Performance Evaluation and Economic Sustainability of the PAU Model Batch Type Paddy Straw Biogas Plant

Abstract: This study evaluates the performance and economic viability of the Punjab Agricultural University (PAU) Model Batch Type Paddy Straw Biogas Plant in rural India, addressing critical challenges in agricultural residue management and sustainable energy production. Data collected from two plants over four months showed an average daily biogas production of 1.46 to 3.13 m^3 per day, with a total gas production of 296 m^3 in a period of four months. Plant performance correlated moderately with ambient temperature. Economic analysis revealed annual savings of Rs. 47,600 through reduced LPG use and biogas slurry sales. The study concludes that the PAU Model is technically efficient and economically viable, offering a sustainable solution for paddy straw management and rural energy security. These findings have significant implications for policymakers and rural development practitioners in promoting sustainable agriculture and renewable energy adoption in developing regions.

Keywords: Paddy straw, Biogas, Agricultural Waste Management, Sustainable Agriculture

1. Introduction

India's rapid economic growth has led to anincreased energy demand, with 151.3 GW primarily beingsourced from non-renewable thermal sources. This heavy reliance on imported fossil fuels poses environmental, sustainability, and economic challenges for the country (Bhattacharyya et al., 2021). As the country seeks to address the challenges posed by its reliance on non-renewable energy sources, the efficient utilization of its vast agricultural waste resources presents a promising opportunity for sustainable energy development. India produces around 683 million tons of crop residues each year. For every tonne of rice harvested, approximately 1.4 tonnes of straw are left behind on the crops(Satpathyand Pradhan, 2020). While approximately 80% of this volume is utilized for purposes such as animal feed, fuel, and industrial applications, a significant portion of the remaining surplus, estimated to be between 87 and 178 million tons, remains to beincinerated in the fields (Datta et al., 2020).In Northern India, particularly in states like Punjab, Haryana, and Uttar Pradesh, paddy cultivation remains a major agricultural activity, resulting in the production of vast quantities of paddy straw as a by-product (Singh and Kumar, 2019). However, the management of this agricultural residue poses a significant environmental and economic challenge. Farmers commonly resort to burning paddy straw in the fields, leading to severe air pollution, soil degradation, and loss of valuable biomass resources.

To address this pressing issue, various ex situ management strategies have been proposed and are beingimplemented. Among these, biogas production from paddy straw emergesas a promising solution that not only mitigates the environmental problems associated with straw burning but also offers multiple benefits to farmers and rural communities. Biogas production through anaerobic digestion of paddy straw presents a sustainable approach to waste management while generating renewable energy and organic fertilizer (Saharan et al., 2024).Paddy straw is a lignocellulosic biomass composed of carbohydrate polymers, including cellulose and hemicellulose, which are covalently or non-covalently linked with lignin, as well as extractives and inorganic compounds (Shafie et al., 2013). Its chemical composition typically consists of 38-40% glucan, 20-22% xylan, 3-4% arabinan, 13-15% lignin, and 17-20% ash. The lignocellulosic properties of paddy straw make it a promising substrate for anaerobic digestion (Chaudhary et al., 2024, Karwasra et al., 2022).The conversion of paddy straw into biogas offershighly beneficial outcomesfor farmers in several ways. Firstly, it provides a clean and renewable source of energy that can be utilizedfor cooking, lighting, and even electricity generation, reducing dependence on fossil fuels and lowering energy costs for rural households. Secondly, the process yields nutrient-rich organic compost as a by-product, which can be used to enhance soil fertility and reduce the need for chemical fertilizers (Panda and Jain, 2023). This not only improves agricultural productivity but also promotes sustainable farming practices (Parshad et al., 2024).

In light of these potential benefits, the Punjab Agricultural University (PAU) has developed a model batch type paddy straw biogas plant designed specifically for theefficient utilization of paddy straw (Chalotra and Sooch, 2020). This innovative technology aims to address the challenges of paddy straw management while providing a sustainable energy solution for rural areas. However, for widespread adoption and long-term viability of this technology, it is crucial to conduct a comprehensive evaluation of its performance and economic sustainability.

This research paper focuses on the performance evaluation and economic sustainability analysis of the PAU Model Batch Type Paddy Straw Biogas Plant. The study seeks to assess the technical efficiency, biogas yield, and overall performance of the plant under various operational conditions. Additionally, it examines the economic aspects, including capital and operational costs, potential revenue streams, and long-term financial viability. By providing a thorough techno-economic evaluation, this research aims to contribute valuable insights into the feasibility and potential impact of implementing such biogas plants as a sustainable solution for paddy straw management and rural energy needs.

2. Methodology

2.1 Study Design

This study was conducted to evaluate the performance and economic sustainability of the PAU Model Batch Type Paddy Straw Biogas Plant. The research was based on two biogas plants installed by the Confederation of Indian Industry (CII) in consultation with the Punjab Agricultural University (PAU) Ludhiana Centre. These plants were specifically designed to utilize paddy straw as the primary feedstock for biogas production.

