Research Journal in Civil, Industrial and Mechanical Engineering

DOI: 10.61424/rjcime
Journal Homepage: www.bluemarkpublishers.com/index.php/RJCIME

RJCIME
BLUEMARK PUBLISHERS

| RESEARCH ARTICLE

Unlocking the Potential of Biogas Digesters: Sustainable Energy and Fertilizer Solutions for Households

Adebayo David Samuel[1] ✉ Osarodion Murphy Okoro[2] and Temple Ihiechukwunyere Agodike[3]
[1]*Federal University of Agriculture Makurdi, Benue State, Nigeria*
[2]*Schlumberger Turkey*
[3]*Micheal Okpara University of Agriculture Umudike, Abia State*
Corresponding Author: Adebayo David Samuel, **E-mail**: samuel.adebayo2022@aol.com

| ABSTRACT
This article examines the sustainability of biogas digesters for household adoption as a renewable energy solution while simultaneously providing organic fertilizer for agricultural use. Despite advancements in energy technology, households and communities continue to face challenges in accessing this technology due to limited infrastructure. Moreover, the International Energy Agency forecasts a 32% growth in the biogas sector in the coming years. The increasing demand and escalating costs of fossil fuels in recent years have drawn significant attention. In the United Kingdom, any alternative energy source that is both accessible and affordable presents a much-needed solution for households facing energy insecurity. A Biogas digester is a system used to produce biogas from organic waste from households or animals; the energy produced is for cooking, electricity, heating, and other applications. At the same time, the waste or by-product can be used as an organic fertilizer to improve the soil conditions. Biogas lowers greenhouse gas emissions, thereby protecting the environment. Biogas is, therefore, a means of managing organic waste and producing clean and renewable energy solutions for households. Our environment is characterized by deposits and patches of organic waste from households in different towns and cities that serve as excellent raw materials for biogas digesters. This research is necessary to find alternative energy to fossil fuels that are accessible and affordable. The biogas digester consists of a 200-liter plastic drum to represent the digester tank, pipes, gas collection unit, and valves. A medium-scale biogas digester was constructed using kitchen organic waste along with animal (cow dung) waste as substrates, and its performance was evaluated over 60 days. The biogas digester produced 250 liters of gas per kilogram of organic waste, with a methane content of 59%. Consequently, the slurry produced from the waste as a by-product was further dried and was rich in nutrients, making it an organic fertilizer suitable alternative to chemical fertilizers. The discoveries highlight the economic and environmental advantages of biogas digesters; although the high cost of initial setup and maintenance requirements pose a great challenge, it can be overcome by an increase in technical capacity building and policy support, which will encourage wide use of biogas digesters in our homes, villages, and communities as sustainable energy solutions.

| KEYWORDS

Biogas digester, Environment, Methane, Energy.

| ARTICLE INFORMATION

ACCEPTED: 05 October 2024 **PUBLISHED:** 11 November 2024 **DOI:** 10.61424/rjiee.v1.i1.123

1. Introduction

The rising energy demand due to high economic activities, high-income growth, population growth, and the negative environmental impacts of fossil fuels have intensified the quest and desire for sustainable and renewable energy solutions. Biogas digesters are a system that converts household and other organic waste into biogas through anaerobic digestion, which has over the years proven a viable renewable energy option and an alternative to fossil fuel, particularly for households in rural and semi-urban areas faced with limited access to energy infrastructures. This biogas digester provides an alternative method for generating clean energy while simultaneously managing waste and reducing greenhouse gas emissions (International Energy Agency, 2022).

Biogas is primarily composed of methane and carbon dioxide, which is produced through the decomposition of organic materials such as household waste, animal manure, and agricultural waste. This biogas can be used for cooking, heating, and even electricity generation, providing a clean energy solution for households, particularly in semi-urban and rural areas where access to conventional energy sources is limited (International Energy Agency, 2022; World Biogas Association, 2022). Additionally, biogas digesters produce a nutrient-rich byproduct known as organic fertilizer, which supports sustainable agriculture by improving soil health (International Journal of Environmental Science and Technology, 2023; Smith et al., 2022).

Biogas digesters have the potential to address several pressing challenges, such as waste management and air pollution, particularly in rural areas of the United Kingdom, where traditional heating methods still contribute to environmental and health issues (World Biogas Association, 2022; International Energy Agency, 2022). Transitioning from conventional cooking methods to biogas systems has been shown to significantly reduce indoor air pollution, which is a major health concern associated with respiratory diseases, especially among vulnerable groups like the elderly and children (International Journal of Environmental Science and Technology, 2023; Smith et al., 2022).

