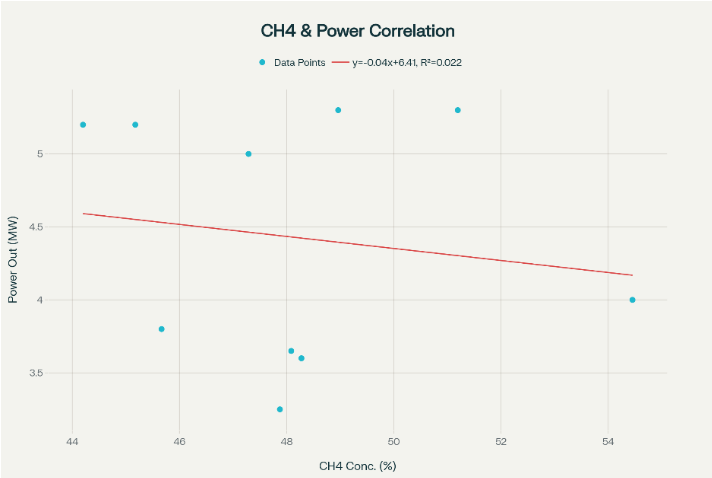

Fig. 3. Corelation between CH_4 and Power

3.4 Temporal Patterns

Analysis of monthly trends revealed distinct operational phases. The initial phase (August-December 2023) exhibited relatively stable but lower power output (3.25-3.80 MW), despite moderate methane concentrations. The second phase (January-June 2024) demonstrated enhanced power generation capacity (4.00-5.30 MW), suggesting possible operational improvements or system modifications during this period.

The April 2024 data point merits particular attention, displaying the highest methane concentration (54.45%) but intermediate power output (4.00 MW). This discrepancy reinforces the conclusion that compositional optimization alone cannot guarantee proportional energy gains without concurrent operational optimization.

4 Discussion

4.1 Interpretation of Gas-Power Relationships

The weak statistical relationships observed in this study contrast with theoretical expectations of strong positive correlations between methane concentration and energy output. This disparity can be attributed to several operational factors that modulate the theoretical composition-energy relationship:

Power generation depends not only on methane concentration but also on total biogas volume flow rate. A high CH_4 percentage in low-volume biogas yields less energy than moderate CH_4 concentration in high-volume production. The absence of volumetric flow data in this study represents a limitation that may explain the weak correlations observed.

Combined heat and power unit operational efficiency varies with load conditions, maintenance status, and ambient temperature. Suboptimal CHP performance can suppress energy output even when biogas quality is excellent, decoupling the composition-generation relationship.
System downtime for maintenance, feeding disruptions, or process instabilities reduces effective operational hours, thereby diminishing monthly average power output independent of gas composition.

4.2 Oxygen Intrusion and Aerobic Inhibition

The December 2023 oxygen spike (8.55%) represents a critical operational concern. Oxygen presence in biogas systems indicates aerobic intrusion, which inhibits methanogenesis through several mechanisms:

- Direct toxicity to obligate anaerobic methanogens
- Competition from aerobic microorganisms for substrate
- Oxidation of intermediate compounds essential for methanogenesis
- Reduced methane partial pressure affecting thermodynamic favorability

Literature reports that oxygen intrusion can decrease methane production by 10-20% under suboptimal conditions. Addressing this through improved sealing and storage systems represents a priority optimization target.

4.3 Benchmark Comparison

Comparing the observed mean CH_4 concentration (48.12%) with literature benchmarks (50-70%) reveals a 2-22 percentage point deficit. This gap represents significant optimization potential. Studies have demonstrated that strategic interventions can increase methane content by 10-15%, translating to proportional energy gains when volumetric constraints are addressed.

4.4 Optimization Strategies

Based on empirical findings and literature synthesis, eight evidence-based optimization strategies are proposed:
The carbon-to-nitrogen ratio fundamentally influences microbial metabolism and methane yield. Optimal C:N ratios range from 20:1 to 30:1, supporting balanced microbial growth without nitrogen limitation or ammonia inhibition. Implementation strategies include:

- Feedstock characterization and blending to achieve target C:N ratio of 25:1
- Co-digestion of complementary substrates (e.g., high-carbon agricultural residues with nitrogen-rich food waste)
- Regular monitoring and adjustment based on process performance indicators

Potential impact: 10-15% increase in methane production.

