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Experimental Investigation of The Effect Of Agricultural Waste Composition On The Rate Of Biogas Production
A Research Paper Submitted for the Degree of Doctor of Philosophy

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ABSTRACT
In modern lifestyles, people rely heavily on technological gadgets to streamline daily operations. These devices depend entirely on electricity, causing consumption metrics to rise daily. Because a major portion of global electricity is produced via fossil fuels, this reliance leads to severe environmental pollution and escalating fuel costs over time. An indirect and sustainable solution to this crisis lies in engineering highly efficient alternate fuels, such as biogas generated from degradable waste streams. Furthermore, the nutrient-rich digestate byproduct of this process serves as a potent agricultural fertilizer. To optimize the technology, biogas plants must be manufactured with highly efficient designs. Various operational parameters uniquely influence the overall biogas production rate, meaning running conditions must be carefully balanced. Critical variables such as operating temperature, water content, slurry pH, and organic loading rate (OLR) dictate the system's maximum output velocity. Agricultural solid residues, particularly banana plant waste, currently pose massive disposal and environmental challenges for farmers. Anaerobic digestion (AD) provides an ideal pathway to convert this unproductive agricultural waste into high-value clean energy. Despite its clear advantages, advanced technical innovations and widespread awareness of this technology remain relatively limited. This study analyzes existing literature to establish optimal parameter boundaries and investigates preliminary experimental trials assessing banana waste digestion kinetics.

Keywords: *Biogas, Banana plant, agricultural waste, anaerobic digestion (AD), alternate fuel.*

1. INTRODUCTION TO BIOGAS

Biogas is a renewable and environmentally friendly source of energy produced through the anaerobic decomposition of organic materials such as agricultural residues, food waste, municipal organic waste, and animal manure by microorganisms. This biological process, known as anaerobic digestion, occurs in oxygen-free conditions within specially designed systems called anaerobic digesters or biodigesters. Biogas may be generated naturally in wetlands and landfills or intentionally produced in controlled anaerobic digestion systems for use as a sustainable energy source (Al-Wahaibi et al., 2020; Oyaro et al., 2020).
Biogas mainly consists of methane (CH_4) and carbon dioxide (CO_2), along with small amounts of hydrogen sulfide (H_2S), water vapour, hydrogen, nitrogen, and other trace gases. Methane is the primary combustible component, making biogas an effective fuel for cooking, heating, electricity generation, and combined heat and power (CHP) systems. After the removal of impurities such as carbon dioxide and hydrogen sulfide, biogas can be upgraded to biomethane, a high-quality renewable fuel with properties similar to natural gas. Biomethane can be compressed and used as compressed natural gas (CNG) for transportation or injected into natural gas distribution networks (Dorella et al., 2018).
From an environmental perspective, biogas is considered a carbon-neutral energy source because the carbon dioxide released during combustion is approximately equal to the amount absorbed by plants during photosynthesis, thereby creating a closed carbon cycle. In addition to reducing greenhouse gas emissions, anaerobic digestion provides an efficient waste management solution by converting organic waste into renewable energy and nutrient-rich digestate that can be used as organic fertilizer. The composition and yield of biogas depend on several factors, including the type of feedstock, substrate characteristics, digester design, pH, temperature, hydraulic retention time, and operational conditions (Al-Wahaibi et al., 2020; Oyaro et al., 2020).

1.1 The Indian Biogas Landscape

India has a long history of utilizing biogas as a sustainable source of renewable energy, particularly in rural areas where cattle manure has traditionally served as the primary feedstock. The widespread adoption of household and community-based "gobar gas" plants has enabled rural households to meet their cooking and lighting needs while simultaneously improving waste management practices. Over the years, technological advancements have led to the development of cost-effective and efficient biogas plant designs, such as the Deenabandhu model, which is widely recognized for its simple dome-shaped structure, lower construction cost, and improved gas production efficiency compared with earlier models.

In recent years, the scope of biogas production has expanded beyond cattle dung to include agricultural residues, municipal organic waste, food waste, and agro-industrial by-products. Crop residues such as rice straw, rice husk, and banana waste have demonstrated significant potential as alternative feedstocks for anaerobic digestion, thereby reducing dependence on conventional biomass while providing an environmentally sustainable solution for agricultural waste disposal (Ghatak & Mahanata, 2018; Rahim et al., 2019). The efficiency of anaerobic digestion is strongly influenced by operational parameters such as temperature, substrate composition, and mixing conditions, making proper digester management essential for maximizing biogas yield (Babaei & Shayegan, 2019).