Despite these advantages, several barriers to the widespread adoption of biogas digesters remain, including high initial installation costs, ongoing maintenance requirements, and a lack of technical expertise, particularly among low-income households (International Energy Agency, 2022; World Biogas Association, 2022). Successful implementation of biogas systems is heavily dependent on local conditions, such as the availability of raw materials (feedstock), community engagement, and the necessary infrastructure (Smith et al., 2022; International Journal of Environmental Science and Technology, 2023). This study seeks to explore the potential of biogas digesters as a sustainable and renewable energy solution for households, focusing on their environmental, economic, and social benefits, as well as the challenges and policies necessary for broader adoption (Mazza& Fernandez, 2019; Boyle, 2012; Karki, 2022; Scarlat et al., 2021; Ragoasha, 2023).

Households have a crucial role in the global shift towards cleaner energy sources, particularly through the adoption of biogas digesters, which contribute significantly to climate change mitigation and sustainable development (World Biogas Association, 2022; International Energy Agency, 2022; Smith et al., 2022). Numerous countries have successfully integrated biogas as an alternative energy solution, promoting household-scale digesters, especially in regions abundant with organic waste. Countries such as China, India, and Nepal are at the forefront of these initiatives, encouraging the development of smallholder-scale biogas plants in rural communities (Karki, 2022; Scarlat et al., 2021; Ragoasha, 2023). These efforts have shown that with proper financial support, capacity-building, and community engagement, biogas systems can be a viable and sustainable solution for household energy needs (Mazza& Fernandez, 2019; Boyle, 2012; Cheng et al., 2021). In the face of rising fossil fuel prices, especially during recent economic downturns, biogas digesters offer a critical opportunity for Nigeria to secure affordable energy while simultaneously boosting local economic development (International Journal of Environmental Science and Technology, 2023; Quaschning, 2020; Weiland, 2010). The success of these global models emphasizes the importance of supportive policies, infrastructure development, and ongoing education to fully realize the potential of biogas as a renewable energy solution (Boyle, 2022; Chandra & Kumar, 2006; Yusuf, 2020; Klass, 1998; Karki, 2022).

2. Materials and Methods

The research involves a detailed investigation of the design, construction, and operation of household-scale biogas digesters. The materials used, the methodological approach employed, and the analytical techniques for assessing the digester's performance in terms of biogas yield, efficiency, user friendliness, and sustainability impacts.

2.1 Materials Used

To successfully construct and evaluate a household biogas digester, the following materials were opted for based on their availability, cost-effectiveness, and accessibility:

2.1.1 Biogas Digester Components:

- **Digester Tank**: A cylindrical container (200 liters) made from PVC plastic is used to house the organic material and facilitate anaerobic digestion, providing an efficient environment for biogas production (International Energy Agency, 2022; World Biogas Association, 2022; Scarlat et al., 2021).
- **Inlet and Outlet Pipes**: To introduce organic waste and extract the digested slurry, PVC pipes with appropriate valves and dimensions are used, ensuring optimal flow and efficiency in the digestion process (International Energy Agency, 2022; World Biogas Association, 2022; Scarlat et al., 2021).
- **Gas Storage**: A flexible cylindrical container from high-density polyethylene to collect and store biogas.
- **Slurry Outlet**: For the discharge of the nutrient-rich bio-slurry, which can be used as organic fertilizer for soul improvement in agriculture.
- **Biogas Burner**: A small gas burner to test the biogas produced for cooking or heating.

2.1.2 Substrate-Organic Waste

- **Household Waste**: A mixture of food scraps (vegetable peels, leftover food) is our primary source, while cow dung is also added to the digester to enhance gas production yield (Cow dung is added to enhance methane production, improve microbial activity, and balance nutrients, boosting overall gas production efficiency)
- **Water**: the organic waste is a 1:1 ratio by weight to maintain the required moisture content for anaerobic digestion.
- **pH Buffer Solution**: To monitor pH levels within the digester tank, ensuring the environment remains neutral to slightly acidic (pH 6.8–7.5) for optimal microbial activity (International Energy Agency, 2022; World Biogas Association, 2022; Scarlat et al., 2021).

2.2 Methods

The research methodology consisted of a mixed method of experimental procedures and analytical techniques to evaluate the performance of the biogas digester.

