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Advancing Renewable Energy in Rural India: An techno-economic Evaluation of the Deenbandhu Biogas Model in Rajasthan

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Abstract: This research investigated the potential of biogas technology, particularly the Deenbandhu model, as a sustainable energy solution for Rajasthan. In the backdrop of increasing energy demands due to population growth and industrialization, and heavy reliance on imported fossil fuels, the study highlights biogas as a viable alternative. Employing a multifaceted approach, including surveys, interviews, and economic and energy analyses, the research evaluated the adoption, efficiency, and economic viability of biogas plants. Despite Rajasthan's substantial livestock resources indicating a high potential for biogas production, a significant gap exists between theoretical and actual plant installations. The study revealed the socio-economic and environmental benefits of biogas, such as reduced time and labor for women and children, health improvements, decreased dependence on traditional fuels, and enhanced soil fertility through application of biogas slurry. It concludes that fostering biogas technology can effectively reduce fossil fuel reliance, lower CO_2 emissions, and aid India's transition to a low-carbon economy, provided the barriers to adoption are addressed and dissemination strategies under the NBMMP are enhanced.

Key words: Biogas technology, Deenbandhu biogas model, economic viability, renewable energy, rural energy strategy.

The burgeoning human population and the rapid industrialization in India have significantly escalated the demand for energy across various sectors, including domestic, industrial, institutional, agricultural, commercial, and public domains. Presently, a majority of this energy demand, accounting for 92%, is met through fossil fuels-coal (56.26%), oil (29.47%), and natural gas (6.18%). The reliance on these non-renewable resources has not only led to substantial financial outlays for imports but has also contributed to environmental degradation, with fossil fuel combustion emitting 2.59 bt of CO_2 in 2018-19 (Global Carbon Project, 2020). Recognizing these challenges, the Indian Government has been steering the country towards renewable energy resources to mitigate the expenses associated with fossil fuel imports and reduce CO_2 emissions.

Biomass emerges as a pivotal component in transitioning to a low-carbon economy. Recognizing its potential, the Ministry of New and Renewable Energy (MNRE) promulgated the National Policy on Biofuels in 2018, advocating for energy production from various biomass sources such as bio-waste, weeds, agro-wastes, and animal wastes (MNRE, 2011). Biomass, predominantly produced with a water content ranging between 45 to 95%, is amenable to biological fermentation processes including anaerobic digestion (biogas) or biochemical routes (ethanol and methanol). Biogas production through anaerobic digestion represents a sustainable bioconversion technology, providing renewable gaseous fuel while simultaneously stabilizing and reducing waste volume. Typically composed of methane (50 to 70%), carbon dioxide (30 to 45%), and traces of other gases, biogas and its byproduct, digested slurry, are highly beneficial. The slurry, rich in nitrogen (1.5 to 2%), phosphorus (1%), and potash (1%), serves as a superior organic manure compared to traditional farmyard manure due to the breakdown of organic matter during digestion (Nijaguna, 2002).

In India, cattle dung is predominantly used as feed material for biogas plants, leveraging the substantial livestock population, particularly in states like Rajasthan. Despite its vast potential for biogas production, indicated by a considerable livestock count and favorable demographic and agricultural profiles, Rajasthan has a notable gap between the potential and actual installation of biogas plants. This study aims to bridge this knowledge by examining the factors influencing the adoption and implementation of biogas technology, especially under the National Biogas and Manure Management Program (NBMMP). It focuses on assessing the dissemination strategies, environmental benefits, net energy output, and economic viability of family-sized biogas plants in Rajasthan. In India, Ministry of New and Renewable Energy sponsored a scheme New National Biogas and Organic Manure Program (NNBOMP) since 1981 wherein a total of 8 designs of biogas plant were approved for subsidy. Among those all, Deenbandhu biogas plant based on cow dung is one of the economic and popular.

