Adoption of Biogas As A Clean Cooking Practice and Adoption of Biogas Slurry As A Sustainable Agriculture Practice in Tribal Households in the Trimbakeshwar Block of the Nashik District, Maharashtra, India

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Abstract
This study investigated the impact of an innovative "Integrated Renewable Energy and Sustainable Agriculture" (IRESA) intervention model, implemented in a tribal community in rural Maharashtra, India, aimed to address the dual challenges of limited access to clean cooking energy and unsustainable agricultural practice of using chemical fertilizers. The IRESA model, centred on household-level biogas units with the application of biogas slurry in crop cultivation and a social enterprise for value-added organic fertilizer production, was evaluated 3 years post-implementation to assess its sustainability and impact on livelihoods. Employing a quantitative survey approach, which included a sample of 49 households, the research examined the situation regarding cooking energy usage and application of chemical fertilizers. Findings reveal a complete adoption of biogas for cooking from ceasing the use of polluting fuels like crop residues and cow dung cakes, significantly reducing indoor air pollution and drudgery for women, thus contributing to SDG 7. A substantial decrease in annual expenditure on chemical fertilizers indicated reduced reliance on them, coupled with increased agricultural income attributed to the use of biogas slurry as an organic fertilizer, which is aligned with SDG 15. This study highlights the potential of integrated, community-driven models to promote clean energy access and sustainable agriculture, contributing valuable insights into the long-term impacts of such interventions in rural Indian contexts.

Keywords: Adoption, Biogas, Biogas Slurry, Chemical fertilizers, IRESA (Integrated Renewable Energy and Sustainable Agriculture), Sustainable Agriculture.

1. Introduction

While climate-induced challenges have started threatening agricultural sustainability, the extensive use of external inputs, mainly chemical fertilizers and pesticides, further degrades soil, surface water, groundwater, and air quality. This degradation subsequently impairs soil fertility, biodiversity, and the overall ecosystem in the long term, resulting in serious health hazards to living organisms (Ahmad et al., 2024; Sharma et al., 2019; UNEP, 2022). Pesticides are detrimental to human and environmental health and adversely impact habitats, the quality of ecosystem services, and biodiversity (European Commission, 2022; Kumar and Dev, 2017). They further affect the sustainability of food production and, consequently, human health and food security (UNEP, 2022). Contemporary agriculture fails to provide a sustainable livelihood option for a significant majority, specifically 85% of marginal and small farmers in India. In comparison to the global average, the consumption of fertilizers is higher in India, with substantial implications for soil contamination, insect infestation, crop nutrition issues, and increased cultivation costs (Jatav and Naik, 2023). Despite high production costs and decreased profitability, farmers continue to be driven by the extensive use of chemical fertilizers and pesticides due to their indispensability for high yields, controlling harvest losses caused by weeds, diseases, insects, and pests (Tudi, et. al., 2021), and concerns regarding the economic viability of implementing sustainable agricultural practices (Wilson and Tisdell, 2001).

Sustainable agriculture refers to meeting human needs for present and future generations through means of crop and livestock farming activities that are technically appropriate, economically viable, and socially acceptable without adversely impacting the environment (Zoveda, 2014; Muhie, 2022; Paul et al., 2023). Sustainable agricultural practices (SAP) encompass integrating crop and livestock, organic fertilizers, integrated pest management, crop rotation and diversification, agroforestry, conservation tillage, and other methods (Bhatnagar et. al., 2024; Swami and Parthasarthy, 2024). The United Nations, as part of the Sustainable Development Goals (SDGs), has called for global action to reduce reliance on chemical fertilizers and pesticides in response to environmental and human health concerns (Brunelle et al., 2024). Furthermore, the adoption of sustainable agriculture practices has been emphasized in SDG 15, 'life on land.' The Indian government, through various schemes and programs, promotes the implementation of sustainable agricultural practices (Mittal et al., 2018; Swami and Parthasarthy, 2024).

In addition to the extensive utilization and dependence on chemical fertilizers for agricultural practices, another equally significant rural concern is SDG 7. This goal aims to ensure 'access to affordable, reliable, sustainable, and modern energy for everyone by 2030' and includes access to clean cooking practices as one of its targets. Achieving clean cooking practices has remained an elusive goal in rural India. The lack of access to clean cooking fuel creates health, environmental, economic, and social burdens (Ali & Khan, 2022). The continued utilization of inefficient energy sources such as fuelwood, crop residues, and cattle dung cakes is a major contributor to indoor or household air pollution, resulting in significant health risks to family members (Arora and Mishra, 2022; Goldemberg et. al., 2018). Frequently, marginalized populations, including women and children, disproportionately experience adverse health effects (Guta et. al., 2024). In India, over 750 million individuals continue to rely on firewood and other solid fuels for cooking (Gould, et. al., 2020). The National Family Health Survey (NFHS) 2015–16 reported that 75% of rural Indian households utilized solid fuels for cooking (Gupta et. al., 2020). Ray and Smith (2021) stated that household air pollution from cooking with solid fuels leads to 1.6–3·8 million premature deaths annually from associated illnesses. The combustion of biomass for cooking contributes to respiratory infections and a range of non-communicable diseases (Khaiwal and Smith, 2018). The utilization of solid fuels in cooking not only has health implications but also climate and environmental impacts. Despite this substantial toll, individuals in poverty continue to employ conventional cooking practices due to habituation, the absence of cost, and the affordability of clean fuels and technology being a major obstacle to adoption, given their economic circumstances. As Ramasubramanian and Ramakrishna (2023) indicate, the lack of reliable access to clean fuel is an impediment to eradicating poverty (SDG 1), as it limits opportunities for income generation and hinders access to essential services.