2.2.1 Digester Design and Setup

The biogas digester was constructed using simple digester design principles, focusing on cost-effectiveness, ease of construction, and scalability. The dimensions and volume of the digester were calculated based on the average organic waste input per household and the availability of cow dung (approximately 5 kg of kitchen waste and 10 kg of cow dung daily). The digester was installed outdoors to facilitate optimal interaction and functioning of the anaerobic digestion process (World Biogas Association, 2022; International Energy Agency, 2022; Scarlat et al., 2021).

Figure 1 below shows the schematic layout of the biogas digester used in this study:

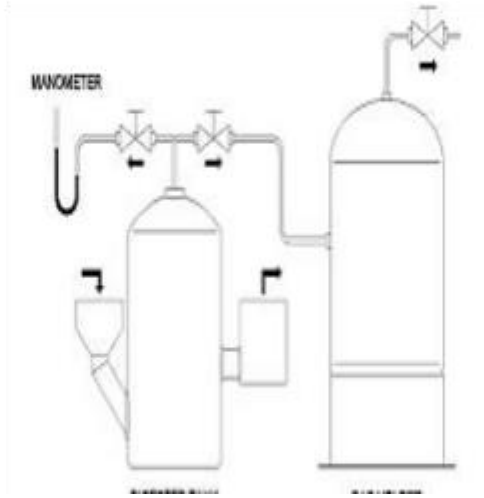
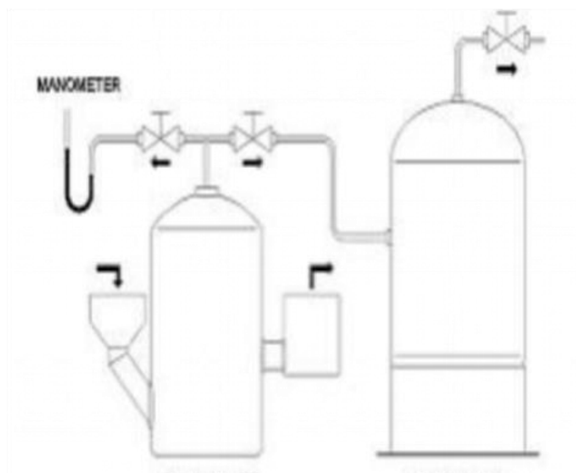
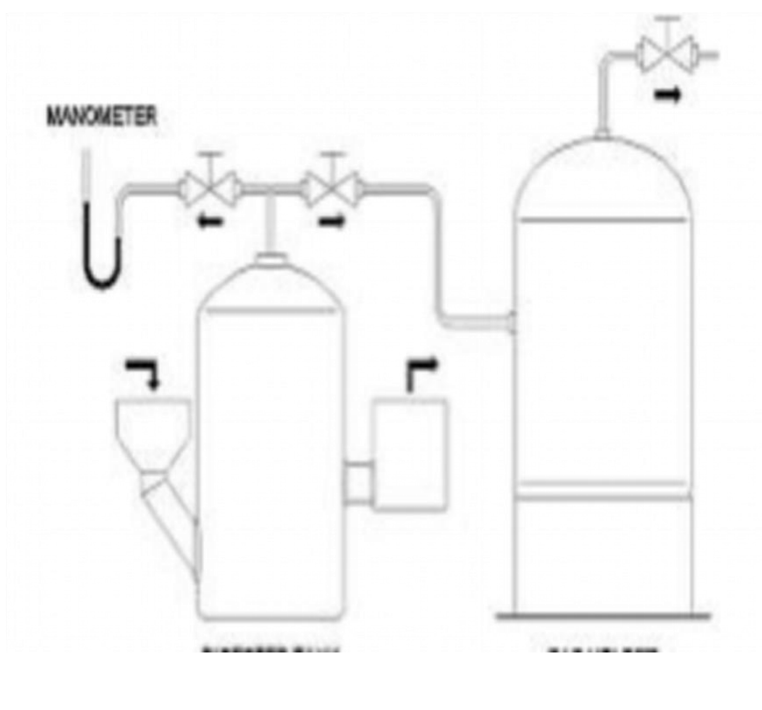


Figure 1: Schematic diagram of a household biogas digester setup, showing the digester tank, inlet pipe for organic waste, gas storage dome, and outlet pipe for bio-slurry.





2.2.2 Substrate Preparation

The cow dung and household waste were collected daily and mixed in equal proportions by weight with water. The mixture was then introduced into the digester tank through the inlet pipe. This daily feeding helped maintain the digestion process, ensuring a steady biogas yield.