Given its agrarian landscape and substantial livestock population, Rajasthan holds a high potential for biogas production. With the second-largest livestock population in India, the state has potential to use biogas technology for rural energy supply (DAHD, 2019). Despite its potential for 0.915 million family-sized biogas plants, as per the MNRE's assessment, only 72 thousand have been installed till 2018-19 (Akshay Urja Portal, 2023). Knoema (2024) on its portal has shown the number of biogas plans to be 72886 in 2022 indicating an increase of 0.67% in last decade. This gap presents a crucial opportunity for enhancing rural energy security and mitigating climate change by replacing a substantial amount of fossil fuel with biogas.

By employing a comprehensive methodological approach that combines qualitative surveys, beneficiary interviews, economic modeling, and process analysis, this study endeavors to provide in-depth insights into the status, challenges, and prospects of biogas technology in Rajasthan.

Materials and Methods

A multifaceted research approach was adopted for evaluating comprehensively the status and potential of biogas technology in India, with a specific focus on Rajasthan. The study was aimed to understand energy consumption patterns, emphasize vital role of biomass, and delve into the specific dynamics of livestock and biogas potential of Rajasthan. A stratified sampling technique was employed to select a diverse range of households based on their use of biogas plants, particularly the Deenbandhu model (Fig. 1). This model was chosen due to its widespread adoption and cost-effectiveness. Surveys and structured interviews were conducted with the beneficiaries of biogas plants to gather detailed information. The study meticulously quantified the construction materials, embodied energy, and manpower required to build a 2 cubic meter Deenbandhu biogas plant. This analysis of energetics was aimed to calculate the total energy input necessary, encompassing the energy consumed during the production of construction materials and the manual labor involved over the lifecycle of biogas plant.

For technoeconomic assessment of biogas plant construction in Rajasthan for this study the data from the National Biogas and Manure Management Program (NBMMP) among other sources (BDTC Udaipur) were used. The growth rate, regional distribution, and yearly trends of biogas plant installations were calculated using this data to get a macro perspective of

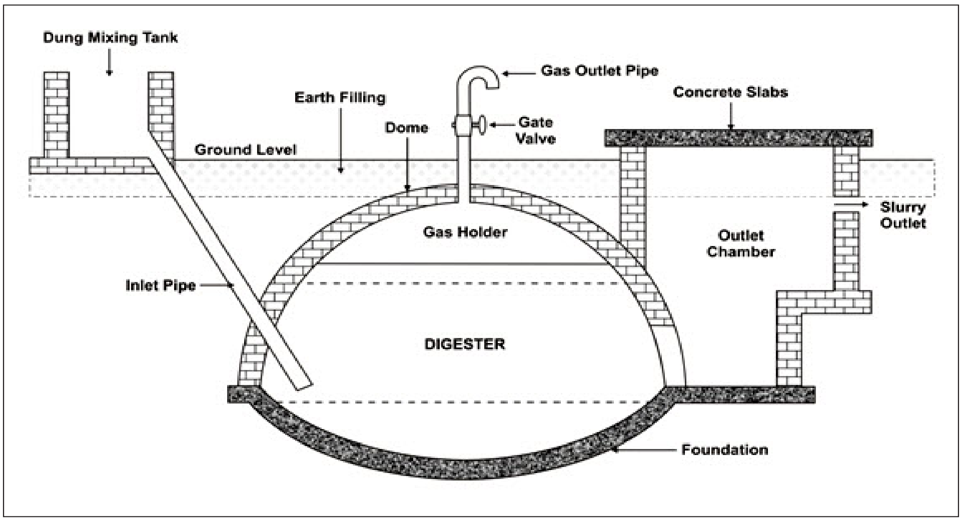

Fig. 1. Design of Deenbandhu Biogas Plant.

the technology's reach and development in the state. Environmental benefits of biogas technology were evaluated by calculating the potential CO_2 savings. Besides, a detailed economic analysis of a 2 m^3 Deenbandhu biogas plant was conducted, which included calculating the net present value (NPV), benefit to cost (B/C) ratio, and payback period for various operational scenarios.

This was done by combining qualitative and quantitative methods, including surveys, interviews, economic modeling, and process analysis (for evaluating net energy production throughout its operational life which also assesses the energy invested in constructing, operating, and maintaining a biogas plant) to approximate annual benefits, operating costs, discount rates, and the plant's expected lifetime.