Real-time monitoring of critical parameters enables proactive intervention before process upsets occur:

- **pH Control:** Maintain 6.5-7.2 range to support methanogen activity and prevent volatile fatty acid accumulation
- **Temperature Management:** Stabilize at 35-40°C (mesophilic) or 50-55°C (thermophilic) depending on system design
- **Automated Control Systems:** Deploy sensors and feedback loops for continuous optimization

Potential impact: 15-20% efficiency gain through reduced process variability.

HRT represents the average duration substrate remains in the digester, directly affecting degradation completeness. Optimal HRT balances throughput with conversion efficiency:

- **Typical Range:** 30-50 days for lignocellulosic substrates, 15-30 days for readily degradable materials
- **Adjustment Strategy:** Gradual HRT modification with continuous performance monitoring
- **System-Specific Optimization:** Empirical determination through controlled trials

Studies demonstrate biogas production increases from 46.8 to 89.1 mL/g total solids when HRT extends from 20 to 60 days for wheat straw digestion. However, excessively long HRT reduces volumetric productivity, necessitating site-specific optimization.

Potential impact: 15-25% stability improvement and yield enhancement.

OLR defines the quantity of volatile solids fed per unit reactor volume per day (kg VS/m³/day), balancing substrate availability with microbial processing capacity:

- **Optimal Range:** 1.4-3.0 kg VS/m³/day for most systems, substrate-dependent
- **Overloading Consequences:** pH decline, volatile fatty acid accumulation, process acidification, methane yield reduction
- **Under-loading Consequences:** Suboptimal reactor utilization, reduced volumetric productivity

Research indicates highest methane yield (0.25 m³ CH_4/kg VS) occurs at OLR of 1.4 kg VS/m³/day for vegetable waste, with progressive decline at higher loading rates.

Potential impact: 15-25% yield optimization through OLR fine-tuning.

Strategic additive use can overcome kinetic limitations and enhance microbial activity:

- **Biochar:** Provides microbial habitat, adsorbs inhibitors, facilitates electron transfer (7-15% yield increase)
- **Trace Elements:** Supplements of iron, nickel, cobalt support metalloenzyme function in methanogens (10-20% enhancement)
- **Alkaline Buffers:** Prevent pH excursions during high-rate digestion (stabilization benefit)

Potential impact: 7-30% production enhancement depending on additive type and dosing.

Fugitive methane emissions represent both economic loss and environmental liability:

- **Airtight Storage Systems:** Prevent methane escape from digestate storage (primary emission source)
- **Gas Collection Optimization:** Eliminate leaks in piping and fittings through regular inspection
- **Pressure Management:** Maintain slight positive pressure to prevent air ingress while avoiding safety hazards

Methane emissions ranging from 0.1% to 13.7% have been documented, with digestate storage identified as the primary source. Addressing this through improved infrastructure offers 1-5% energy recovery potential.

Emerging technologies offer step-change performance improvements:

- **Microbial Electrolysis Cells (MEC):** Apply small electrical potential to enhance methanogenesis and accelerate hydrolysis (20-50% increase potential)
- **Pretreatment Technologies:** Thermal, chemical, or mechanical pretreatment to improve substrate digestibility (5-30% enhancement)
- **Membrane Separation:** Upgrade biogas to 96%+ biomethane through CO_2 removal, enabling natural gas grid injection

Implementation requires cost-benefit analysis considering capital investment, operational complexity, and expected returns.

- **Operator Training:** Ensure personnel competency in process monitoring, troubleshooting, and intervention
- **Performance Benchmarking:** Track key performance indicators (KPIs) and compare against design values

Potential impact: 10-20% downtime reduction, improved long-term reliability.

5 Conclusion

This investigation of biogas plant performance through analysis of 10 months of operational data revealed that theoretical relationships between gas composition and energy generation are substantially modulated by operational factors in real-world facilities. The key findings and conclusions are:

Weak Compositional Correlations: Methane concentration exhibited weak negative correlation with power output ($r = -0.15$, $p = 0.68$), demonstrating that compositional optimization alone is insufficient for performance maximization.

Operational Dominance: Factors including biogas volume, CHP efficiency, maintenance practices, and process stability exert controlling influence on energy generation, often superseding compositional effects.