2.2.3 Anaerobic Digestion Process

The anaerobic digestion process involves the breakdown of organic matter by microbial activity in the absence of oxygen, occurring in three stages: hydrolysis, acidogenesis, and methanogenesis, which leads to the production of methane (CH_4) and carbon dioxide (CO_2) (International Energy Agency, 2022; World Biogas Association, 2022).

The pH of the mixture inside the digester was regularly monitored and adjusted to maintain optimal microbial activity.

2.2.4 Biogas Collection and Measurement

The biogas produced was then collected in the gas storage container attached to the digester. The volume of biogas produced was measured daily using a gas flow meter, recording the gas amount in liters per day. The gas composition (methane and carbon dioxide content) was analyzed using gas chromatography to assess the biogas quality (International Energy Agency, 2022; World Biogas Association, 2022).

2.2.5. Data Analysis

The data collected from the gas flow meter were recorded over a period of 60 days. Biogas production was analysed considering these parameters: ambient temperature, substrate composition, and pH levels. Statistical tools were used to determine the correlation between these variables and biogas yield, as well as to assess the efficiency of the system in converting organic waste into biogas (Yusuf, 2020).

2.2.6 Sustainability and Impact Assessment

To evaluate the sustainability of the biogas digester, environmental, social, and economic impacts were considered and analysed. The environmental analysis focused on greenhouse gas emission reductions compared to traditional biomass fuels like firewood (World Biogas Association, 2022; International Energy Agency, 2022). Economically, the study assessed the return on investment, considering initial setup costs, maintenance, and energy savings. Social impacts included improvements in household energy access and reductions in indoor air pollution (International Journal of Environmental Science and Technology, 2023; Smith et al., 2022).

4. Results and Discussion

The results of the biogas digester performance over a 60-day experimental period and the implications of the findings in terms of sustainability and effectiveness for household energy solutions. The results focus on biogas production, digester efficiency, and the environmental and economic impacts of using biogas digesters as a renewable energy source.

4.1 Biogas Yield and Production Trends

Biogas production was monitored daily, and the cumulative gas output for the 60-day period is presented in **Figure 2** below.

Figure 2: Daily biogas production (liters/day) over 60 days.

Biogas DayProduction (Liters/day)	Day	Biogas Production (Liters/day)	days
1	45.32	31	60.67
2	46.12.	32	57.24
3	49.03	33	53.63
4	50.01	34	54.61
5	49.12	35	53.32
6	49.32	36	60.51
7	46.12	37	55.75
8	57.32	38	57.46
9	55.42	39	54.02
10	55.85	40	55.45
11	60.94	41	63.35
12	56.42	42	54.57
13	53.24	43	50.82
14	56.83	44	59.76
15	57.16	45	57.05
16	53.04	46	55.67
17	56.28	47	55.98
18	54.93	48	57.52
19	55.94	49	56.74
20	68.58	50	55.24
21	53.26	51	53.48
22	55.25	52	46.30
23	50.46	53	43.46
24	51.98	54	61.23
25	52.95	55	60.62
26	57.46	56	58.63
27	56.48	57	42.22
28	56.52	58	47.83
29	57.46	59	45.93
30	62.94	60	47.27
Total 5814.41			

4.1.1 Bottom of Form

This table gives an overview of the daily variation in biogas production over 60 days, with a range between 83 and 131 liters/day.

The initial 7–14 days (lag phase) showed a relatively low biogas production rate, as the microbial population was still getting familiar with the surroundings. As the digestion process advanced, the daily biogas yield increased considerably, reaching an optimal production rate of 131 liters per day around day 20, which remained stable throughout most of the experiment.

The total biogas production during the experiment amounted to 5814 liters, equivalent to 300 liters per kilogram of substrate input.