Since the 1980s, biogas technology has been established in India, demonstrating considerable potential in rural areas due to the substantial livestock population and widespread cattle ownership among rural households (Mottaleb et al., 2022). Despite this, the uptake of biogas remains limited (Dabas et. al., 2018). The production of biogas and its by-product slurry offers multiple advantages, including the reduction of air pollutants and greenhouse gas emissions, the mitigation of groundwater and soil contamination, and the generation of organic fertilizer through anaerobic digestion. This process enhances the nitrogen content in the slurry compared to untreated animal manure. However, India's current biogas production, at 2.07 billion m^3/year, falls significantly short of its estimated potential of 29–48 billion m^3. The widespread adoption of biogas technology is hindered by a combination of financial, social, and institutional factors (Mittal et al., 2018). Several factors constraining the diffusion of biogas technologies in rural India include financial/economic factors like high capital costs, lack of purchasing power, a limited amount of government subsidy, and limited access to easy credit for low-income households. Market barriers include the local availability of free and cheaper alternatives like traditional solid biomass, fuelwood, and cattle dung and the weak distribution network of LPG. Social factors such as the low status of women and limited decision-making power act as barriers to the penetration of clean fuel. Technical and infrastructural factors such as a shortage of cattle dung and water, and low temperatures during winter can result in non-functionality. (Dabas et al., 2018; Mittal et al., 2018).

In the context of both access to clean cooking and reducing reliance on chemical fertilizers, biogas, and the slurry together provide an eco-friendly approach that helps reduce reliance on synthetic fertilizers by recycling organic waste that can be used as a plant fertilizer (Williams, et. al., 2022), thus contributing to improving soil health and sanitation as well as reducing indoor pollution and greenhouse gas emissions. Biogas slurry is a leftover slurry produced by the anaerobic breakdown of biogas source substrates like animal manure or plant debris. Using biogas slurry as an organic fertilizer is an environmentally friendly solution that improves soil health, reduces soil erosion, and enhances crop nitrogen uptake, growth, and agricultural productivity (Mukhtiar et. al., 2024). It is a cost-effective solution for producing fertilizers. In India, government policies encourage farmers to use biogas slurry as fertilizer. With large livestock, animals produce 730 MT of dung annually (or 2 MT per day), of which 60% is recoverable. On average, 0.3 kg of slurry is produced from 1 kg of cow dung (Yadav et al., 2023). As a by-product of biogas production, slurry has great potential for clean and green agriculture (Dabas et al., 2018). Another potential benefit for the economy at large is that increased use of organic fertilizers, such as biogas slurry, can help reduce the country’s dependence on imported chemical fertilizers and subsidies (Aggarwal et. al., 2024; Yadav et al., 2023).

This paper presents insights from the field research on an innovative intervention model that generated ‘renewable energy for cooking’ and ‘organic fertilizer.’ This intervention model was implemented in collaboration between an NGO, ‘BAIF Development Research Foundation (hereafter BAIF)’ and a CSR partner, ‘State Bank of India’, in villages of the Trimbakeshwar block in the Nashik district of Maharashtra, India. The study aimed to understand the impact of the intervention model on the livelihoods of participating households. With the focus on knowing the impact, the study was undertaken in 2023-24, three years after the implementation was completed and intervention partners had withdrawn from the project villages. The time chosen to conduct the study provided an opportunity to inquire about the sustainability of the intervention. This study contributes to the scarce literature on farmers' experiences of applying biogas slurry as a fertilizer and the impacts generated from this in the rural Indian context. Section 2 provides the background of implementing the biogas slurry-based intervention model, followed by Section 3 on the materials and methods. Section 4 presents the study's results, and Section 5 presents the discussion and conclusions.

2. Integrated Renewable Energy and Sustainable Agriculture (IRESA)

BAIF has developed the "Integrated Renewable Energy and Sustainable Agriculture (IRESA)" model, which offers a comprehensive package centred around household-level biogas units. While this intervention may initially appear to be solely a biogas initiative, its innovative strategy lies in integrating the crop-livestock system within a social enterprise framework. This dual-purpose approach facilitates not only sustainable energy generation for cooking but also the production of value-added organic manure to enhance soil fertility. The IRESA model aims to achieve multiple objectives, including providing access to renewable energy and organic production inputs while also boosting farmers' incomes. It serves as a practical solution for advancing clean energy practices and promoting sustainable agricultural methods, focusing on the optimal utilization of existing resources for both renewable cooking energy and organic manure production for improved soil health.

The prerequisites for installing household-level IRESA units were as follows.

- Household-level availability of water and three milking cattle is essential. A unit measuring $2m^3$ is capable of producing a minimum of 1 ton of organic cake per annum, while the biogas generated will adequately support cooking needs for a household comprising 4 to 6 members.
- The recommended installation area for the biogas unit is approximately 300 square feet, preferably located close to the house or farm. It is important that the distance from the unit to the kitchen does not exceed 150 meters.
- Additionally, the site for the biogas unit should be open to the sky and situated on level ground with soft soil.
- Individuals who are willing to participate in this social enterprise are sought.

The IRESA biogas unit consisted (i) A compact, standardized, pre-fabricated, failure-proof, clean, and easy-to-install biogas unit, (ii) Ergonomic and efficient slurry handling and water recycling through an in-house developed low-cost filter, (iii) Solids and liquids separation, with 90% solids recovery, about 1.5 tons (Dry Matter) slurry cake per annum with up to 50% water recycling. (iv) Value addition of drip-enabled filtered slurry (about 10,000 litres/year) for enhanced in-situ production of quality organic nutrients. Figure 1 represents the function of the IRESA unit at the household level. The total cost of one IRESA biogas unit was INR 37,500; the contribution of the participant households was INR 6,000, and the remaining cost was the subsidy.