Net present value (NPV) was calculated by assuming that annual benefits and annual operating cost are uniform over the lifetime t, NPV of the biogas plant can be expressed as –

$$NPV = ((A_b - VC)\ [1-(1+i)^{-t}])/i\ -\ FC$$

where, A_b: Annual benefits from the biogas plant; VC: Annual operating cost (Variable Costs) of the biogas plant; i: Discount rate reflecting the time value of money; t: Lifetime of the biogas plant in years; FC: Fixed Costs or the initial investment cost of the biogas plant.

The Benefit to Cost ratio (B/C ratio) for evaluating the financial viability of the biogas plant is expressed as:

$$B/C = A_b/(VC+iFC/[1-(1+i)^{-t}])$$

where, Ab: Annual benefits from the biogas plant; VC: Annual operating cost (Variable Costs) of the biogas plant; i: Discount rate reflecting the time value of money; FC: Fixed costs or the initial investment cost of the biogas plant; t: Lifetime of the biogas plant in years.

The payback period (PBP) is a financial metric that calculates the time required for an investment to generate cash flows or profits sufficient to recover the initial investment cost. For a biogas plant, considering its initial setup costs and annual net savings, the payback period can be calculated as:

$$PBP = FC/(A_b - VC)$$

where, FC: Fixed costs or the initial investment cost of the biogas plant; A_b: Annual benefits from the biogas plant; VC: Annual operating cost (Variable Costs) of the biogas plant.

In this study, both LPG and firewood cases are considered to calculate annual benefits in terms of fuel and value of slurry equal to urea and direct sale values are considered to calculate annual benefits in terms of slurry.

To understand the social implications, the study involved interviews with biogas plant beneficiaries. Five districts were chosen for evaluation. A total of 129 biogas plants, implemented by BDTC Udaipur, NGOs Humana People to People India (HPPI), Bandikui (Dausa), Jamna Lal Kani Ram Bajaj Trust Sikar, Ambuja Cement Foundation, Chirawa (Jhunjhunu) were visited and the information was collected

Table 1. Biogas plant constructed under NBMMP in Rajasthan during 2009-10 to 2016-17

Financial year	Size wise number of biogas plant constructed				Total biogas plant constructed	Annual biogas production potential (m^3)	Cumulative biogas production potential (m^3)	*Cumulative CO_2 saving per annum (ton)
	2 m^3	3 m^3	4 m^3	6 m^3				
2009-10	31	-	-	-	31	62	62	200.26
2010-11	88	12	-	-	100	212	274	885.02
2011-12	196	18	11	9	234	544	818	2642.14
2012-13	183	29	14	12	238	581	1399	4518.77
2013-14	316	13	12	12	353	791	2190	7073.70
2014-15	847	37	15	16	915	1961	4151	13407.73
2015-16	394	14	16	12	436	966	5117	16527.91
2016-17	369	25	17	16	427	977	6094	19683.62
Total	2424	148	85	77	2734			

*Anaerobic technology can save 3.23 ton of CO_2 equivalent m^{-3} $year^{-1}$ (Pathak *et al.*, 2009).

The questionnaire aimed to gather information from small-scale biogas plant owners in Rajasthan regarding various aspects of their experience with biogas technology. It covered topics such as the primary purpose of the biogas plant, duration of ownership, types of feedstock used, satisfaction with performance, challenges faced, impact on household energy expenses and health, government support received, disposal of bio-slurry, recommendations for improvement, and overall recommendations for others considering biogas technology. The summary emphasizes the importance of understanding user experiences, challenges, and suggestions to enhance the effectiveness and adoption of biogas technology in Rajasthan.

Result and Discussion

Profile of biogas beneficiaries

As per the study, most of the biogas beneficiaries in the Rajasthan State were female. Average household size was six with maximum household size of 11 and minimum household size of three. Out of the total households, 88.66% adopted 2 cubic meter capacity biogas plant followed by 4 cubic meter (5.41%), 3 cubic meter (3.1%), 6 cubic meter (2.81%) and one cubic meter (0.10%). Only Deenabandhu biogas plant was adopted by the beneficiary due to its low maintenance and initial investment compared to other models such as KVIC, Janata and prefabricated designs.