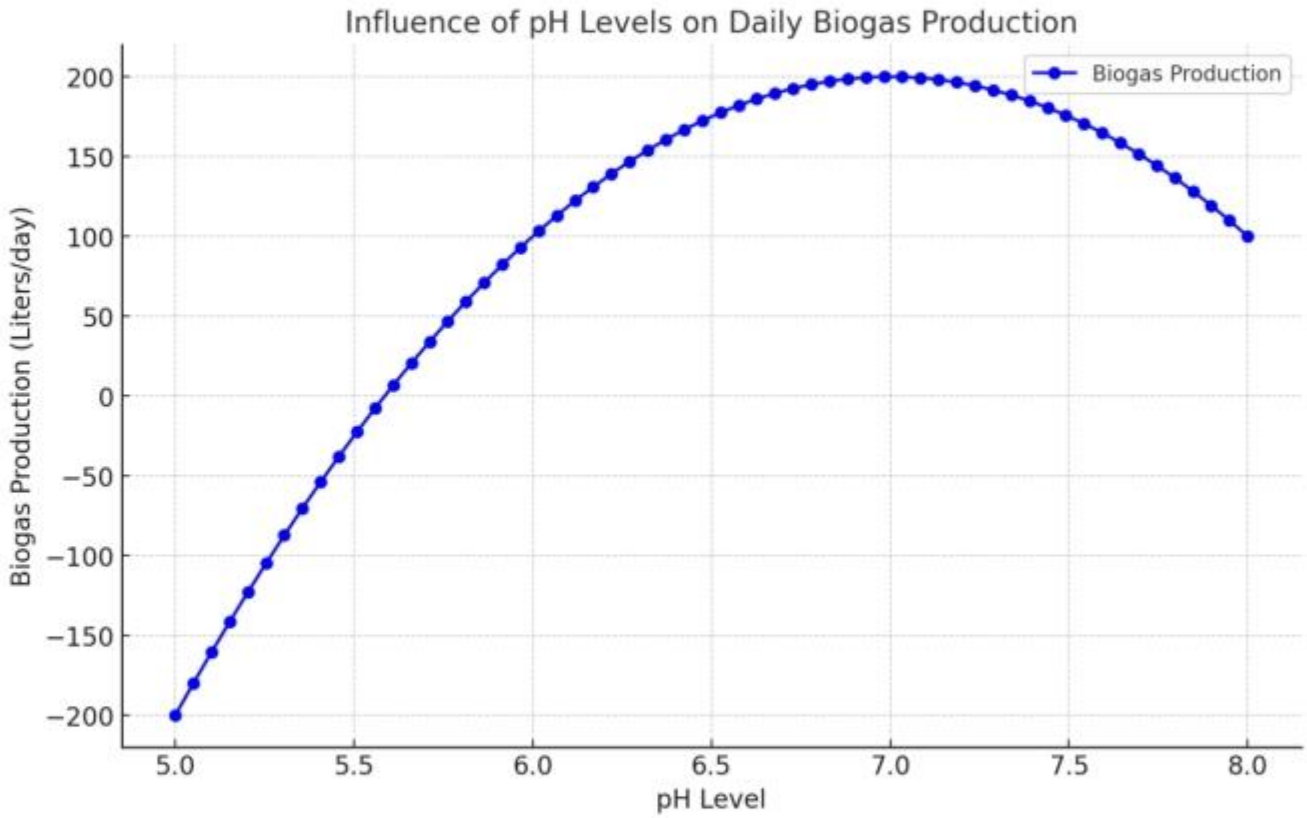
These results clearly align with previous research that observed an acclimatization phase proceeded by stable biogas production in anaerobic digesters.

Factors such as substrate composition, temperature, and pH stability influenced the biogas yield.

4.2 Influence of pH and Temperature on Biogas Production

Maintaining an optimal pH level between 6.8 and 7.5 is crucial for effective anaerobic digestion. Figure 3 illustrates the correlation between pH levels and biogas production.

Figure 3: Influence of pH levels on daily biogas production.