85 IRESA units with 5G filters were installed in four villages in the year 2020-21. The first output after the installation of the IRESA units was the production of clean cooking fuel. At the same time, the intervention enabled efficient handling of slurry and nutrient-rich water that have very high commercial value if utilized effectively.

Figure 1: IRESA PLANT: Input and output for one unit

2.1 Installation of the IRESA units and operationalization of the model in the field

The intervention of IRESA was implemented in the Trimbakeshwar block of the Nashik district in the state of Maharashtra, India. Trimbakeshwar is predominantly a tribal block with scheduled tribes constituting 80.2 percent, and 92.8 percent of the population in the block resides in the rural area. The literacy rate of the block is 68.91 percent (Census, 2011). Trimbakeshwar block shares a boundary with three blocks of Nashik, on the north with Peint, on the east with Nashik, and the southern east side with the Igatpuri block. On the west side, the boundary is shared with the Palghar district, while on the northern side, the boundary is shared with the Gujarat state. As per long-term rainfall analysis for 24 years from 1998 to 2021, the normal rainfall in the Trimbakeshwar block was 2249.2 mm, while the average rainfall data for 2012 to 2022 was 1950 mm (CGWB, 2022). The farmers in the intervention village cultivat rice, finger millet, little millet, and black gram in the Kharif season and wheat, chickpea, and peas in the Rabi season. The vegetables cultivated are bitter gourd, bottle gourd, pumpkin, tomato, and onion.

In the Trimbakeshwar block, IRESA units were installed in 85 farmer households across three villages. Farmers received education and training on efficient slurry handling systems and the optimal use of separated slurry to address the shortcomings of a traditional biogas unit. In the traditional biogas model, high-value “biogas slurry” is often wasted or used inefficiently, preventing the realization of ‘true’ commercial viability of the family-size biogas plants. The key innovation in IRESA was the development and integration of ‘prototype slurry-filters’. With the introduction of these slurry filters, the model enabled efficient and hassle-free slurry collection while also facilitating solid-liquid separation. Additionally, participating households were provided with training and continuous hand-holding support for the operation and maintenance of the IRESA units.

The comprehensive IRESA model developed was grounded in the principles of the 3 ‘R’s: “Recycle, Reuse, and Reduce”. The purpose of the model was to optimize resource utilization at all levels by effectively harnessing the available livestock resources and cow dung to generate sustainable clean energy for cooking. Additionally, IRESA also aimed at producing value-added organic manure and fertilizer to improve soil fertility, and further closing the loop with farm production. Farmers received training and education on the efficient use of separated slurry, both at the Individual level as well as at the group level. At the household level, the slurry as manure to crops on the farm was delivered through a drip system to boost the yields.

At the group level, the social enterprise known as PROM (Phosphate Rich Organic Manure) was established. The PROM enterprise is now entirely managed by a Farmer Producer Company (FPO) of women farmers as a social enterprise. The social enterprise played an instrumental role in upscaling the model from an individual-based intervention to a community-based model, thereby maximizing the impact locally. As a ubiquitously known fact, phosphorus is one of the most important nutrients for plant growth, along with nitrogen and potash. The IRESA model helped produce manure that combined organic slurry cake with Rock Phosphate and added microbial additives such as phosphate-soluble bacteria (PSB), resulting in substantial value addition in the farm inputs. The organic nature of PROM is expected to result in a gradual increase in soil health in terms of the soil structure, its moisture-retaining capabilities, and microbial count, while also leaving residues of Phosphate in the soil. This innovation will reduce the physical hardships and economic costs of farmers by decreasing the need to use phosphate-rich chemical fertilizer for the second crop. The PROM enterprise has resulted in generating income at the local level. Photo 1 presents the process of Bio-PROM production.

Photo 1: Photographs showing the process of Bio-PROM production

3. Material and Methods

3.1 Study Area, duration and sample

The study mainly employed a quantitative approach using the survey method for collecting the primary data. The secondary data was collected from the social enterprise records. This pertained to the sales records of the social (PROM) enterprise. The sample households randomly selected for the study were 49, which was 57 percent of the total 85 participant households. The sample households were spread across three villages of the Trimbakeshwar block of the Nashik district, which has a predominance of tribal population. The data was collected in the period from December 2023 to February 2024. The interview schedule was designed to elicit data from the farmer households that had installed IRESA units in their houses and it mainly had close-ended questions. The respondents were female members of the households. As the objective of the research was to understand the impacts created, the data was compared with the pre-intervention situation to track the changes, if any, that occurred after the intervention. The collected data was verified and entered in a data entry format created in MS Excel. The cross-tabulation, simple average, and percentage were used to analyze the data.

3.2 Sample characteristics

The demographic data showed that all the sample households were male-headed. Being the tribal predominant block, 83.67 percent (N=41) of the sample households belonged to the social category of Scheduled Tribes (STs), whereas 16.33 percent (N=8) were from Other Backward Castes (OBCs). The data on the poverty line cards showed that 81 percent of the sample had below-the-poverty-line (BPL) cards, while 16.3 percent possessed the above-poverty-line (APL) cards. The educational status of the respondents in the sample households revealed that 61.2 percent of respondents never had any schooling, with 18.3 percent completing primary-level education (up to class 5), while 12.2 percent falling in the range of middle school (class 6-9), and only 4 respondents (8.1 percent) studied up to the class 10.

As Table 1 shows, except for one farmer, the remaining 97.95 percent were smallholder farmers. Amongst these smallholder farmers, a significant percentage, i.e. 61.22 per cent, were marginal farmers owning up to 1 hectare of land, and 36.73 percent (N=18) were small farmers. Agriculture is the primary occupation and the main source of income for the respondent households. Each sample household owned at least 3 cattle. Paddy and maize were the main crops cultivated, while almost all households cultivated fodder crops.