The study sites were located in two villages in the Fatehabad district of Haryana, India:

1. Village Dholu, Block Bhuna,District Fatehabad, Haryana
2. Village Maghawali, Block Ratia, District Fatehabad, Haryana

Both plants were of similar design and capacity, adhering to the PAU model specifications for batch-type paddy straw biogas plants. The biogas plant has a capacity to utilize 16 quintals of paddy straw and 4 quintals of cattle dung per batch, which is processed over a period of approximately 3-4 months. This translates to a total annual capacity of 64 quintals, achievable through four batches per year. This dry fermentation biogas plant is made up of M.S Sheet and has 4 m^3 digester capacity. Detailed specification of the biogas plant is given in Fig. 1.

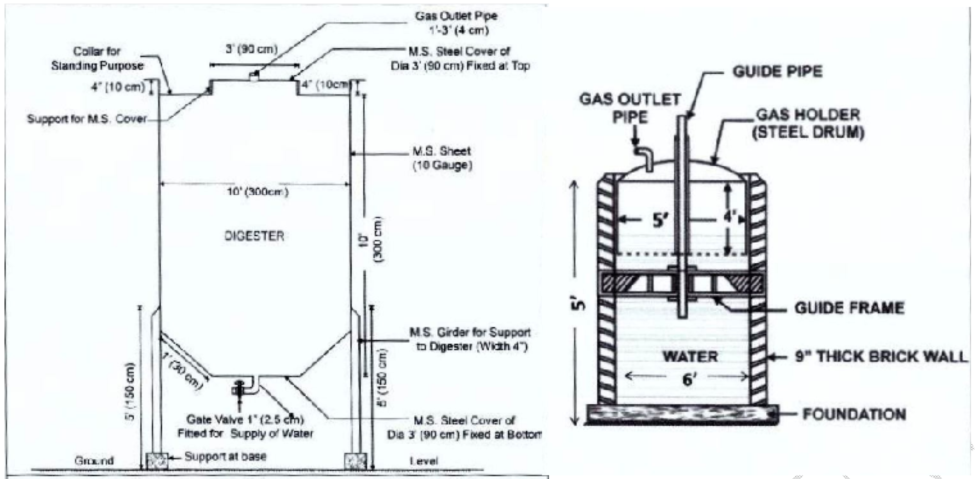

Fig 1. Detailed specification of PAU model batch type paddy straw biogas plant digester and gas holder

The selection of these sites allowed for a comprehensive assessment of the technology's performance under real-world conditions in rural settings.The research employed a mixed-methods approach, combining quantitative data collection for technical and economic analysis with qualitative data gathering to capture user experiences and perceptions. The study was conducted over a four-month period from June to September 2023, encompassing a full operational cycle of the biogas plants.

Key aspects of the study design included:

1. Continuous monitoring of biogas production at the Dholu village plant using a biogas flowmeter.
2. Daily temperature recordings to analyze the relationship between ambient temperature and biogas yield.
3. Collection of economic data, including installation costs, operational expenses, and potential income streams.
4. Gathering of qualitative data through farmer interviews to assess user satisfaction and the broader impact of the biogas plants on agricultural practices and rural livelihoods.

Fig. 2: PAU Model Batch Type Paddy Straw Biogas Plant at Dholu village

This comprehensive approach was designed to provide a holistic understanding of both the technical performance and the economic viability of the PAU Model Batch Type Paddy Straw Biogas Plant, with the aim of informing future implementations and policy decisions regarding sustainable paddy straw management and rural energy solutions.

2.2 Data Collection

Different types of data are collected for a comprehensive evaluation. Technical data is recorded to assess operational performance and efficiency, economic data is collected and analyzed to evaluate economic feasibility, and qualitative data is gathered to examine user experience, social impact, and environmental benefits, which are discussed in detail in the sub-sections below.

2.1 Technical Performance

The data collection process for evaluating the technical performance of the PAU Model Batch Type Paddy Straw Biogas Plant was meticulously planned and executed. At the installation in Dholu village, Block Bhuna, District Fatehabad (Fig. 2), a biogas flowmeter (Make: Itron Metering Systems) was installed to accurately measure daily biogas production (Fig. 3). This device recorded the cumulative biogas output in cubic meters over a four-month period from June to September 2023.

Daily biogas production was calculated by noting the difference in cumulative readings between consecutive days. The flowmeter data was recorded manually by trained local operators and cross-verified by research team members during regular site visits to ensure accuracy.