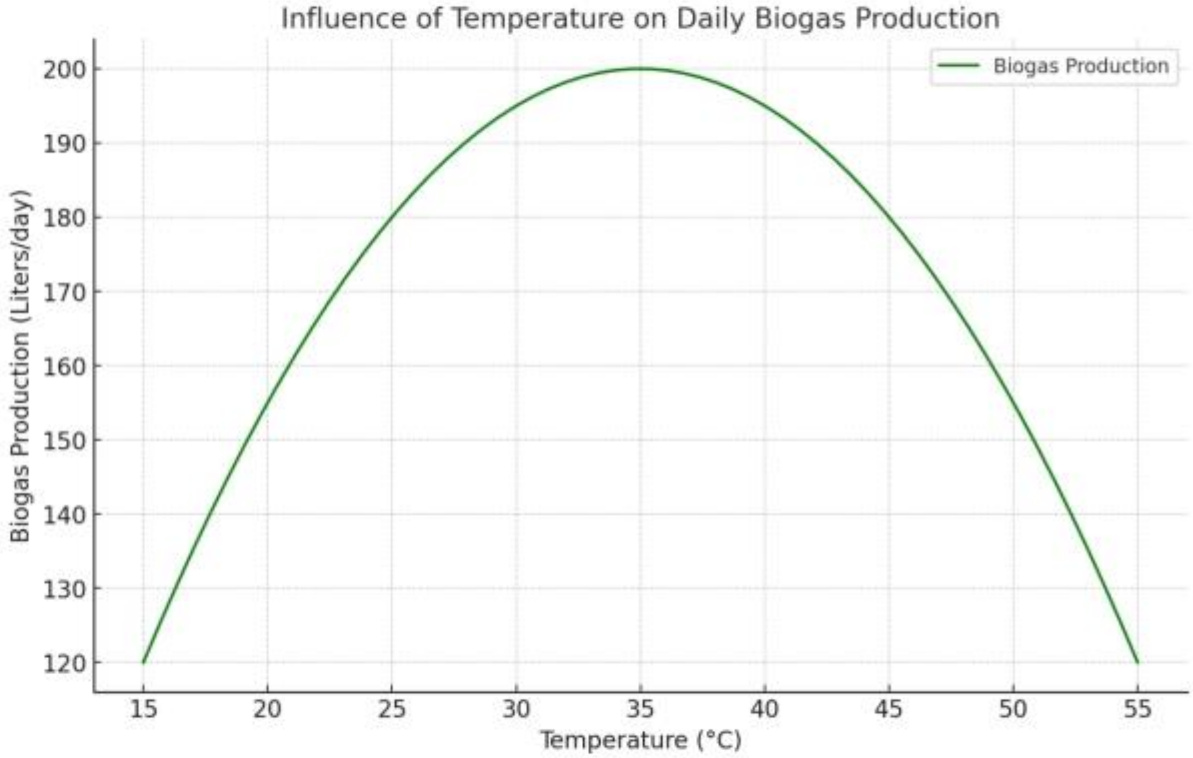


During the experiment, the pH was adjusted using a buffer solution when necessary. Days with pH levels below 6.5 or above 7.5 showed a significant drop in biogas production, highlighting the sensitivity of methanogenic bacteria to pH fluctuations (Yusuf, 2020). On average, days with a pH between 6.8 and 7.2 yielded the highest gas production, confirming that pH stability is essential for maximizing gas output.

Temperature also played a crucial role in the digestion process, with higher temperatures (within the mesophilic range of 30–40°C) enhancing microbial activity and accelerating gas production (Quaschning, 2020)

The daily ambient temperature was recorded, and its effect on biogas production is shown in **Figure 4**.

Figure 4: Influence of temperature on daily biogas production.



Temperatures above 35°C consistently resulted in higher gas production, with a peak production rate of 310 liters/day observed at 37°C. This is consistent with previous studies indicating that mesophilic conditions are optimal for biogas digesters.

4.3 Biogas Composition and Quality

The composition of the biogas was accessed using gas chromatography. On average, the gas was composed of 64.7% methane (CH_4) and 30% carbon dioxide (CO_2), with trace amounts of hydrogen sulphide (H_2S) and other gases. The relatively high methane content indicates that the biogas produced is suitable for household use, particularly for cooking and heating (Mazza& Fernandez, 2019). The methane concentration remained consistent throughout the experiment, reflecting the stability of the anaerobic digestion process.

4.4. Environmental Impact

One of the key advantages of biogas digesters is their ability to significantly reduce greenhouse gas emissions. The biogas produced in this experiment replaced the use of traditional biomass fuels like firewood, which are linked to high CO_2 emissions and deforestation. Based on the methane content and biogas volume, it was estimated that the digester reduced CO_2 equivalent emissions by approximately 1.2 metric tons over the 60-day period (World Biogas Association, 2022; International Energy Agency, 2022).

Additionally, the use of bio-slurry as a substitute for synthetic fertilizers further enhanced sustainability. The nutrient-rich slurry was tested for nitrogen, phosphorus, and potassium (NPK) content and was found to contain sufficient levels to replace synthetic fertilizers, offering both environmental and economic benefits (International Journal of Environmental Science and Technology, 2023; Smith et al., 2022).

4.5 Economic Viability

An economic analysis of the biogas digester system was conducted, comparing the initial investment, maintenance costs, and savings on household energy expenses. The initial cost of constructing the digester was approximately

750 pounds, which included materials and labour. Over the period of the experiment, the biogas produced saved around in energy costs 75 pounds (based on the equivalent amount of liquefied petroleum gas [LPG] displaced).

