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### RESEARCH ARTICLE

## ADVANCED TECHNOLOGIES OF TECHNO-ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF AGRICULTURAL WASTE-BASED ANAEROBIC DIGESTION

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energy; sustainability

### Abstract

This study evaluated the energy, economic, and environmental performance of converting agricultural waste into bioenergy through anaerobic digestion. The system utilized agricultural residues including rice husk, sugarcane bagasse, corn stalks, vegetable waste, and cattle manure. The optimized digestion process produced biogas with a calorific value of approximately 22.4 MJ/m<sup>3</sup> and an estimated electricity generation potential of 1.85 kWh/m<sup>3</sup>. The annual large-scale implementation potential was approximately 145,000 kWh/year. Economic analysis indicated a capital investment of approximately \$45,000 and annual operational costs of \$2,200, with a reported net return on investment of 31.5% and payback period of 3.2 years. Environmental analysis estimated annual carbon reduction of approximately 125 tons. The findings demonstrate the potential of agricultural-waste-based anaerobic digestion as an integrated waste-management, renewable-energy, and sustainability approach.

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### Introduction:-

Agricultural residues are frequently disposed of through open-field burning, landfilling, and uncontrolled decomposition. These practices contribute to environmental pollution and loss of potentially useful organic resources. Anaerobic digestion provides a route for converting biodegradable agricultural residues into biogas and nutrient-rich digestate. The research evaluated the technical feasibility of this approach together with energy, economic, and environmental outcomes. The thesis identifies techno-economic evaluation as an important component of an optimized agricultural-waste-to-bioenergy system. Economic feasibility, energy generation, and greenhouse-gas reduction are considered together to assess the practical applicability of the system.

### Agricultural Waste Feedstocks and Digestion System:-

The study considered rice husk, sugarcane bagasse, corn stalks, vegetable waste, and cattle manure. Rice husk had a C/N ratio of 45:1, volatile solids of 78.2%, and pH 6.8. Sugarcane bagasse had a high C/N ratio of 120:1. Corn stalks had a C/N ratio of 35:1 and volatile solids of 88.4%. Vegetable waste had a C/N ratio of 15:1 and high moisture content. Cattle manure had a pH of 7.4 and acted as a co-substrate and inoculum source.

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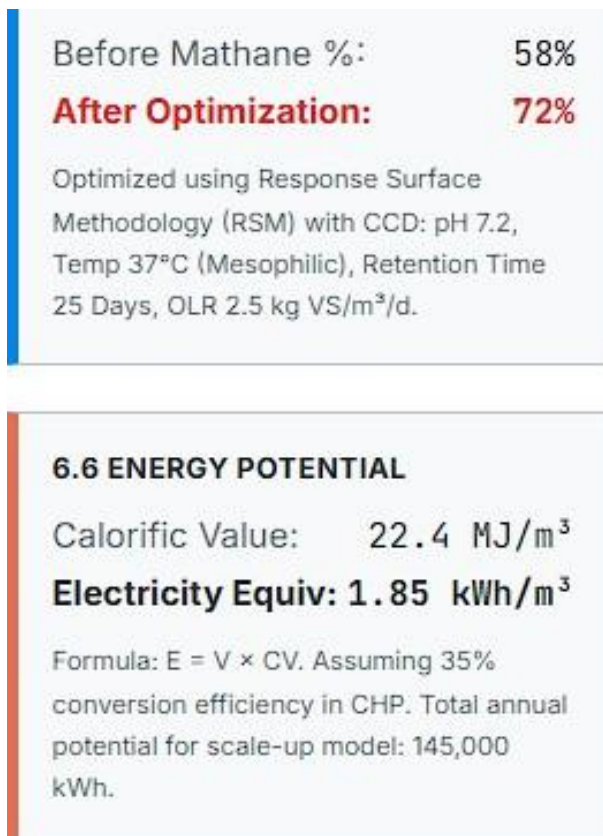
Co-digestion helped maintain nutrient balance and improved methane productivity compared with individual substrates. Pretreatment consisted of mechanical shredding below 2 mm followed by 2% sodium hydroxide treatment at 70°C for 60 minutes.