Status of biogas plant constructed in the state

Most of biogas plants (81.34%) of the state are constructed in sub humid and humid region covering three districts where annual rainfall ranged between 40-80 cm and temperature ranged from 28-32°C. Table 1 show a trend of increment of annual biogas plant constructed in Rajasthan during 2009 to 2017. Total biogas plant installation rate each year has been increasing till 2014-15. The highest number of biogas plants were installed during 2014-15 while the highest biogas plant installation growth rate was recorded during 2010-11 (69%) followed by 2014-15 (61.42%). LPG usages have increased in India over the last decade, whereas dung use has decreased significantly (Hanbar and Karve, 2002). The Pradhan Mantri Ujjawala Yojana might be a major cause in decrement of biogas adopters in 2015-16 and 2016-17. Under this scheme, a total of 80 million LPG connections were provided at a very low cost (MOPNG, 2021).

Energetics of a biogas plant

In terms of adoption, the 2 cubic meter Deenbandhu biogas plant constituted a significant percentage among different available sizes, making the analysis of its energetics particularly relevant. This study focuses on the 2 cubic meter model due to its widespread usage. To calculate the total energy input required for constructing this size of the biogas plant, the actual quantity of materials used is accounted for, along with their respective per unit embodied energy- the energy consumed during the production of these materials. This systematic approach enables a comprehensive understanding of the energy dynamics associated with the 2 cubic meter Deenbandhu biogas plant.

Table 3 shows the actual amount of material required for construction of a family-sized biogas plant (Sharma and Samar, 2017). It is

Table 2. Total embodied energy for Deenbanhu Biogas Plant (*Rubab and Kandpal, 1995*)

Material	Unit	Quantity	Per unit embodied energy intensity (MJ)	Total embodied energy intensity (MJ) E_e
Brick	Nos.	1100	5.9	6490
Cement	Bag	15	305	4575
Concrete	Cubic meter	1.27	1600	2032
Sand	Cubic meter	3.5	990	3465
GI pipe	Kg	1	16.4	16.4
PVC pipe	Kg	2	77.2	154.4
Epoxy Paint	Kg	2	5	10.0
Subtotal (A)				16742.8
Man power (B)	Nos.	1	2263	2263
Grand total (A+B) Energy Input				19005.8
Energy Output				256960
Energy yield ratio				13.52

predicted that a family-sized biogas plant will require around half an hour of manual labor every day for feeding the material. If human labor is assumed to be 5 MJ man-day^{-1}, then this ordinary job consumes 0.31 MJ energy day^{-1}. A biogas plant requires a total of 2263 MJ of energy over its 20-year lifespan (Rubab and Kandpal, 1995). The entire amount of energy used by the plant is determined as follows:

Energy Input = Energy consumed for production of constructional material Energy consumed by labor during lifespan

It is assumed that biogas plant is producing gas at its 88% rated capacity. Biogas has calorific value of 20 MJ m^{-3}. Therefore, the energy output from biogas plant is calculated by calorific value of biogas as-

Energy Output = Biogas produced during lifespan Production efficiency Calorific value of biogas

Energy yield ratio can be estimated by dividing the energy output to the energy input. The energy yield ratio for a family-sized Deenbandhu biogas plant (2 m^3) was 13.52 which isgood (Table 2). It also showed that biogas technology is more energetically advantageous.

Economic analysis of a biogas plant

Under this study, a detailed economic analysis of a 2 m^3 Deenbandhu biogas plant has been carried out and empirical estimates of payback period, net present value and benefit-cost ratio were calculated.