Table 1: Distribution of sample households as per the landholding

Sr. Nos.	Land Ownership	No. of sample households	Percentage
1	Marginal Farmers (up to 1 hectare)	30	61.22
2	Small Farmers (>1 hectare up to 2 hectares)	18	36.73
3	Medium Farmers(>2 hectares up to 4 hectares)	1	2.04
	Total	49	100

The demographic background of the respondent households indicated the homogeneity among the sample, which is reflected not only in the tribal background of the majority of the sample but also in other aspects like smallholder farmers, households with low educational levels, and BPL cardholders.

As per the NSS 75th round consumer expenditure survey (Government of Maharashtra, 2022) conducted during 2017-2018, the average household size in rural Maharashtra was 4.4 persons. The data on the household size, as presented in Table 2, showed that the average household size in the sample was 8. In the sample households, 36.73 percent (N=18) had a small family size with 3-6 family members, while there were 12 households (24.48 percent) that had a household size of 7-8 members, and combined household size of 9 to 13 members was 39 percent (N=19) in the sample.

Table 2: The household size

Sr. Nos.	No. of Family Members	No. of sample households	Percentage
1	3-6 members	18	36.73
2	7-8	12	24.48
3	9-10	9	18.36
4	11-13	10	20.40
	Total	49	100
	Average household size	8	

From Table 3 on the ownership of cattle, it is found that cow ownership is significantly higher than that of buffaloes. Only 16 percent (N=8) of the respondents did not own cows, compared to 71 percent (N=35) reporting not owning buffaloes.

Table 3: Cattle owned by the sample households

Sr. Nos.	**No. of Cows**	No. of Respondents	Percentage of Respondents	**No. of Buffaloes**	No. of Respondents	Percentage of Respondents
1	0	8	16.32	0	35	71.4
2	1	4	8.16	1	2	4.08
3	2	33	67.34	2	7	28.57
4	**3**	1	2.04	**3**	1	2.04
5	4	1	2.04	4	2	4.08
6	5-6	2	4.08	5-6	2	4.08
	Total	49			49	

4. Findings/Results

4.1 Adoption of IRESA for cooking

The findings show that all sample households have successfully adopted the IRESA model and reported that they have been operating the bio-gas unit along with prescribed practices. The respondents reported that during the pre-intervention period, crop residues/fuelwood and cow dung cakes was used for both the purposes of cooking and heating water for bathing.

All participating households reported a complete transition for energy source for cooking from crop residue/fuelwood, cow dung cakes, and liquefied petroleum gas (LPG) to biogas energy. In the pre-intervention period, as seen in Table 4, households utilized multiple energy sources for cooking, including fuelwood/crop residue, cow dung, and LPG. Fuelwood/crop residue was the principal source of energy for cooking among all households irrespective of the land category they belonged to. Cow dung served as a supplementary source to fuelwood/crop residue for 69 percent (N=34) of households, amongst which 44 percent were marginal farmers, 22 percent were small farmers, and 2 percent were medium farmers. The usage of fuelwood/crop residue and LPG was reported by 12 percent (N=6) each by marginal and small farmers, indicating LPG usage existed in both marginal and small farmer households. Following the adoption of the IRESA model, fuelwood/crop residue use persisted solely for water heating purposes, primarily for bathing, and its use for cooking was entirely discontinued in all sample households. Consequently, households perceived health benefits from the cessation of unclean, polluting fuels that emit smoke and toxic substances. Additionally, no reliance on LPG was observed during the post-intervention period. In contrast to the post-intervention period, the pre-intervention period did not feature any household that exclusively used clean fuel, such as LPG, for cooking.

Table 4: Farmer category-wise sources of cooking fuel during pre-intervention

No.	Sources of cooking	Marginal Farmers HHs (up to 1 hectare)		Small Farmers HHs (>1 hectare Up to 2 hectare)		Medium Farmers HHs (>2 hectare Up to 4 hectare)		Total	Percentage
		Nos.	%	Nos.	%	Nos.	%		
1.	**Fuelwood/crop residue**	2	4.08	0	0	0	0	2	4.08
2.	**Fuelwood/crop residue, cow dung cakes**	22	44.89	11	22.44	1	2.04	34	69.37
3.	**Fuelwood/crop residue, LPG**	6	12.24	6	12.24	0	0	12	24.48
4.	**Fuelwood/crop residue, cow dung cakes, LPG**	0	0	1	2.04	0	0	1	2.04
	Total	**30**	**0**	**18**		**1**		**49**	**99.97**

4.1.2 Efficient utilization of time

The data revealed that the adoption of IRESA biogas led to a reduction in cooking time by one hour per day compared to the pre-intervention period, which predominantly utilized fuelwood/crop residue as the primary energy source. During the pre-intervention period, individuals dedicated an average of two hours or more to cooking activities. Conversely, the post-intervention period demonstrated a decrease in average cooking time to merely one hour.

Furthermore, substantial time savings have been reported concerning fuelwood/crop residue collection. Table 5 illustrates that, in comparison to the pre-intervention period, there has been a significant reduction in the time spent collecting fuelwood/crop residues during the post-intervention period. Except for one household that spent one hour, all households (97.94 percent) previously spent 4-6 hours per week collecting before the intervention. In contrast, during the post-intervention period, no household reported spending this amount of time. Specifically, 37 percent (N=18) of households spent 30 minutes, and 63 percent (N=31) spent one hour, indicating a substantial decrease in the time allocated to crop residues/fuelwood collection. Respondents indicated that the continued collection of crop residues/fuelwood in the post-intervention period was solely for heating water for bathing, rather than for use as cooking fuel.