#### Energy Performance:-

##### Biogas Production:-

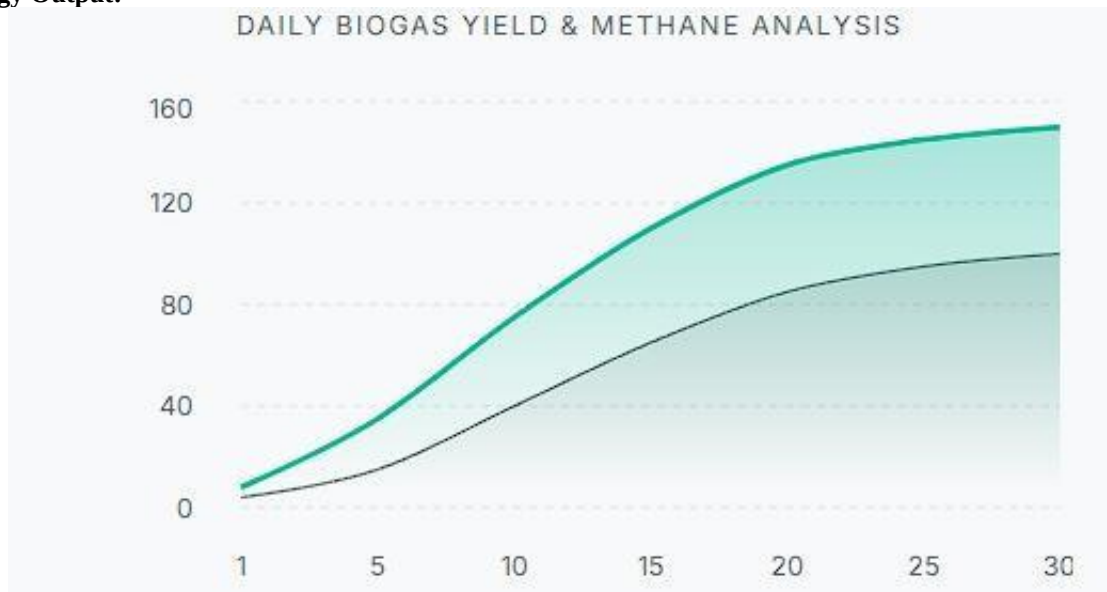
The digestion process operated under mesophilic conditions and progressed through lag, active methanogenesis, and stabilization phases. Gas production was relatively low during Days 1–5, increased substantially between Days 5 and 20, and reached peak production around Day 20. Cumulative biogas yield at the peak period was approximately 140–150 m<sup>3</sup>, while methane production steadily increased.

##### Methane Quality:-



**Figure 1. Methane purity before and after optimization and energy potential reported in the thesis.**

Optimization using Response Surface Methodology and Central Composite Design increased methane purity from 58% before optimization to 72% after optimization. The optimized operating conditions were 37°C temperature, 25 days retention time, and an organic loading rate of 2.5 kg VS/m<sup>3</sup>/day.

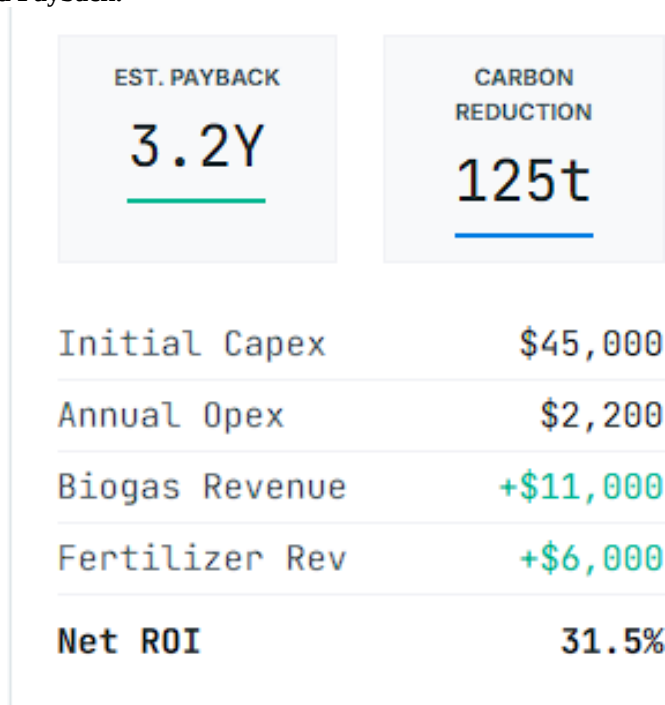
**Energy Output:-**

**Figure 2. Daily biogas yield and methane analysis.**

The calorific value of purified biogas was approximately 22.4 MJ/m<sup>3</sup>. The estimated electricity generation potential was 1.85 kWh/m<sup>3</sup>. The annual large-scale implementation potential was approximately 145,000 kWh/year. These results indicate the practical applicability of the produced biogas as a renewable energy source for rural electrification and industrial applications.