The Government of India has further strengthened the role of biogas through initiatives such as the GOBAR-DHAN (Galvanizing Organic Bio-Agro Resources Dhan) scheme, which promotes the scientific management of biodegradable waste for the production of biogas, compressed biogas (CBG), and organic manure. Such initiatives contribute to cleaner energy production, improved sanitation, and reduced environmental pollution. Furthermore, the utilization of crop residues for biogas production provides an effective alternative to open-field residue burning, thereby helping to reduce greenhouse gas emissions and air pollution while supporting sustainable agricultural practices (Bhuvaneshwari et al., 2019). These developments demonstrate the growing importance of biogas in achieving India's renewable energy, waste management, and circular economy objectives.

1.2 Objectives of the study

1. To design and fabricate a laboratory-scale anaerobic digester incorporating a variable-speed mechanical agitator for controlled substrate mixing.
2. To investigate the influence of agitator operating parameters, including rotational speed (rpm), mixing duration, and mixing frequency, on the anaerobic digestion process and biogas production.
3. To measure and analyse daily biogas production and methane concentration throughout the digestion period using appropriate gas measurement techniques, and to evaluate the effects of different agitation conditions on biogas yield.
4. To evaluate the quality of the digestate by analysing its physicochemical properties, including pH, total solids (TS), volatile solids (VS), nutrient content (N, P, and K), and organic matter reduction, to determine its suitability as an organic fertiliser.
5. To assess the environmental and economic performance of the developed anaerobic digester by estimating greenhouse gas emission reduction, waste management benefits, energy recovery potential, operating costs, and overall economic feasibility.
6. To recommend an optimised farmer-scale anaerobic digester design based on the experimental findings, considering cost-effectiveness, operational simplicity, energy efficiency, and suitability for rural agricultural applications.

2. REVIEW OF LITEARTURE

The increasing global demand for energy, coupled with the depletion of fossil fuel resources and growing environmental concerns, has intensified the search for sustainable and renewable energy alternatives. Among the available renewable energy sources, biogas has emerged as an environmentally friendly technology capable of addressing both energy shortages and organic waste management. In India, where agriculture contributes significantly to the national economy and supports a large proportion of the rural population, enormous quantities of agricultural residues are generated every year. However, the inadequate utilization of these residues often leads to open-field burning and uncontrolled dumping, resulting in severe air pollution, greenhouse gas emissions, and loss of valuable biomass resources (Bhuvaneshwari et al., 2019). Consequently, the conversion of agricultural residues into biogas through anaerobic digestion has gained increasing attention as a sustainable waste management and renewable energy strategy.

India is the world's largest producer of bananas, generating substantial quantities of agricultural waste after harvesting. Banana pseudo-stems, leaves, peels, and stalks constitute a significant proportion of this waste and are generally discarded without productive utilization. Recent studies have demonstrated that these lignocellulosic residues possess considerable potential for biogas production through anaerobic digestion. Rahim et al. (2019) reported that banana peel waste is a suitable substrate for methane generation and can contribute to decentralized renewable energy production while simultaneously reducing environmental pollution associated with agricultural waste disposal. The effective utilization of banana biomass therefore offers both environmental and economic benefits, particularly for rural communities seeking sustainable energy alternatives.

2.1 Critical Thermodynamic and Chemical Control Variables

The efficiency of anaerobic digestion is governed by several operational and environmental parameters that directly influence microbial activity and methane production. The anaerobic digestion process comprises four sequential stages, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each involving distinct microbial communities that require favourable operating conditions for efficient substrate conversion.

Among these operational parameters, temperature is one of the most influential factors affecting biogas production. Ghatak and Mahanata (2018) investigated the effect of temperature on biogas production from rice straw and rice husk and reported that thermophilic digestion enhanced the degradation of lignocellulosic biomass and improved methane yield compared with lower operating temperatures. Similarly, Babaei and Shayegan (2019) observed that higher temperatures accelerated microbial activity and increased the initial rate of biogas production. However, they also noted that excessively high temperatures could adversely affect methanogenic microorganisms, resulting in reduced process stability. These findings suggest that maintaining an optimum operating temperature is essential for achieving maximum biogas production and ensuring stable digester performance.