Table 5: A comparison between times spent per week in fuelwood collection during pre and post-intervention

Sr. Nos.	Time Spent in crop residues/fuel wood collection per week	Pre-Intervention		Post-Intervention	
		No. of HHs	Percentage of HHs	No. of HHs	Percentage of HHs
1	30 minutes	0	0	18	37
2	1 hour	1	2.04	31	63

3	4 hours	12	24.48		
4	5 hours	16	32.65		
5	6 hours	20	40.81		
	Total	49		49	

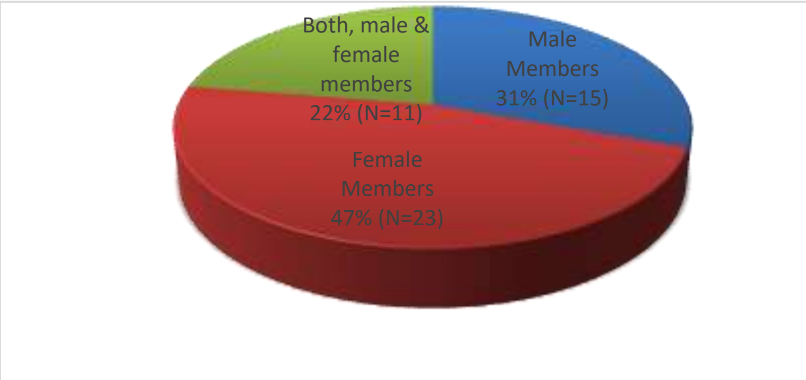

Figure 2: Family members engaged in crop residues collection in pre-intervention

As observed from Figure 2, during the pre-intervention period, women bore the responsibility of fuelwood collection in the maximum percentage (47, N=23) of households, while in 31 percent (N=15) of households, it was the responsibility of male members. In 22 percent (N=11) of households, it was found that both male and female household members shared the responsibility of collecting the fuelwood.

Beyond the substantial reduction in cooking and fuelwood collection time, women reported that biogas mitigated the physical demands of collecting crop residues/fuelwood, the difficulties associated with fire ignition, the inconsistency of heat output.

4.1.3 Perceived health benefits

The adoption of IRESA biogas for cooking has resulted in significant health benefits by addressing indoor air pollution and considerably reducing the daily workload, especially for women in the community. Women reported that their kitchens are now free from smoke, leading to improved indoor air quality. These smoke-related issues included eye irritation, headaches, coughing, nausea, and overall poor indoor air quality, contributing to significant discomfort and inconvenience. In the post-intervention period, all respondents unanimously indicated that the elimination of smoke resulted in a noticeably cleaner household environment. They no longer experience issues such as itching, eye irritation, headaches, coughing, or nausea, which were previously caused by the smoke from polluting fuels used for cooking before the intervention.

By eliminating traditional cooking fuels like fuelwood and cow dung cakes, women have saved valuable time that was once spent on gathering crop residues, making dung cakes, and cleaning sooty utensils. The biogas system offers a cleaner and more efficient alternative for cooking, which not only conserves time but also enhances overall household efficiency. This shift has empowered women to redirect their time and energy toward other tasks, such as agricultural and household work.

4.1.4 Indirect Economic Benefits

During the pre-intervention period, respondents' farms, mainly crop residue of paddy husk, served as the source of fuel for cooking for 85.71 percent (N=42) of households, as seen from Table 6, whereas only 14.28 percent (N=7) relied on the forest.

Table 6: Sources of cooking fuel during pre-intervention

Sr. Nos.	Source of fuelwood during the pre-intervention	No. of Households	Percentage of Households
1	Own farm	42	85.71
2	Forest	7	14.28
	Total	49	100

As seen from Table 7, in the pre-intervention period, 93.87 percent (N=46) of households spent more than 2,000 Indian Rupees (INR) per annum on the transportation of crop residues and fuelwood from farms and forests. However, in the post-intervention period, all households' expenses decreased to up to INR 500 per annum.

Table 7: Crop residue and fuelwood transportation cost per year during pre and post-intervention

Sr. Nos.	Pre-intervention			Post-intervention		
	Per Year Expenditure on Fuel wood	No. of HHs	Percentage of HHS	Per Year Expenditure on Fuel wood	No. of HHs	Percentage of HHS
1	Up to INR 200			Up to INR 200	1	2.04
2	INR 200 - 500			INR 200 - 500	48	97.95
3	INR 500 - 1000	2	4.08	INR 500 - 1000		
4	INR 1001 - 2000	1	2.04	INR 1001 - 2000		
5	INR 2001 - 3000	16	32.65	INR 2001 - 3000		
6	INR 3001 - 4000	29	59.18	INR 3001 - 4000		
7	INR 4001 - 5000	1	2.04	INR 4001 - 5000		
		49			49	

4.2 Adoption of IRESA: Impacts on Agriculture

This sub-section presents the intervention's impact on annual expenditure on chemical fertilizers and annual income from agriculture.

Table 8 compares annual expenditures on chemical fertilizers during both the pre-intervention and post-intervention periods. In the pre-intervention phase, respondents exclusively applied chemical fertilizers and did not apply organic fertilizers. However, in the post-intervention period, the awareness, knowledge, and information gained through the project intervention have encouraged farmers to incorporate organic fertilizers alongside chemical ones. Notably, all households reported using biogas slurry as an organic fertilizer on their farms. Except for one respondent, all participants believed that applying biogas slurry has significantly improved soil fertility and increased harvests. This positive perception among farmers is evidenced by a reduction in chemical fertilizer expenditures, coupled with a rise in annual agricultural income.