Fig.3: Installed Biogas flowmeter at village Dholu Plant

In addition to biogas production data, ambient temperature was also monitored to analyze its impact on biogas yield. A digital thermometer was used to record daily maximum and minimum temperatures, and the average daily temperature was calculated as the mean of these readings. The composition of the input feedstock, specifically the quantity of paddy straw used per batch and any pre-treatment processes applied, was also documented. The hydraulic retention time (HRT) for each batch was noted to understand the digestion cycle duration. Any operational issues, such as clogging or leakages, were thoroughly documented to assess the plant's reliability and maintenance requirements.

To maintain data integrity, regular calibration of the biogas flowmeter was performed to ensure accuracy of measurements. This comprehensive approach to data collection allowed for a detailed analysis of the biogas plant's efficiency, productivity, and operational characteristics under varying environmental conditions.

2.2 EconomicData

To comprehensively assess the economic viability of the PAU Model Batch Type Paddy Straw Biogas Plant, various financial metrics and cost-benefit analysis data were collected. The initial installation costs of the biogas plants were meticulously documented, including the expenses incurred for the construction, equipment, and any additional infrastructure required. Operating costs were also carefully monitored, covering labour expenses, raw materials, maintenance, and any other recurring costs associated with the operation of the plants.

In addition to documenting costs, the study also gathered data on potential revenue streams. One significant source of savings was the replacement of LPG (Liquefied Petroleum Gas) with biogas for cooking and heating purposes. The study recorded the amount of LPG typically used by the households and compared it with the biogas produced, calculating the associated financial savings. Another economic benefit considered was the income generated from the sale or use of biogas slurry, a byproduct of the anaerobic digestion process. This slurry acts as a rich organic fertilizer and can be sold or used on the farm, reducing the need for chemical fertilizers and thereby further enhancing economic sustainability.

2.3 Qualitative Data

To gain a deeper understanding of the social and economic impacts of the PAU Model Batch Type Paddy Straw Biogas Plant, qualitative data was collected through in-depth interviews and questionnaires with farmers and other stakeholders. These interactions aimed to capture the perceptions, experiences, and opinions of the users regarding the biogas plants, focusing on aspects such as user satisfaction, benefits, and challenges.

The interviews and questionnaires were designed to gather information on the farmers' paddy cultivation practices, including the area under cultivation, straw management practices, and the use of biogas and slurry. Additionally, the study sought to understand the farmers' perceptions of the economic benefits of the biogas plants, including any changes in their income or expenses, and their overall satisfaction with the technology.

The qualitative data collection process also explored the social impacts of the biogas plants, including any changes in the farmers' quality of life, health, and well-being. The study examined how the biogas plants had affected the farmers' daily routines, including cooking and heating practices, and whether they had noticed any improvements in their indoor air quality.

Furthermore, the study investigated the farmers' willingness to adopt and promote the biogas technology, including any suggestions they had for improving the design, operation, or maintenance of the plants. This qualitative data provided valuable insights into the human dimension of the biogas plants, complementing the quantitative data and offering a more comprehensive understanding of the technology's impacts and potential for scalability and sustainability.

3. Result and Discussion

3.1 Plant Performance and Biogas Production

The performance evaluation of the PAU Model Batch Type Paddy Straw Biogas Plant in Dholu village revealed significant insights into its operational efficiency and biogas production capacity (Fig. 4-7). Sixteen quintals of paddy straw and four quintals of cattle dung are loaded into the digester, with the remaining space filled with water. The paddy straw and cattle dung are alternately layered for efficient digestion.The paddy straw bales were directly added to the digester without any pre-treatment. To facilitate uniform distribution, the strings of bales were cut and then bales was spread evenly inside the digester.Over the four-month study period from June to September 2023, the plant demonstrated variable biogas production rates, influenced by several factors including ambient temperature and operational conditions. The data collected from the biogas flowmeter showed that the average daily biogas production ranged from 1.46 to 3.13m^3per day, with the highest production observed in July and August.The plant exhibited a gradual increase in daily biogas production during the initial weeks of operation in June, likely indicating a start-up phase where the microbial community was establishing itself within the digester. This observation highlights the importance of allowing adequate time for the system to reach stable operation when implementing new biogas plants (Karwasra et al., 2022 and Kaur and Phutela, 2014).