Another important parameter influencing anaerobic digestion is pH. Methanogenic microorganisms are highly sensitive to changes in acidity and generally perform best within a neutral pH range. During the acidogenesis stage, the rapid accumulation of volatile fatty acids may decrease the pH and inhibit methane-producing microorganisms if appropriate buffering mechanisms are not maintained. Babaei and Shayegan (2019) emphasized that maintaining stable pH conditions is critical for sustaining microbial activity, preventing process failure, and maximizing methane generation. Accordingly, buffering agents are frequently employed in anaerobic digesters to stabilize pH and maintain favourable conditions for methanogenesis.

Mechanical mixing also plays a significant role in improving digester efficiency. Proper mixing enhances the uniform distribution of microorganisms, nutrients, and temperature throughout the digester while preventing sedimentation and scum formation. Babaei and Shayegan (2019) reported that controlled mixing improved substrate contact with microbial populations and increased overall gas production. However, excessive or continuous agitation may disrupt microbial aggregates and negatively affect syntrophic relationships among microbial communities, thereby reducing methane yield. Their findings indicate that intermittent mixing strategies provide a better balance between operational efficiency and microbial stability than continuous agitation.

Overall, the reviewed studies demonstrate that temperature, pH, and mixing conditions are among the most critical operational variables affecting anaerobic digestion performance. Proper optimization of these parameters significantly enhances methane production, improves digester stability, and increases the overall efficiency of biogas generation from agricultural residues. These findings provide an important scientific foundation for developing efficient anaerobic digestion systems utilizing banana waste and other lignocellulosic biomass resources.

3. RESEARCH GAP AND EXPERIMENTAL METHODOLOGY

Previous studies have extensively investigated anaerobic digestion using cattle manure, food waste, and other agricultural residues. However, limited research has examined the co-digestion of lignocellulosic banana pseudostem waste with cattle manure under controlled mechanical agitation conditions. Furthermore, the combined influence of substrate composition and agitation on biogas yield, methane concentration, digestate quality, and overall system performance remains insufficiently explored. Most existing studies have focused either on substrate optimisation or digester operating conditions independently, with comparatively few evaluating their combined effects. This research addresses these gaps by experimentally investigating the performance of different substrate combinations under both agitated and non-agitated conditions to identify an efficient and practical digestion strategy suitable for rural agricultural applications.

To achieve these objectives, the study will employ a laboratory-scale batch anaerobic digester and conduct seven experimental setups, comprising one control and six treatment trials, over identical hydraulic retention periods. The experimental treatments are as follows:

- **Control:** 100% cattle manure (cow dung) without banana pseudostem.
- **Trial 1:** 80% cattle manure + 20% chopped banana pseudostem (without mechanical agitation).
- **Trial 2:** 80% cattle manure + 20% chopped banana pseudostem (with interval mechanical agitation).
- **Trial 3:** 50% cattle manure + 50% chopped banana pseudostem (without mechanical agitation).
- **Trial 4:** 50% cattle manure + 50% chopped banana pseudostem (with interval mechanical agitation).
- **Trial 5:** 100% chopped banana pseudostem (without mechanical agitation).
- **Trial 6:** 100% chopped banana pseudostem (with interval mechanical agitation).

During each experimental setup, daily biogas production, methane concentration, pH, temperature, total solids, volatile solids, and digestate characteristics will be monitored and analysed. The comparative evaluation of these treatment conditions will facilitate the identification of the optimum substrate composition and agitation strategy for enhancing biogas production, improving digestate quality, and supporting the development of a cost-effective farmer-scale anaerobic digestion system.

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3.1 Standardized Slurry Preparations

To maintain statistical consistency, all trials are standardized to an exact 4:3 water-to-solid mass ratio. Each configuration blends precisely 3,000 grams of processed solid substrate with 4,000 milliliters (4 Liters) of clean water. The resulting multi-phase slurry is loaded into rigid acrylonitrile butadiene styrene (ABS) plastic bioreactors with a total volume of 10 liters. The liquid slurry occupies exactly 70% of the internal reactor volume, leaving a clean 30% upper headspace for biogas collection and pressure stabilization.