Annual cost: The total running cost of biogas plant was calculated by adding fixed cost and operational cost. For a family-sized biogas plant the collection and feeding of dung is mostly done by family members, hence cost of labor is not included and only the cost of dung input is used as the annual operational cost. The total fixed cost (capital cost) of 2 m^3 Deenbandhu biogas plant was calculated to be Rs. 25600 (Table 3). The annual maintenance cost is assumed to be 4% of the capital cost. Hence, the total annual variable cost for a 2 m^3 size biogas plant is-

Variable cost = Operational cost + Maintenance cost

Variable cost = 365 *days* $\times$ $2\ m^3 \times 25$ *kg dung* $m^{-3} \times$ *Rs. 1.0 kg dung*$^{-1}$ + (0.04×25600)= *Rs. 19274*

Annual benefits: Benefit of biogas plant is a critical step for analysis of cost benefits ratio. However, it is difficult to specify market price of the two principal output i.e. biogas and digested slurry of biogas plant. Hence, an indirect approach for evaluating the benefits of the two outputs is to allocate market value in terms of alternative sources for the same end use.

Biogas is mostly used for cooking purpose. Benefits derived from the use of biogas must be evaluated in comparison with other energy sources in terms of their ability to meet energy demands for cooking. According to a survey about family cooking fuel consumption of Rajasthan, about 33% households are using only LPG while 56% of households are dependent on

Table 3. Fixed cost (constructional cost) of 2 m³ Deenbandhu biogas plant (Sharma and Samar, 2017)

Constructional material				
Material	Unit	Cost per unit	Quantity	Price
Brick	Nos.	Rs. 5	1100	5500
Cement	Bag	Rs. 370	15	5550
Concrete	Cubic meter	Rs. 900	1.27	1145
Sand	Cubic meter	Rs. 1100	3.5	3850
GI pipe	Set	Rs. 200	1.0	200
PVC pipe	Meter	Rs. 105	2.0	210
Paint	Kg	Rs. 350	2.0	700
Sub Total - A				17155
Mason Cost				
Mason required for 6 days	No. per day	Rs. 600 per day	1	3600
Labor required for 6 days	No. per day	Rs. 400 per day	2	4800
Sub Total - B				8400
Total Cost (Sub Total A + Sub Total B)				25555
Round off cost (Fixed cost (FC) in Rs.)				25600

solid fuels with LPG supplement connections and remaining 11% households are dependent only on solid fuels such as firewood, dung cakes, coal and agricultural residues (CEEW, 2020). Hence, the cost of biogas is calculated in terms of energy equivalent quantity of firewood and LPG.

Biogas annual value (B_v) $= 365 \times 2\ m^3 \times n_p \times [(Q_b \times n_{bc})/(Q_{cf} \times n_{cf})] \times P_{cf}$

where, n_p represents average annual biogas generation as a fraction of its rated capacity. Q_b is calorific value of biogas, Q_{cf} is calorific value of conventional fuel, n_{bc} is efficiency of a biogas stove and n_{cf} is efficiency of conventional stove.

Biogas plants produce fertilizer in the form of digested slurry which can be compared to aerobic composting or chemical fertilizer production. Nitrogen in cattle dung is retained when processed through a biogas unit but a small part of nitrogen is lost in open pit composting due to evaporation (Kharpude *et al.*, 2017). Hence, the quality of the digested slurry as a fertilizer is dependent on the route taken after post-digesting stage. In this study two routes are taken, first in which it is assumed that a fixed percentage of nitrogen remains in the animal dung after digested anaerobically in a biogas plant, which is defined by the nitrogen retention factor (N_{rf}) while in second method, direct sale value of biogas digested slurry at 30% moisture content is taken. A total of 10.8 tons of slurry is produced by a 2m³ biogas plant annually at 30% moisture content.

Biogas digested slurry value (Sv) $= 365 \times 2\ m3 \times Nrf \times (100/46.6) \times \text{cost of urea } (Pu)$

Total annual benefit arising from the biogas plant is sum of value of biogas as well as digested slurry.