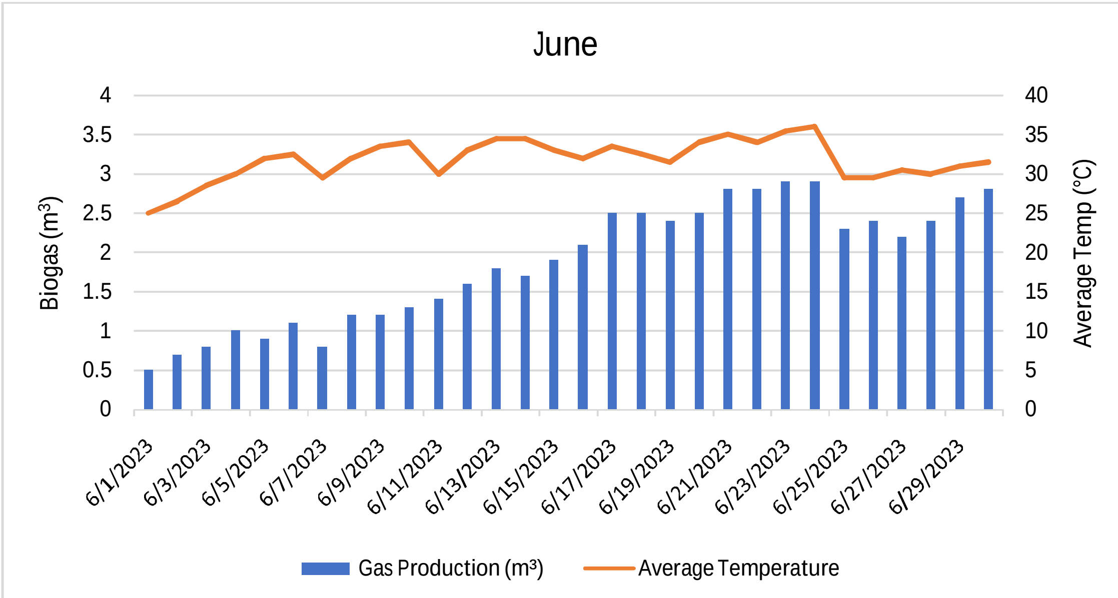

Fig. 4: Daily biogas production along with average temperature for the month of June, 2023

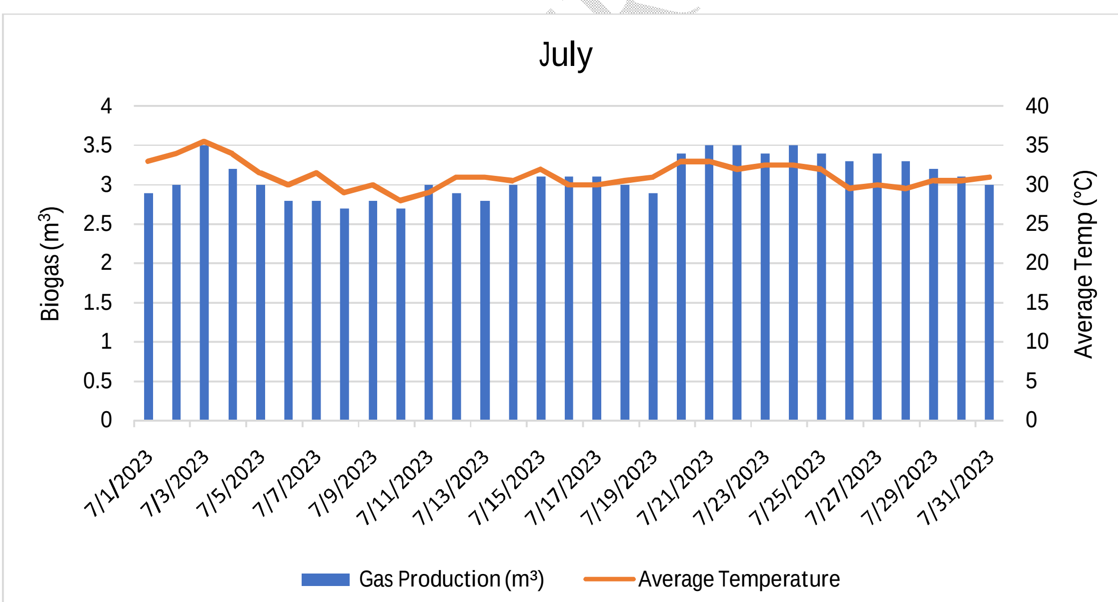

Fig. 5: Daily biogas production along with ambient temperature for the month of July, 2023