4. EXPERIMENTAL SETUP


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5. EXPERIMENTATION, DATA ACQUISITION, AND RESULTS

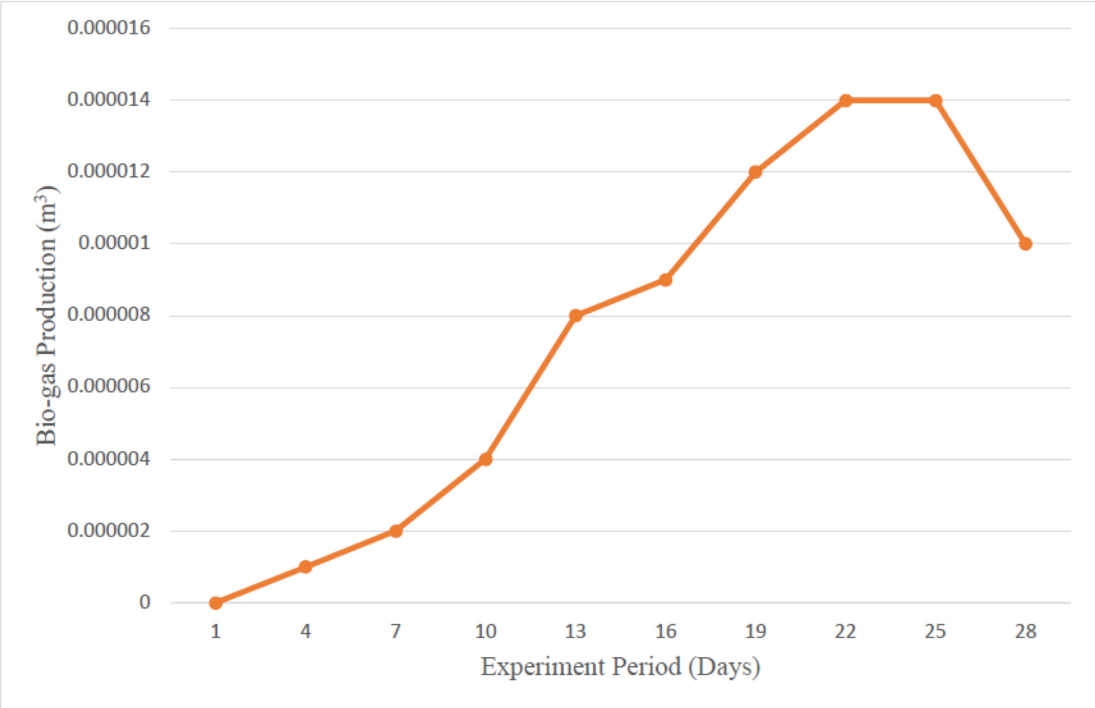
Initial laboratory testing evaluated the baseline co-digestion of agricultural banana pseudostem residues combined with rural cattle dung. The solid raw feed mass consisted of 2,500 grams of fresh cattle dung combined with 500 grams of clean banana pseudostems, providing an 80:20 mixing ratio. To minimize mass-transfer resistance during hydrolysis, the pseudostems were shredded into standardized particles (~L 5 mm x W 5 mm) before being blended with water. The mixed slurry was processed under tightly regulated mesophilic conditions maintained between 29°C and 33°C via an external temperature-controlled water bath. The trial ran for a continuous 28-day hydraulic retention time (HRT). Daily gas yield was quantified using a standard fluid-displacement configuration, where escaping biogas displaced water from a calibrated collection tank. The displaced water volume was measured and drained at matching 24-hour intervals.

5.1 Chronological Gas Production Records

Day	Biogas (m^3)	Day	Biogas (m^3)	Day	Biogas (m^3)
1	0.000000	11	0.000005	21	0.000015
2	0.000000	12	0.000006	22	0.000014
3	0.000001	13	0.000008	23	0.000015
4	0.000001	14	0.000009	24	0.000016
5	0.000002	15	0.000009	25	0.000014
6	0.000003	16	0.000009	26	0.000013
7	0.000002	17	0.000010	27	0.000010
8	0.000003	18	0.000010	28	0.000010
9	0.000004	19	0.000012		
10	0.000004	20	0.000012		

Over the course of the 28-day digestion cycle, the unagitated slurry produced a total cumulative biogas volume of 0.000217 m^3. The system showed a clear lag phase during the first week, generating negligible gas volumes as the microbial cultures acclimated to the fibrous lignocellulosic structures. Gas production accelerated sharply after Day 10, rising steadily toward a peak yield of 0.000016 m^3 on Day 24. Following this peak, gas production dropped significantly between Days 25 and 28, indicating substrate depletion.

From the data shown in Table 1, total biogas generated during the period of 28 days is 0.000217 m3. During this study we observe that a`er the 25th and 26th day of experiment the producRon rate falls considerably. At the iniRal days of experiment there is no significant amount of collecRon of gas generated. A`er 10th day, amount of biogas producRon rises sharply as seen in Figure.