**Economic Performance:-****Capital and Operational Costs:-**

The economic analysis reported a total capital investment of approximately \$45,000 for establishing the plant. Annual operational costs were approximately \$2,200.

**Return on Investment and Payback:-**

**Figure 3. Economic and environmental performance summary reported in the thesis.**

Revenue was associated with biogas sales and fertilizer by-products. The reported net return on investment was 31.5%, with an estimated payback period of 3.2 years. The thesis therefore identifies the system as financially viable for rural and industrial implementation.

**Practical Economic Significance:-**

The economic results indicate that agricultural waste can be converted into a useful energy resource while generating value from biogas and digestate. The relatively low reported annual operational cost compared with the initial capital investment supports the economic feasibility described in the study.

**Environmental Performance:-****Waste Management and Emission Reduction:-**

The proposed system reduces the need for open-field burning of crop residues and prevents uncontrolled methane emissions associated with waste decomposition. The thesis estimated an annual carbon reduction of approximately 125 tons.

**Digestate Utilization:-**

Digestate produced during anaerobic digestion can be utilized as organic fertilizer. Its use can support sustainable agricultural practices and reduce dependence on chemical fertilizers.

**Integrated Sustainability Benefits:-**

The system integrates agricultural waste utilization, renewable energy production, economic profitability, and environmental sustainability. The combined outcomes support the use of anaerobic digestion as a waste-management and energy-production strategy.

**Table 1. Energy, Economic, and Environmental Performance of the Anaerobic Digestion System**

| Parameter                                   | Result                                                                                                   |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Digestion conditions                        | Mesophilic                                                                                               |
| Days 1–5                                    | Low gas production                                                                                       |
| Days 5–20                                   | Increased biogas production                                                                              |
| Peak biogas production                      | Around Day 20                                                                                            |
| Cumulative biogas yield                     | 140–150 m <sup>3</sup>                                                                                   |
| Methane purity before optimization          | 58%                                                                                                      |
| Methane purity after optimization           | 72%                                                                                                      |
| Optimized temperature                       | 37°C                                                                                                     |
| Optimized retention time                    | 25 days                                                                                                  |
| Optimized organic loading rate              | 2.5 kg VS/m <sup>3</sup> /day                                                                            |
| Calorific value of purified biogas          | 22.4 MJ/m <sup>3</sup>                                                                                   |
| Electricity generation potential            | 1.85 kWh/m <sup>3</sup>                                                                                  |
| Annual large-scale implementation potential | 145,000 kWh/year                                                                                         |
| Capital investment                          | \$45,000                                                                                                 |
| Annual operational cost                     | \$2,200                                                                                                  |
| Return on investment (ROI)                  | 31.5%                                                                                                    |
| Payback period                              | 3.2 years                                                                                                |
| Revenue sources                             | Biogas sales and fertilizer by-products                                                                  |
| Annual carbon reduction                     | 125 tons/year                                                                                            |
| Waste-management benefit                    | Reduction in open-field burning and uncontrolled methane emissions                                       |
| Digestate utilization                       | Organic fertilizer                                                                                       |
| Overall sustainability benefit              | Waste utilization, renewable energy production, economic profitability, and environmental sustainability |

**Discussion:-**

The results demonstrate that the optimized anaerobic digestion system has benefits beyond biogas production alone. Improvement in methane purity to 72% increases the quality of the produced fuel, while the calorific value and estimated electricity potential demonstrate its energy application. The reported capital investment, operating cost, ROI, and payback period indicate economic feasibility. At the same time, the estimated carbon reduction and utilization of digestate provide environmental and agricultural benefits. The thesis identifies insufficient techno-economic evaluation as a research gap in previous anaerobic digestion studies, particularly for smallholder agricultural contexts. The present analysis combines energy potential with economic and environmental outcomes to evaluate practical deployment.

**Conclusion:-**

The study demonstrates the technical, economic, and environmental potential of agricultural-waste-based anaerobic digestion. The optimized process produced purified biogas with a calorific value of approximately 22.4 MJ/m<sup>3</sup> and electricity generation potential of 1.85 kWh/m<sup>3</sup>, with annual large-scale potential of approximately 145,000 kWh/year. The reported capital investment was approximately \$45,000, annual operational cost was \$2,200, ROI was 31.5%, and payback period was 3.2 years. Environmental analysis estimated annual carbon reduction of approximately 125 tons. The findings support anaerobic digestion as an integrated approach for waste utilization, renewable energy generation, economic value creation, and environmental sustainability.

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