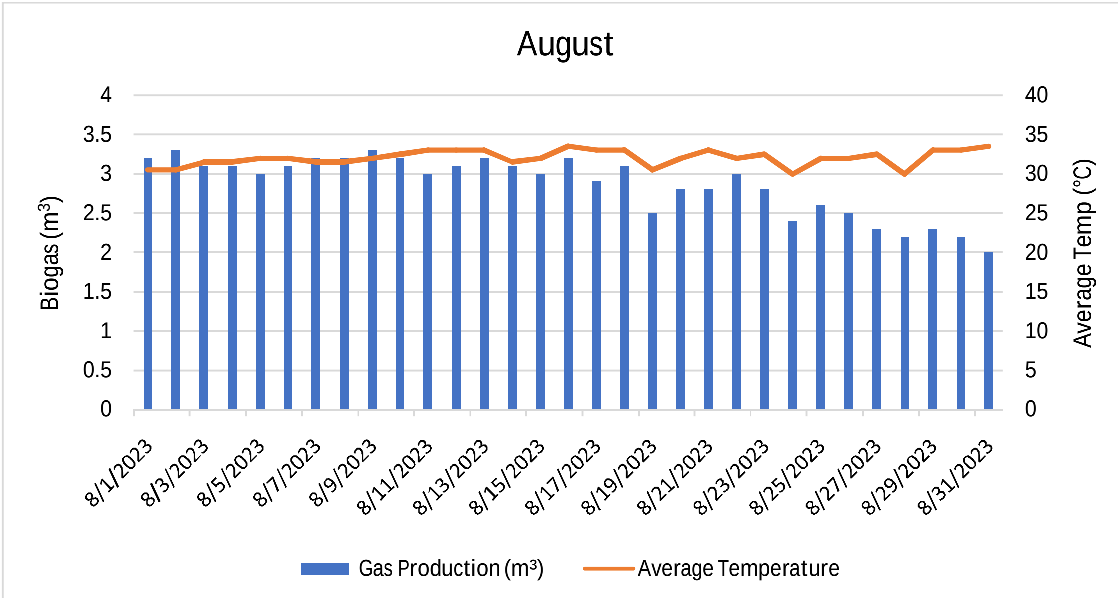

Fig. 6: Daily biogas production along with ambient temperature for month of August, 2023

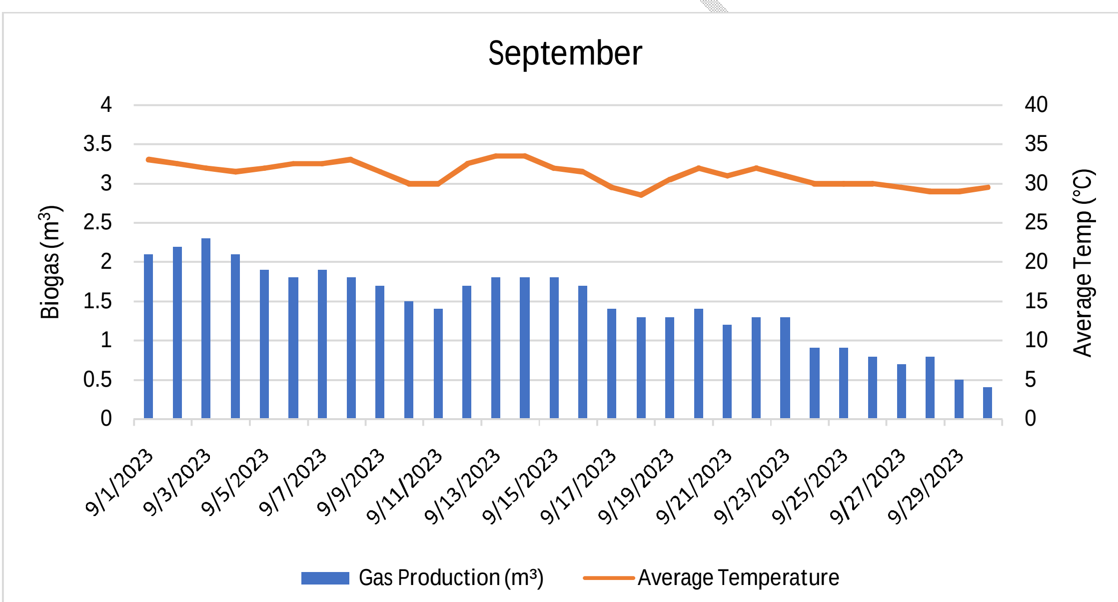

Fig. 7: Daily biogas production along with ambient temperature for the month of Sept, 2023

July emerged as the peak production month, with an average daily biogas yield of 3.13m^3. This coincided with the highest average temperatures recorded during the study period, suggesting a positive correlation between ambient temperature and biogas production efficiency. The plant maintained robust performance through August, with only a slight decrease in average daily production to 3.10m^3. The biogas plant yielded 56.1 m^3 biogas in June, which thereafter increased to 96.3 m^3 and 88.7 m^3 in July and August, respectively.However, a notable decline was observed in September, where the average daily production dropped to 1.46m^{3}which comes out to be 43.7 m^3. This reduction could be attributed to decrease in ambient temperature as the season changed.This yield falls within the expected range for paddy straw-based anaerobic digestion systems, as reported in previous studies, suggesting that the PAU model performs comparably to other established technologies (Chalotra and Sooch, 2020).