6. DISCUSSION AND SYSTEMIC CONCLUSION

This initial investigation demonstrates that post-harvest banana pseudostem residues are highly viable co-substrates for anaerobic digestion when blended with cattle manure. This processing strategy offers rural communities an effective pathway to transform massive agricultural waste streams into manageable, clean energy resources while producing stable organic soil amendments.
However, the volumetric production rates from this initial unagitated trial remain relatively low, likely limited by mass-transfer resistance and the formation of a localized scum layer inside the reactor. These baseline results highlight the operational need for mechanical agitation. Subsequent phases of this research will execute the remaining agitated experimental matrices (Trials 2, 4, and 6). Evaluating these configurations will determine how controlled mixing speeds up structural hydrolysis, prevents localized acidification, and optimizes gas recovery parameters for regional agricultural waste management systems.

7. REFERENCES

1. Agriculture, F. W. (2017). Agriculture, Farmers Welfare and Co-operation Department. Government of Gujarat.
2. Al-Wahaibi, A., Osman, A. I., Al-Muhtaseb, A. H., Alqaisi, O., Baawain, M., Fawzy, S., & Rooney, D. (2020). Techno-economic evaluation of biogas production from food waste via anaerobic digestion.
3. Bhuvaneshwari, S., Hettiarachchi, H., & Meegoda, J. N. (2019). Crop Residue Burning in India: Policy Challenges and Potential Solutions. Int J Environ Res Public Health, 832.
4. Borthakur, A., & Singh, P. (2012). Agricultural research in India: An exploratory study. International Journal of Social Science & Interdisciplinary Research, 59-74.
5. Cioabla, A. E., Ionel, I., Dumitrel, G.-A., & Popescu, F. (2012). Comparative study on factors affecting anaerobic digestion of agricultural vegetal residues. Biotechnology for Biofuels, 5:39.
6. Dorella, M., Romagnoli, F., Fruduls, A., Collotta, M., & Tomasoni, G. (2018). Design of a biogas plant fed with Cladophora Sp. algae and wheat straw. Energy Procedia, 458-466.
7. Ghatak, M. D., & Mahanata, P. (2018). Effect of Temperature on Biogas Production from Rice Straw and Rice Husk. IOP Conference Series: Materials Science and Engineering, 377.
8. Hajji, A., Rhachi, M., Garoum, M., & Laaroussi, N. (2016). The effects of pH, temperature and agitation on biogas production under mesophilic regime. 3rd International Conference on Renewable Energies for Developing Countries (REDEC). IEEE.
9. Jayaraj, S., Deepanraj, B., & Sivasubramanian, V. (2014). Study on the effect of pH on biogas production from food waste by anaerobic digestion. The 9th International Green Energy Conference, 799-805.
10. Kim, J. K., Oh, B. R., Chun, Y. N., & Kim, S. W. (2006). Effects of Temperature and Hydraulic Retention Time on Anaerobic Digestion of Food Waste. Journal of Bioscience and Bioengineering, 328-332.

11. Ogiehor, I. S., & Ovueni, U. J. (2014). Effect of temperature, pH, and solids concentration on biogas production from poultry waste. International Journal of Scientific & Engineering Research, 62-69.
12. Oyaro, D. K., Oonge, Z. I., & Odira, P. M. (2020). Anaerobic Digestion of Banana Wastes for Biogas Production. Journal of Civil & Environmental Engineering.
13. Padam, B. S., Tin, H. S., Chye, F. Y., & Abdullah, I. M. (2014). Banana by-products: an under-utilized renewable food biomass with great potential. Journal of Food Science and Technology, 3527-3545.
14. Rahim, I. R., Lando, A. T., Asriyanti, E., & Ihsan, M. (2019). Feasibility Study of Biogas from Banana Peel Waste. IOP Conference Series: Materials Science and Engineering, 676.
15. Sambo, A. S., Garba, B., & Danshehu, B. G. (1995). Effect of some operating parameters on biogas production rate. Renewable Energy, 343-344.
16. Sasse, L. (1988). Biogas Plants. Deutsches Zentrum für Entwicklungstechnologien - GATE.
17. Scientific Reports. Babaei, A., & Shayegan, J. (2019). Effects of temperature and mixing modes on the performance of municipal solid waste anaerobic slurry digester. Journal of Environmental Health Science Engineering, 1077-1084.
18. Sibiya, N. T., Muzenda, E., & Tesfagiorgis, H. B. (2014). Effect of Temperature and pH on The Anaerobic Digestion of Grass Silage. 6th Int'l Conf. on Green Technology, Renewable Energy & Environmental Engg., 198-201.