Optimization Potential: Mean CH_4 concentration (48.12%) fell below literature benchmarks (50-70%), indicating substantial improvement potential through evidence-based interventions.

Integrated Approach Necessity: Maximum efficiency gains require synergistic application of multiple optimization strategies encompassing substrate management

(C:N optimization), process control (pH, temperature, HRT, OLR), additive integration, emission mitigation, advanced technologies, and operational excellence.
Projected Impact: Comprehensive optimization implementation can increase average power generation by 10-30% while enhancing process stability and environmental performance.
Sustainability Advancement: Biogas optimization contributes to greenhouse gas mitigation, waste management, circular economy development, and renewable energy transition objectives aligned with global climate targets.
Future research should address identified limitations through integration of volumetric flow monitoring, comprehensive substrate characterization, multi-parameter process tracking, techno-economic analysis, and extended temporal monitoring. The findings provide actionable guidance for biogas facility operators and contribute to the knowledge base supporting sustainable bioenergy development globally.

References

1. IPCC. (2021). Sixth Assessment Report: Global Carbon and Other Biogeochemical Cycles and Feedbacks. Cambridge University Press. https://doi.org/10.1017/9781009157896.007
2. Gülşen, H., Akkuş, A., Yolun, A., & Aslan, M. (2022). Determination of the Electrical Potential of Solid Wastes in Adıyaman Province. Kahramanmaraş Sütçü İmam University Journal of Engineering Sciences, 3(25), 173-182.
3. Chen, W.-K. (1993). Linear Networks and Systems. Belmont, CA: Wadsworth, pp. 123–135.
4. Akyürek, Z., & Çetinkaya, A. Y. (2023). Biogas Potential and Its Role in Circular Economy: A Case Study of Turkey's Waste Management Systems. Journal of Cleaner Production, 416, 137845. https://doi.org/10.1016/j.jclepro.2023.137845
5. Lyng, K.-A., & Brekke, A. (2023). Environmental Life Cycle Assessment of Biogas Production from Municipal Solid Waste. Waste Management, 171, 291–301. https://doi.org/10.1016/j.wasman.2023.09.015
6. IEA. (2022). Renewables 2022. Paris: IEA. https://www.iea.org/reports/renewables-2022
7. International Energy Agency (IEA). (2023). World Energy Outlook 2023: The Role of Bioenergy in Net-Zero Pathways. Retrieved from https://www.iea.org/reports/world-energy-outlook-2023
8. Upreti, B. R., & van der Horst, D. (2024). Social Acceptance of Renewable Energy Projects: Lessons from Biomass and Biogas Initiatives. Energy Research & Social Science, 108, 103387. https://doi.org/10.1016/j.erss.2023.103387
9. de Mes, T. Z. D., Stams, A. J. M., Reith, J. H., & Zeeman, G. (2003). Methane production by anaerobic digestion of wastewater and solid wastes. In Bio-methane & Bio-hydrogen: Status and perspectives of biological methane and hydrogen production (pp. 58-102).
10. Molino, A., Nanna, F., Ding, Y., Bikson, B., & Braccio, G. (2013). Biomethane production by anaerobic digestion of organic waste. Fuel, 103, 1003-1009.
11. Duan, J., et al. (2025). Boosting biogas production through innovative data-driven optimization. Nature Scientific Reports, 15, 234.
12. Saboohi, Z., et al. (2025). Advancements in biogas production: process optimization and innovative enhancements. Academic Press Review, 12, 45-78.
13. Holliger, C., et al. (2017). Methane Production of Full-Scale Anaerobic Digestion Plants Calculated from Substrate's Biomethane Potentials. Frontiers in Energy Research, 5, 12.

14. Şanlı, M. (2022). Impact of process conditions on methane production in anaerobic digestion. METU Graduate Thesis.
15. Babaee, A., & Shayegan, J. (2011). Effect of organic loading rates (OLR) on production of methane from anaerobic digestion of vegetables waste. World Renewable Energy Congress, pp. 411-417.
16. Cerón-Vivas, A., et al. (2019). Influence of pH and the C/N ratio on the biogas production of wastewater. Revista Dyna, 86(209), 138-145.
17. Shi, X. S., et al. (2017). Effect of Hydraulic Retention Time on Anaerobic Digestion of Wheat Straw. BioMed Research International, 2017, 1-8.