Based on the visual analysis of biogas gas production graphs, combined with the average temperature of the day, it is clear that temperature plays a crucial role in the anaerobic digestion process(Mondal & Biswas, 2013).Wu et al. (2006)investigated the impact of abrupt temperature drops in laboratory-scale reactors to mimic potential heating malfunctions. Reducing the temperature from 55 to 20 °C for durations of 1, 5, 12, and 24 hours in various reactors nearly halted biogas production. However, production could be resumed by returning the temperature to 55 °C.Nsair et al. (2020) reviewed that temperature fluctuations should be avoided, with more than ±3 °C/ day under mesophilic conditions and more than ±1 °C/ day under thermophilic conditions.Beside temperature the production of biogas,is influenced by various factors, including the carbon-to-nitrogen (C/N) ratio, food-to-microorganism (F/M) ratio, and pH, which affect the microbial community's balance and activity. The organic loading rate (OLR), hydraulic loading rate (HLR), and presence of toxins also impact the rate of biogas production, and the mode and intensity of mixing the feedstock are critical aspects that affect the efficacy of the digestion process(Tg et al., 2022).The plant performance and biogas production analysis demonstrated the viability of the PAU Model Batch Type Paddy Straw Biogas Plant as a reliable source of renewable energy. The observed variations in production rates highlight the importance of considering seasonal factors and implementing appropriate maintenance protocols to ensure optimal year-round performance. While pre-treatment methods could potentially enhance efficiency, farmers may lack the knowledge and time required to apply such techniques to large quantities of paddy straw.Naik et al. (2022) investigated the conversion of rice straw to biogas was enhanced through anaerobic digestion, using pre-treatment methods such as dilute alkaline and low-power microwave techniques, resulting in biogas yields of up to 418.5 NmL/gVS (96% higher) and 458.8 NmL/gVS (114% higher) respectively. Another such study done by Gandhi et al. (2024)explored ultrasound pre-treatment of rice straw and its combination with anaerobic digestion, optimizing parameters to achieve a 64.63% increase in soluble chemical oxygen demand and nearly four times higher biogas generation compared to untreated samples, demonstrating ultrasound's effectiveness in enhancing biogas production.Although beside temperature, other factors were not studied in the present study.

Despite the overall positive performance, the study encountered some technical challenges, particularly with the biogas flowmeter malfunctioning due to moisture accumulation. This issue resulted in data gaps for several days in August, which were addressed through interpolation based on the plant's performance trends. Additionally, a minor digester leakage was detected and promptly repaired in early September, which may have contributed to the lower production rates observed in that month.These challenges are not new and are commonly encountered, as previously reported by Afridi and Qammar (2020) for other types of biogas plant also.

3.2 Economic Analysis

The economic feasibility analysis of a paddy straw-based biogas plant reveals promising potential. With an annual paddy utilization of 64 quintals, the plant offers significant savings on LPG cylinders, averaging Rs. 20,400 per year. While operating costs amount to Rs. 17,600 annually, the additional income from biogas slurry sales (Rs. 44,800) substantially boosts the plant's economic viability. The net annual savings of Rs. 47,600 indicate a positive financial outcome. However, with an initial investment of Rs. 4,00,000, the payback period extends to approximately 8.4 years, suggesting a long-term commitment is necessary to realize the full economic benefits of this sustainable energy solution. The economic analysis demonstrates that the PAU Model Batch Type Paddy Straw Biogas Plant is not only environmentally sustainable but also economically viable for rural households. The combination of energy cost savings, additional income from organic fertilizer, and relatively low operational costs makes this technology an attractive investment for farmers, with the potential to significantly improve their economic conditions while promoting sustainable energy use and waste management practices.

3.2.1 Economic Feasibility Analysis of a Paddy Straw-Based Biogas Plant:

- Paddy straw utilization: 64 quintals (16 quintals/batch @ 4 batches/year) of paddy can be utilized per year.
- Annual savings from LPG cylinders:
  - Minimum savings: 1 cylinder/month * 12 months * Rs. 850 = Rs. 10,200 per year
  - Maximum savings: 3 cylinders/month * 12 months * Rs. 850 = Rs. 30,600 per year

  Average savings: (Rs. 10,200 + Rs. 40,800) / 2 = Rs. 20,400 per year
- Annual operating costs:
  - Paddy straw cost: Rs. 9,600 (64 quintals@ Rs150/quintal)
  - Labour cost: Rs. 8,000 (Rs 2000/ filling and refilling)

  Total annual operating cost: Rs. 9,600 + Rs. 8,000 = Rs. 17,600
- Additional income from biogas slurry:
  - Amount of slurry produced per year: 56 quintals (14 quintal/batch)
  - Price of slurry: Rs. 8/kg

  Annual income from slurry: 5600 kg x Rs. 8/kg = Rs. 44,800 per year
- Net annual savings:

  Net annual savings = Annual savings from LPG + Annual income from slurry - Annual operating costs

  Net annual savings = Rs. 20,400 + Rs. 44,800 - Rs. 17,600 = Rs. 47,600
- Payback period (years to recover the cost of the plant):

  Payback period = Cost of plant / Net annual savings

  Payback period = Rs. 4,00,000 / Rs. 47,600 = 8.4 years

3.3 User Experience and Social Impact

The user experience and social impact of the PAU Model Batch Type Paddy Straw Biogas Plant were evaluated through interactions with farmers in both Dholu and Maghawali villages (Fig. 8). The feedback received was overwhelmingly positive, with farmers expressing satisfaction with the plant's performance, ease of operation, and the benefits it provided.