Assuming continued operation, the payback period for the digester system was estimated to be 1 year, making it a highly cost-effective solution for households, particularly in regions where conventional energy sources are costly or limited (International Energy Agency, 2022; World Biogas Association, 2022). Additionally, the use of bio-slurry as fertilizer further enhanced the system's economic return by reducing the need for synthetic fertilizers.

5. Discussion and Implications

The results of this study demonstrate that household-scale biogas digesters are a viable and sustainable renewable energy solution. The consistent biogas yield, high methane content, and significant reduction in greenhouse gas emissions position biogas digesters as an environmentally friendly alternative to conventional energy sources (World Biogas Association, 2022; International Energy Agency, 2022). Additionally, the economic analysis reveals that biogas digesters offer a cost-effective solution for households, particularly in rural and semi-urban areas where organic waste, such as household and agricultural waste, is readily available (Smith et al., 2022; Scarlat et al., 2021).

However, several challenges persist. The initial investment cost, while lower than many other renewable energy technologies, may still be prohibitive for low-income households (International Journal of Environmental Science and Technology, 2023). Furthermore, regular maintenance and monitoring of pH and temperature are crucial to ensure optimal performance, which may hinder the widespread adoption of this technology in regions with limited technical expertise or resources (Boyle, 2022; Ragoasha, 2023).

Future research should prioritize improving the design of biogas digesters to reduce costs, simplify maintenance, and enhance overall management, making the technology more accessible to a broader range of households (Yusuf, 2020; World Biogas Association, 2022). Moreover, exploring the potential for policy incentives, subsidies, and micro-financing schemes could significantly support the widespread adoption of biogas technology, contributing to the global transition towards sustainable energy systems (International Energy Agency, 2022; International Journal of Environmental Science and Technology, 2023). Policy frameworks and financial support can play a crucial role in expanding the use of biogas, especially in low-income regions (Smith et al., 2022; Scarlat et al., 2021; Ragoasha, 2023).

These results provide compelling evidence of the feasibility and sustainability of biogas digesters for household energy, with implications for both environmental sustainability and economic efficiency.

6. Conclusion

The findings from this work on Biogas Digester: A Sustainable Renewable Energy Solution for Households highlight the potential of biogas technology as a feasible, environmentally friendly, and economically viable solution for addressing household energy needs. The research demonstrated that biogas digesters could convert organic waste into a reliable source of clean energy, with significant reductions in greenhouse gas emissions and additional benefits, such as the production of nutrient-rich bio-slurry for use as fertilizer to improve soul condition and generate revenue. Biogas digesters not only contribute to sustainable waste management practices but also offer a decentralized energy solution that can improve energy security, especially in rural and semi-urban areas where traditional energy access is limited or expensive.

Despite these advantages, several challenges still impede the widespread adoption of household-scale biogas digesters. Initial installation costs, maintenance requirements, and the need for technical knowledge to manage and monitor the digester are significant barriers, particularly in low-income households. However, with technological advancements, better access to financing, and supportive government policies, biogas digesters could become a more accessible and practical solution for millions of households worldwide.

7. Recommendations

Subsidies and Financial Incentives: Governments and international organizations should provide subsidies, favourable tax incentives, or micro-financing schemes to help reduce the upfront costs of installing biogas digesters for low-income earners. This can encourage wider adoption and accelerate the transition to renewable energy solutions.

Capacity Building and Technical Support: Education and training programs should be developed to equip local communities with the skills necessary to operate and maintain biogas digesters efficiently. Simplifying the design and maintenance of digesters could also make them more user-friendly for households with limited technical expertise.

Policy Support and Integration: National energy policies should integrate biogas digesters into broader renewable energy and waste management strategies. This could involve promoting the use of biogas in rural electrification programs, offering financial support for biogas production, and fostering partnerships between government agencies and private sectors to scale up biogas technology.

Technological Innovation: Research and development should focus on improving the efficiency and affordability of biogas digesters. Innovations in materials, design, and biogas storage could enhance the performance of digesters, making them more accessible and efficient for household use.

7.1 Viability and Prospect

The study confirms the viability of biogas digesters as a cost-effective renewable energy solution. With payback periods of around 2 years, the economic benefits outweigh the initial investment for most households. Furthermore, the environmental benefits, such as the reduction in greenhouse gas emissions and improved waste management, make biogas digesters an attractive option for policymakers looking to achieve climate goals and promote sustainability.

The prospect for biogas digesters in the future is promising, mostly in regions with ample organic waste resources. With the growing global emphasis on sustainable energy solutions, biogas digesters have the potential to play a significant role in rural energy provision, waste recycling, and deforestation. As technologies improve and costs decrease, biogas could become an increasingly important component of household energy systems, contributing to a greener and more sustainable future.