Annual benefits $(A_b) = B_v + S_v$

In assessing the economic viability of a 2 m³ Deenbandhu biogas plant, our analysis encompassed four scenarios based on fuel and fertilizer alternatives. Results (Table 4 and 5) indicated varied financial outcomes across these scenarios. The economic assessment of replacing firewood with slurry in a 2 m³ Deenbandhu biogas plant revealed significant financial advantages. The NPV for this scenario was markedly high at 282,542, indicating substantial long-term benefits over other fuel and fertilizer combinations. This high NPV underscores the considerable economic gain from the investment in the long run. Furthermore, the Benefit to Cost (B/C) ratio for the Firewood and slurry combination was the most favorable among all scenarios, standing at 2.49. This suggests that for every rupee invested, there is an approximate return of 2.49 rupees, reflecting the economic efficiency and profitability of this scenario. Additionally, the Payback Period for this configuration was the shortest at 5 months, indicating a rapid recovery of the initial investment compared to other scenarios. This quick payback period highlights the immediate financial return and

Table 4. Assumption considered for calculating economics of biogas plant

Symbol	Parameter	Base value
n_p	Average biogas generation rate	88%
Q_b	Calorific value of biogas	4713 kCal m^{-3}
Q_{cf}	Calorific value of conventional fuel	4708 kCal kg^{-1} (firewood) 10920 kCal kg^{-1} (LPG)
n_{bc}	Efficiency of a biogas stove	60%
n_{cf}	Efficiency of conventional stove	10% (firewood based cook stove) 65% (LPG cook stove)
N_{rf}	Nitrogen retention factor	60%
P_u	Cost of urea	Rs. 5.36 kg^{-1}
i	Interest rate	10%
t	Lifetime	20 years
P_{cf}	Price of conventional fuel	Rs. 6 kg^{-1} (firewood) Rs. 60 kg^{-1} (LPG)
P_s	Cost of slurry at 30% moisture content	Rs. 3 kg^{-1}

reinforces the viability of adopting the firewood and slurry combination for biogas plants.

Social benefits

As per interviews conducted with the beneficiaries and NGOs, substantial socio-economic benefits of biogas technology were reported. Cent percent of the biogas plants were found to be operational. Almost all biogas plant owners are well-to-do households, basically farmers with an average annual income of Rs. 1.5 Lakhs per annum. The survey result highlights an inverse relation between the level of income and adoption of biogas. The increase in the number of biogas plants as a result of increase in the level of annual income over Rs. 50,000 is reported in as many as 80% cases.

Notably, a reduction in time and effort is observed, particularly benefiting women and children, who redirect this towards education and economic activities. Sixty-seven percent women reported that after installation of biogas plant, time and effort has been reduced for collecting firewood, cooking, and washing utensils. They are using this time to engage in other activities such as farming, petty commerce and so on.

The majority of the households claimed that they were suffering from a variety of smoke-related illnesses, including eye irritation, respiratory issues, headaches, and coughing. However, due to the clean and smokeless environment in the cooking stove created by the installation of biogas, these issues were reduced.

Agriculturally, biogas slurry as a byproduct enhances soil fertility and boosts crop yields. Collectively, these benefits signify biogas as a transformative technology for rural households, enhancing well-being and promoting sustainable development.

Seventy-three percent of the beneficiaries ceased using LPG subsequent to the installation of biogas plants. The remaining beneficiaries have opted to utilize firewood as an alternative energy source to meet additional heat requirements, particularly for dairy purposes.

Conclusion

The study conclusively demonstrated that biogas technology, especially the Deenbandhu model, offers a sustainable and economically viable solution to Rajasthan's energy needs. Despite its potential, a significant gap exists between the possible and actual installation of biogas plants. Addressing factors hindering adoption, alongside enhancing dissemination strategies under the NBMMP, can bridge this gap. Implementing biogas technology on a broader scale can significantly reduce

Table 5. Economics of 2 m^3 Deenbandhu biogas plant

Parameter	LPG and slurry	LPG and Urea equivalent	Firewood and slurry	Firewood and Urea equivalent
NPV	216131	-37857	282542	28553
B/C Ratio	2.14	0.8	2.49	1.15
Payback period	6 months	1 year and 5 months	5 months	1 year

reliance on fossil fuels, lower CO_2 emissions, and support India's transition to a low-carbon economy.

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