Fig.8: Interaction of research team with the farmers for feedback

The biogas plant also had a positive impact on the farmers' quality of life. The provision of a reliable and clean source of energy for cooking reduced their dependence on traditional fuels, such as firewood, kerosene and LPG. The farmers reported a significant reduction in indoor air pollution, which is a major health risk in rural areas.

3.3.1 Environmental Benefits

The PAU Model Batch Type Paddy Straw Biogas Plant offers several environmental benefits that make it an attractive solution for rural energy needs. One of the most significant advantages is the reduction in greenhouse gas emissions. By utilizing paddy straw as a feedstock, the plant reduces the amount of this biomass that would otherwise be burned in the fields, releasing methane and other harmful gases into the atmosphere. Additionally, the biogas produced by the plant is a clean-burning fuel that can replace fossil fuels, further reducing emissions.

The plant also helps to mitigate the environmental impacts associated with paddy straw burning, such as air pollution and soil degradation. By converting paddy straw into biogas, the plant reduces the amount of particulate matter and other pollutants released into the air, improving local air quality. Furthermore, the slurry produced by the plant is a nutrient-rich organic fertilizer that can replace chemical fertilizers, reducing the environmental impacts associated with fertilizer use(Haque et al., 2022).

The plant's design and operation also promote sustainable agriculture practices. By utilizing paddy straw as a feedstock, the plant encourages farmers to adopt conservation agriculture practices, such as reduced tillage and crop rotation, which can improve soil health and reduce erosion. Additionally, the plant's use of biogas as a fuel source reduces the demand for fossil fuels, which can help to mitigate climate change.

Overall, the PAU Model Batch Type Paddy Straw Biogas Plant offers a range of environmental benefits that make it an attractive solution for rural energy needs. By reducing greenhouse gas emissions, mitigating the impacts of paddy straw burning, and promoting sustainable agriculture practices, the plant can help to create a more sustainable and environmentally friendly energy system.

4. Conclusion and Recommendations

The findings of this study have significant implications for the widespread adoption of the PAU Model Batch Type Paddy Straw Biogas Plant in rural areas. The plant's ability to provide a reliable and clean source of energy, while also promoting sustainable agriculture practices, makes it an attractive solution for rural energy needs. However, the study also highlights the need for adequate government support and subsidies to make the technology more accessible and affordable for farmers.Burg et al. (2021) also reported similar findings, which involved investigating the behavior of Swiss farmers towards anaerobic digestion and the impact of incentives on their participation in biogas production. The study, which used a survey and an Agent-Based Model, found that revenue from energy production is the primary driver for biogas facility development, and significant changes are required at multiple levels to fully mobilize the resources' potential.González-Arias et al. (2021)

examined the economic viability of upgrading biogas to biomethane in the Brandenburg region of Germany, using various plant sizes as a basis for their analysis. They found that green policies and subsidies are essential for implementing green energy in smaller-sized plants.

To address the challenges and limitations identified in the study, it is recommended that the government increase the subsidy provided for the installation of biogas plants. This would help to reduce the upfront costs for farmers and make the technology more economically viable. Additionally, the government could provide training and capacity-building programs for farmers to ensure that they have the necessary skills and knowledge to operate and maintain the plants effectively.

Furthermore, it is recommended that the government promote the use of biogas plants through awareness campaigns and outreach programs. This would help to educate farmers about the benefits of the technology and encourage them to adopt it. The government could also provide incentives for farmers who adopt the technology, such as subsidies for the purchase of biogas-powered appliances and their maintenance.

The PAU Model Batch Type Paddy Straw Biogas Plant demonstrates significant potential as a reliable and clean energy source for rural areas, while simultaneously promoting sustainable agricultural practices and contributing to a more environmentally friendly future. By addressing the challenges and limitations identified in this study, it is possible to promote the widespread adoption of this technology and improve the lives of rural communities.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.Name, version, Model: nvidia/Llama-3.1-Nemotron-70B-Instruct-HF

Source: Nvidia

Prompt: Improve my text in english for any grammatical mistakes.

Reference

Afridi, Z. U. R., &Qammar, N. W. (2020). Technical Challenges and Optimization of Biogas Plants. *ChemBioEng Reviews*, *7*(4), 119–129.

Bhattacharyya, P., Bisen, J., Bhaduri, D., Priyadarsini, S., Munda, S., Chakraborti, M., Adak, T., Panneerselvam, P., Mukherjee, A., Swain, S., Dash, P., Padhy, S., Nayak, A., Pathak, H., Kumar, S., &Nimbrayan, P. (2021). Turn the wheel from waste to wealth: Economic and environmental gain of sustainable rice straw management practices over field burning in reference to India. *The Science of the Total Environment*, *775*, 145896.