Before the intervention, 46.94 percent of farmers (N=23) spent between INR 15,000 and INR 20,000 annually on chemical fertilizers, with an average expenditure of INR 19,869 within this range. During the pre-intervention phase, 84 percent of farmers reported spending over INR 10,000 per year on chemical fertilizers. However, following the intervention, the introduction of organic biogas slurry on farms significantly reduced expenditures on both chemical fertilizers. In the post-intervention period, 57 percent of farmers reported spending up to INR 5,000 annually, with a mean expenditure of INR 3,864, while 41 percent spent between INR 10,000 and INR 15,000, averaging INR 7,117. In the pre-intervention period, 31 farmers (63 percent) were spending more than INR 15,000 on chemical fertilizers; however, this number dropped to zero in the post-intervention phase, marking a remarkable change. Overall, the average chemical fertilizer spending among all farmers decreased substantially to INR 23,581, compared to INR 1,04,369 during the pre-intervention period.

Table 8: Pre and Post-Intervention comparison of expenditure on chemical fertilizers

Categories of Annual Expenditure on fertilizer (in INR)	**Pre-intervention**			**Post-intervention**		
	No. of Farmers with expenditure on chemical fertilizers	**Percentage of Farmers**	**Mean Expenditure on chemical fertilizers**	**No. of Farmers with total expenditure on Chemical Fertilizers**	**Percentage of Farmers**	**Mean Expenditure on Chemical Fertilizers**
2,500 - 5,000	1	2.04	4,500	28	57.14	3,864.28
5,101- 10,000	7	14.29	10,000	20	40.81	7,117.5
10,001-15,000	10	20.41	15,000	1	2.04	12,600
15,001 - 20,000	23	46.94	19,869.57	0	0	0
21,001 - 25,000	7	14.29	25,000	0	0	0
25,001-30,000	1	2.04	30,000	0	0	0
Total	**49**	**100**		**49**	**100**	

Table 9 compares annual expenditures on chemical fertilizers during the pre-intervention and post-intervention periods as per farmer categories. During pre-intervention among marginal and small farmers, 24 percent (N=12) each spent in the range of INR 15,101 to INR 20,000; while 14 percent (N=7) of marginal farmers spent in the range of INR 20,101 to INR 25,000. Fourteen percent (N=7) of marginal farmers spent between INR 5,101 to INR 10,000 in pre-intervention on the purchase of chemical fertilizers. In the post-intervention period, expenditure on chemical fertilizers between INR 2,500 to INR 5,000 was reported by all marginal and medium farmers, while a similar case was for small farmers, except for one household that reported expenditure between INR 5,101 to INR 10,000. Thus, irrespective of the farmer categories the households belonged to, a significant decline in expenditure on chemical fertilizer was noted in the post-intervention than in the pre-intervention period.

Table 9: Farmer category-wise comparison during pre and post-intervention on expenditure on chemical fertilizers

No.	Expenditure on Chemical Fertilizers (in INR)	Marginal Farmers HHs (up to 1 hectare)				Small Farmers HHs (>1 ha. Up to 2 ha.)				Medium Farmers HHs (>2 ha. Up to 4 ha.)			
		Pre		Post		Pre		Post		Pre		Post	
		Nos.	%	Nos.	%	Nos.	%	Nos.	%	Nos.	%	Nos.	%
1.	2,500 - 5,000	1	2.04	30	61.22	0	0	17	34.69	0	0	1	2.04
2.	5,101 - 10,000	7	14.28	0	0	1	2.04	1	2.04	0	0	0	0
3.	10,101 - 15,000	2	4.08	0	0	2	4.08	0	0	0	0	0	0
4.	15,101 - 20,000	12	24.48	0	0	12	24.48	0	0	0	0	0	0
5.	20,101 - 25,000	7	14.28	0	0	2	4.08	0	0	0	0	0	0
6.	25,101 - 30,000	1	2.04	0	0	1	2.04	0	0	1	2.04	0	0
	Total	30		30		18		18		1		1	

Table 10 presents a comparative picture of annual income in the pre- and post-intervention period as per the land categories of farmers. As observed for all categories of farmers, their yearly income increased significantly after the intervention. In the lowest income range of INR 45,000 to INR. 60,000, there was not a single farmer during the post-intervention period. In the marginal farmers' category in the pre-intervention period, the maximum of farmers, i.e. 28.57% (N=14), earned income in the range of INR 60,101 to INR 70,000; whereas in the post-intervention period, there were only 12.24% (N=6) in this category. A major shift was seen in the post-intervention period in the income category of INR 80,101 to INR 1,00,000, in which 32.65% (N=16) of marginal farmers moved as compared to only one farmer (2.04%) in pre-intervention. A similar change was observed for small and medium farmers as well. During pre-intervention, there were 4.08% (N=2) of small farmers who earned between INR 80,101 to INR 1,00,000; whereas in the post-intervention period, they were 30.61% (N=15). For one medium farmer household, the annual agricultural income in the pre-intervention was in the range of INR 60,101 – INR 70,000, which increased to between INR 80,101 to INR 1,00,000 in the post-intervention period. The respondent informed that the application of the biogas slurry in fields has contributed to reducing expenditure on chemical fertilizers on one hand and improving yield on the other, thus increasing their annual income from agriculture.

Table 10: Comparison of annual agricultural income during pre- and post-intervention as per land category

Sr. No.	Annual Income (in INR)	Marginal Farmers HHs (up to 1 hectare)				Small Farmers HHs (>1 ha. Up to 2 ha.)				Medium Farmers HHs (>2 ha. Up to 4 ha.)			
		Pre		Post		Pre		Post		Pre		Post	
		Nos.	%	Nos.	%	Nos.	%	Nos.	%	Nos.	%	Nos.	%
1	45,000 - 60,000	8	16.32	0	0	2	4.08	0	0	0	0	0	0
2	60,001 - 70,000	14	28.57	6	12.24	5	10.2	1	2.04	1	2.4	0	0
3	70,001 - 80,000	7	14.28	8	16.32	9	18.36	2	4.08	0	0	0	0
4	80,001-1,00,000	1	2.04	16	32.65	2	4.08	15	30.61	0	0	1	2.04
		30		30		18		18		1		1	

Table 11 gives a comparative picture of annual agricultural income as well as the average annual agricultural income for every income category for the sample households. A comparison of households revealed that before the intervention, the majority of households, 40 percent (N=20), earned between INR 60,000 - INR 70,000, with an average annual income of INR 68,000; followed by 32 percent (N=16) who earned between INR 70,000 to INR 80,000, with a mean annual income of INR 75,937. Farmers' yearly income increased significantly after the intervention, with 63 percent falling (N=31) between INR 80,000 to INR 1,00,000, with an average annual income of INR 85,871. In contrast, there were only 6 percent (N=3) of farmers during pre-intervention in this category.