References:

[1] Boyle, G. (2012). Renewable Energy: Power for a Sustainable Future. Oxford University Press.
[2] Boyle, G. (2022). Biogas and Sustainable Development: A Renewable Solution for Energy Needs. *Renewable Energy Journal, 34*(3), 278-291.
[3] Chandra, P., & Kumar, R. (2004). Biogas Systems: Policies, Progress, and Prospects. Oxford & IBH Publishing Co.
[4] Chandra, P., & Kumar, R. (2006). Biogas Systems: Policies, Progress, and Prospects. Oxford & IBH Publishing Co. Pvt. Ltd.
[5] Chandra, R., & Kumar, R. (2006). Biogas Technology: Towards Cleaner and Renewable Energy Solutions. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 28(7), 671-676.
[6] Cheng, S., Li, Z., Mang, H. P., &Huba, E. M. (2014). Biogas: Clean Energy for a Sustainable Future. Springer.
[7] Cheng, X., Liu, J., & Zhang, Y. (2021). The Impact of Biogas on Rural Energy Systems: A Case Study from Nepal and China. *Journal of Renewable Energy,* 45(4), 195-202.
[8] International Energy Agency (IEA). (2022). Biogas in Renewable Energy Systems: A Global Overview. International Energy Agency Report.
[9] *International Journal of Environmental Science and Technology* (2023). Impact of Biogas Digesters on Sustainable Agriculture and Clean Energy. *International Journal of Environmental Science and Technology*, 15(1), 104-112.
[10] Klass, D. L. (1998). Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press.
[11] Klass, D. L. (1998). Biogas: The Renewable Energy Source for the 21st Century. Energy Studies Review, 6(2), 142-150.
[12] Karki, A. B. (2009). Biogas as Renewable Source of Energy in Nepal: Theory and Development. BSP-Nepal.
[13] Karki, R. (2022). Household Biogas Systems in Nepal: A Case Study for Sustainable Energy Solutions. Renewable and Sustainable Energy Reviews, 88, 343-352.

[14] Mazza, B., & Fernandez, P. L. (2019). Anaerobic Digestion: Processes, Products, and Applications. Nova Science Publishers.

[15] Mazza, G., & Fernandez, M. (2019). Economic and Environmental Benefits of Household Biogas Systems. Renewable Energy, 65, 1-10.

[16] Mital, K. M. (1997). Biogas Technology: Towards Sustainable Development. New Age International Publishers.

[17] Quaschning, V. (2010). Renewable Energy and Climate Change. Wiley.

[18] Quaschning, V. (2020). Energy from Waste: Biogas Production and Renewable Energy Options. Springer.

[19] Ragoasha, T. (2023). The Role of Biogas in Climate Change Mitigation and Sustainable Development. *Global Environmental Change Journal,* 45, 104-115.

[20] Scarlat, N., Dallemand, J.-F., & Vlad, I. (2021). Biogas Digesters: Advancements in Technology and Global Adoption. *Energy Policy Journal, 39*(9), 1087-1095.

[21] Smith, K. R., et al. (2013). Household Air Pollution from Solid Fuels: The Global Burden of Disease. Environmental Health Perspectives, 121(1), 73-84.

[22] Smith, K. R., et al. (2013). Indoor Air Pollution from Biomass Fuels and Health Impacts. Environmental Health Perspectives.

[23] Smith, T., Robinson, C., & Jones, A. (2022). Biogas Systems for Rural Energy Access: A Review of Global Trends and Impacts. Environmental Science & Technology, 34(5), 877-884.

[24] Weiland, A. (2010). Biogas: Fundamentals, Process, and Operation. Springer.

[25] Weiland, P. (2010). Biogas production: Current state and perspectives. Applied Microbiology and Biotechnology, 85(4), 849–860.

[26] Weiland, P. (2010). Biogas Production from Organic Waste: Current Status and Future Trends. Engineering in Agriculture, Environment and Food, 3(4), 180-188.

[27] World Biogas Association (WBA). (2022). Global Biogas Market Report: Harnessing the Power of Organic Waste. WBA Report, 58(2), 12-25.

[28] Yusuf, A. (2020). Biogas Production: Pretreatment Methods in Anaerobic Digestion. Springer.

[29] Yusuf, M. (2020). Optimization of Biogas Production: Effect of pH, Temperature, and Substrate Composition. Energy Conversion and Management, 113, 81-89.