Burg, V., Troitzsch, K. G., Akyol, D., Baier, U., Hellweg, S., &Thees, O. (2021). Farmer's willingness to adopt private and collective biogas facilities: An agent-based modeling approach. *Resources Conservation and Recycling*, *167*, 105400.

Chalotra, J., &Sooch, S. S. (2020). Development and Optimization of Mild Steel Biogas Plant for utilizing Paddy Straw Residue. *International Journal of Current Microbiology and Applied Sciences*, *9*(1), 2532–2543.

Chaudhary, G., Chaudhary, N., Saini, S., Gupta, Y., Vivekanand, V., &Panghal, A. (2024). Assessment of pretreatment strategies for valorization of lignocellulosic biomass: path forwarding towards lignocellulosic biorefinery. *Waste and Biomass Valorization*, *15*(1), 1-36.

Datta, A., Emmanuel, M. A., Ram, N. K., & Dhingra, S. (2020). Crop residue management: solution to achieve better air quality. *New Delhi: TERI*, *9*.

González-Arias, J., Baena-Moreno, F. M., Gonzalez-Castaño, M., Arellano-García, H., Lichtfouse, E., & Zhang, Z. (2021). Unprofitability of small biogas plants without subsidies in the Brandenburg region. *Environmental Chemistry Letters*, *19*(2), 1823–1829.

Haque, S., Singh, R., Pal, D. B., Harakeh, S., Alghanmi, M., Teklemariam, A. D., Abujamel, T. S., Srivastava, N., & Gupta, V. K. (2022). Recent Update on anaerobic digestion of paddy straw for biogas production: Advancement, limitation and recommendations. *Environmental Research*, *215*, 114292.

Karwasra, N., Yadvika, Yadav, Y. K., Chaudhary, G., Malik, K., & Verma, K. (2022). A comparative study for biogas production using pressmud, bagasse and paddy straw.*Environment and Ecology*, 40 (3A),1250—1255.

Kaur, K., &Phutela, U. G. (2014). Improving paddy straw digestibility and biogas production through different chemical-microwave pretreatments. *Agricultural Science Digest-A Research Journal*, *34*(1), 8-14.

Mondal, C., & Biswas, G. K. (2013). Effect of temperature on kinetic constants in anaerobic bio-digestion. *Chitkara Chemistry Review, 1*(1), 19–28.

Mothe, S., Sukesh, M., Rao, P. V., & Sridhar, P. (2024). Rice straw anaerobic co-digestion: Comparing various pre-treatment techniques to enhance biogas production. *Bioresource Technology Reports*, 101788.

Naik, G. P., Poonia, A. K., & Chaudhari, P. K. (2024). Maximization of biogas by minimal microwave and alkaline pretreatment of rice straw. *Biomass Conversion and Biorefinery*, *14*(13), 14365-14378.

Nsair, A., Cinar, S. O., Alassali, A., Qdais, H. A., &Kuchta, K. (2020). Operational Parameters of Biogas Plants: A Review and Evaluation Study. *Energies*, *13*(15), 3761.

Panda, S., & Jain, M. S. (2023). A Review on Sustainable Rice Straw Management Through Anaerobic Digestion. *Lecture Notes in Civil Engineering*, 35–46.

Parshad, J., Kumar, R., Chhokar, V., Patil, N., Beniwal, V., Singh, N., Kumar, A., Singh, N., Yogi, R., Kumar, M., Vikram, P., Chauhan, A., & Kumar, A. (2024). Paddy straw management: alternative strategies and emerging technology for sustainable ecosystem. *Pedosphere*.

Saharan, B. S., Dhanda, D., Mandal, N. K., Kumar, R., Sharma, D., Sadh, P. K., Jabborova, D., &Duhan, J. S. (2024). Microbial contributions to sustainable paddy straw utilization for economic gain and environmental conservation. *Current Research in Microbial Sciences*, *7*, 100264.

Satpathy, P., & Pradhan, C. (2020). Biogas as an alternative to stubble burning in India. *Biomass Conversion and Biorefinery*, *13*(1), 31–42.

Shafie, S., Mahlia, T., &Masjuki, H. (2013). Life cycle assessment of rice straw co-firing with coal power generation in Malaysia. *Energy*, *57*, 284–294.

Singh, R., & Kumar, S. (2019). A review on biomethane potential of paddy straw and diverse prospects to enhance its biodigestibility. *Journal of Cleaner Production*, *217*, 295-307.

Tg, I., Haq, I., &Kalamdhad, A. S. (2022). Factors affecting anaerobic digestion for biogas production: a review. Elsevier eBooks, 223–233.

Wu, M., Sun, K., & Zhang, Y. (2006). Influence of temperature fluctuation on thermophilic anaerobic digestion of municipal organic solid waste. *Journal of Zhejiang University SCIENCE B*, *7*(3), 180–185.