Table 11: Comparative data on annual agricultural income during pre- and post-intervention

Sr. Nos.	Annual Income (in INR)	Pre-Intervention			Post-Intervention		
		No. of Households	Percentage of Households	Average Income (in INR)	No. of Households	Percentage of Households	Average Income (in INR)
1	45,000 - 60,000	10	20.04	56,500	5	10.20	41,600
2	60,001 - 70,000	20	40.08	68,000	7	14.28	65,571
3	70,001 - 80,000	16	32.6	75,937	6	12.24	75,333
4	80,001-1,00,00	3	6.12	91,667	31	63.28	85,871

	0						
	Total	49			49		

4.3 Income generated from the social enterprise

The social enterprise of PROM (Phosphate Rich Organic Manure), which is managed by the FPO, is contributing to the local economy. PROM is generating income using local livestock resources to produce value-added organic manure. The PROM customers are spread over six villages in the vicinity. These customers are mainly members of the FPO. The production cost of generating one bag consisting of 50 kg of organic manure is INR 420, while for farmers, the purchasing cost per bag is INR 734 for the years 2020 to 2022. In the year 2023, the purchasing cost per bag slightly increased to INR 750. In the production of PROM, two laborers were employed for approximately three months a year on a part-time basis. The cost incurred toward yearly labour payments was INR 9,000 in the years 2020 and 2021. In 2022, the cost towards labor was INR 14,000, while it was INR 20,000 in 2023.

As presented in Table 12, in the year 2020 the sale of bags was 334, followed by 231 in 2021, 656 in 2022, and 476 in 2023. For the FPO, the total earnings from the social enterprise by selling organic manure from the year 2020 to 2023 was INR 12,53,214.

Table 12: Earning of social enterprise from selling PROM

Year	PROM Bags Sold	Per Bag Cost	Earned in Rs
2020	334	734	2,45,156
2021	231	734	1,69,554
2022	656	734	4,81,504
2023	476	750	3,57,000
Total Earning			12,53,214

In the sample, 63 percent (N=31) of participant households reported selling dry manure or cakes to the social enterprise of PROM after the biogas slurry was separated; the remaining respondents applied it as the manure in their farms. The annual earnings from selling dry manure range between INR 1,175 and INR 27,976. Nine respondents each earned an annual income of up to INR 3,000 and between INR 3,000 and INR 6,000, respectively. One respondent earned INR 27,976 per annum, while five earned in the range of more than INR 6,000 up to INR 10,000. Three respondents stated earning between more than INR 10,000 to INR 17,000.

The respondents opined that the IRESA intervention has led to various benefits and that it has enhanced their quality of life. The use of biogas has helped in keeping the house clean and smoke-free, which has contributed to the betterment of their health. It reduced the drudgery involved in collecting fuelwood and time spent in cooking by using traditional, polluting fuels. The biogas, a renewable energy, is now satisfying the requirement of energy for cooking. It ceased the usage and money spent on the purchase of LPG or polluting fuels. The application of biogas slurry as an organic fertilizer has resulted in increasing the fertility of the soil and improved harvest, in addition to reducing expenditure on chemical fertilizers. All these benefits together have also contributed to increasing household income.

5. Discussion and Conclusion

The findings reveal that the IRESA biogas and bio-slurry intervention model created multiple impacts on the rural livelihoods in the tribal villages of the Trimbakeshwar block in Maharashtra state of India. The intervention's success is particularly noteworthy given the context - a predominantly tribal area with high poverty levels (81% BPL households), low education levels (61.2% with no schooling), and primarily smallholder farmers (98% marginal and small farmers). The impact on the sample households spans clean cooking energy access, health, gender, agricultural dimension of using chemical and organic fertilizer, and economic outcomes.

5.1 Sustained adoption of clean and renewable energy for cooking

The complete adoption of clean, renewable energy in the form of biogas for cooking represents a significant change in household energy practices. All 49 households shifted from using unclean fuels (fuelwood and cow dung cakes) to exclusively using IRESA biogas, renewable non-polluting energy for cooking, indicating acceptance and adoption of clean energy technology. This adoption to biogas is meaningful in the context of the hurdles faced in the sustained adoption of biogas or other clean cooking solutions in India, despite policy measures and government schemes like Pradhan Mantri Ujjwala Yojana to promote LPG or the National Biogas and Organic Manure Programme by the Ministry of New and Renewable Energy (MNRE) (Das, et. al, 2017; Williams, et. al., 2022). The affordability has been the most significant barrier (Ali and Khan, 2022) for low-income households, apart from underlying social environment such as patriarchal norms and attitudes in which cooking fuel decisions are made (Vyas et al., 2021). The continued use of biogas 3.5 years after project completion suggests adoption and affordability for the local context. This adoption of renewable and clean energy for cooking aligns with and is crucial to achieving Sustainable Development Goal (SDG) 7 of "Access to affordable, clean, and sustainable energy to all" (Gill-Wiehl et al., 2021).

5.2 Gender and time-poverty implications of energy transition

The energy transition from using polluting traditional fuels - fuelwood, cow dung cakes, and crop residues - to biogas has yielded multiple benefits: reduced cooking time from 2 hours to 1 hour daily, elimination of indoor air pollution and health concerns it caused, and decreased drudgery associated with fuelwood collection. The intervention has particularly benefited women, who previously bore the primary responsibility for fuelwood collection in nearly 47% of households. The dramatic reduction in monthly time spent collecting fuelwood - from 4-6 hours to just 30-60 minutes - has freed up women's time for other productive activities. Similar findings were reported in a study on biogas usage in Haryana, Rajasthan, and Uttar Pradesh, wherein women saved one hour daily, including time spent carrying fuelwood, plus the additional benefit of reduced drudgery caused by indoor pollution (Dabas et al., 2018). This impact on women's time poverty is significant, especially considering the context where women face multiple demands on their time for agricultural and household work. The intervention's impact on women's time poverty aligns with broader development goals of women's empowerment and gender equality.

5.3 Economic impacts due to the adoption of using biogas slurry as a sustainable agricultural practice

The intervention with the integration of biogas and biogas slurry generated positive agricultural and economic impacts. The adoption of the sustainable agricultural practice of using biogas slurry in the farms by all households was one of the critical factors that resulted in positive economic impacts. In the post-intervention period, economic impacts in terms of the accrued annual income of the households were noted. Various factors contributing to increased income are zero expenditure on LPG and transportation costs incurred on fuelwood and crop residues, small earnings from selling dry manure to the PROM enterprise, and a significant reduction in expenditure on chemical fertilizers through the usage of biogas slurry. Firstly, the average annual spending on chemical fertilizers decreased from INR 1,04,369 to INR 23,581. Secondly, agricultural incomes have increased, with 63% of households now earning between INR 80,000 and 1,00,000 annually, compared to only 6% before the intervention. This outcome is particularly relevant given the national emphasis on promoting organic fertilizers and reducing dependency on chemical fertilizers (Williams et. al., 2022). The findings about the usage of biogas slurry resulting in reduced usage of chemical fertilizers on one hand and increased income on the other are similar to the various studies. The study on the impact of biogas on rural households showed positive effects on farm productivity (Iqbal et al., 2021). The application of a combination of biogas slurry and chemical fertilizers revealed that the yield, as well as financial returns, have been enhanced. The higher maize productivity of 20-24% (Ferdous et al., 2020) and the highest gross return and gross margin for tomatoes were reported (Ferdous et al., 2018). A paper showed that the application of bio-fertilizers rendered economic benefits in terms of expenditure and gross and net income, with higher cost ratio benefits (Ghosh et al., 2021). A longitudinal study conducted in India reported the economic efficiency of biogas units providing the gas equivalent to 3 LPG cylinders, coupled with the usage of biogas slurry in agricultural fields as an organic fertilizer, further reflected reduced expenditure on chemical fertilizers (Dabas et al., 2018). Another study in India concluded that reliance on chemical fertilizers can be reduced by using biogas slurry, which has a significant amount of macro and micronutrients that will increase soil fertility, thus lowering production costs (Nagdev et. al., 2024). Although our study has not looked at improvement in the soil fertility or improved water-holding capacity of the soil, Dabas et al. (2018) informed that farmers regularly applying biogas slurry have reduced the usage of chemical fertilizers and experienced enhanced water-holding capacity of the soil, thereby saving on irrigation water. Reduced application of chemical fertilizers on one hand and increased application of biogas slurry on the other can act to revive the physical-chemical property of soil. Importantly, applying biogas slurry is a sustainable agricultural practice that offers various benefits, such as improved soil structure, nutrient profile, and water-holding capacity (Kumar et. al., 2023). Biogas slurry can serve as an alternative to chemical fertilizers and as a sustainable management measure (Feng et al., 2024). These studies suggest that the use of bio-slurry reduces chemical fertilizer reliance, promotes economic development, improves agricultural sustainability, and positively affects the environment.

5.4 Social Enterprise Development

The establishment of a PROM-producing social enterprise represents an innovative model of circular economy in rural settings. The enterprise has generated revenue (INR 12,53,214 over four years) within the local economy. Plus, it has provided a small income source for 59% of participant households who sell dry manure to the enterprise. This enterprise has potential that needs to be optimally utilized for its growth, and the scope for upscaling needs to be tapped.

In conclusion, this study contributes to the small body of scholarly literature in tribal and rural settings that enquires adoption of two environment-friendly practices of using biogas for cooking and using biogas slurry that led to reduced usage of chemical fertilizers. Thus, the adoption of renewable energy source for cooking contributes to SDG 7 of access to affordable and clean energy, while the adoption of sustainable agriculture practice of using biogas slurry is aligned with SDG 15 of sustainable use of ecosystems. The study provides evidence-based insights that show a generation of sustainable impact through the continued adoption of biogas along with applying biogas slurry in the farms over 3 years after the project intervention was over. The consideration of local contexts was crucial wherein the households have homogenous characteristics, such as tribal group, marginal and small landholding, ownership of a minimum of cattle, and reliance on traditional fuels. The IRESA model's success in combining clean energy access with promoting sustainable agricultural practice and enterprise development offers valuable insights for rural development practitioners and policymakers. It has led to the optimal use of existing resources of dairy animals for sustainable energy generation for cooking, as well as value-added organic manure production that can contribute to soil fertility, facilitating affordability, availability and access for poor rural households.

The findings suggest that similar integrated approaches - combining renewable energy with agricultural improvements and enterprise development - could be effectively replicated in other rural areas, particularly those dominated by smallholder farmers and cattle ownership. However, the success would likely to depend on maintaining strong institutional support and community engagement during the implementation phase. Future research could examine the environmental impacts of reduced chemical fertilizer use on soil fertility, the impacts on crop yield and its reflection in income against the control setting, and the potential for scaling up such integrated intervention models in different geographical and socio-economic contexts.

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