Sustainable Futures 10 (2025) 100856

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

An assessment of biogas adoption potential: A pathway to sustainable development in Nala, Rudraprayag, Uttarakhand, India

Sreevidhya C [a], S. Balamurugan [b,*]

[a] Amrita School for Sustainable Futures, Amrita Vishwa Vidyapeetham, Amritapuri, India
[b] Department of Electrical and Electronics Engineering, Amrita School of Engineering Coimbatore, Amrita Vishwa Vidyapeetham, India

ARTICLE INFO

Keywords:
Sustainable assessment
Energy consumption
Carbon emissions
Sustainability indicators
Environmental Impact

ABSTRACT

India is a major contributor to the development of renewable energy technologies. Firewood and cow dung cakes are the main cooking fuels in rural areas, where biomass makes up 75 % of total energy consumption and pollutes the environment. Decisions to employ clean energy are influenced by intra-household gender disparities because women are largely responsible for cooking and collecting fuel. This study evaluates the use of biogas in line with Sustainable Development Goals (SDG) 7, 5, 13, and 8 while looking at energy consumption, women's labour and carbon emissions in high-altitude community Nala, Rudraprayag, Uttarakhand. The findings show that biogas reduces the amount of time spend by women in firewood gathering by 15 h per month. It also decreases the annual greenhouse gas emissions by 1938.6 kg CO_2e through firewood usage reduction by 5 %. According to these results, biogas is a sustainable energy source that reduces its negative effects on the environment, lowers the work intensity required of women, and advances socioeconomic growth and gender equality. Adoption of biogas addresses important issues with energy use and environmental sustainability and provides a revolutionary route to clean energy in rural, high-altitude low temperature areas.

1. Introduction

Growing energy consumption and its consequences on the environment are directly linked to economic growth. The largest year growth in CO_2 emissions ever occurred in 2021, when global energy-related emissions rose by 6 % to 36.3 Gt CO_2 [1]. Global warming, a significant aspect of climate change, has led to a rise in global temperatures, resulting in various environmental impacts such as greenhouse emissions by the end of this century, global temperatures could rise by 1 °C to 3.7 °C [2]. The average global temperature in 2022 was 1.15 °C higher than the average global temperature between 1850 and 1900, According to a statement from the World Meteorological Organization in May 2023, global temperatures are predicted to reach new highs due to ongoing climate change [3]. Apart from the rise in temperature, two additional noteworthy global impacts of climate change are the melting of polar ice caps and the ascent in sea levels [4].

Furthermore, the use of non-renewable energy sources exacerbates climate change. To address energy needs, several advancements have led to the development and implementation of technologies to harness renewable resources [5]. To achieve the targets set for 2050, world leaders have pledged in the COP26 agreement to slow down climate change and achieve net zero emissions" [6]. Like the rest of the globe, India is committed to implementing a low-carbon economy and increasing the share of renewable energy to meet its energy needs.

The use of solid cooking fuel is associated with higher levels of environmental pollution and health burden [7–9]. According to data from the Global Burden of Disease Study (GBD) 2017 [10], household air pollution was responsible for 0.48 million of the 1.24 million air pollution-related fatalities that occurred in India in 2017, while ambient particle matter pollution was responsible for 0.67 million of those deaths. Although the primary cause of residential air pollution is the burning of solid fuel for cooking and heating, outside influences also play a significant role in contributing to ambient particulate matter pollution. Eliminating biomass from cooking will improve ambient air quality overall by 17.5 %, according to [11].

Like in most other nations, cooking is still mostly the domain of women in India. The Indian Human Development Survey (IHDS) [12, 13] estimates that women make up 98 % of household cooks. Furthermore, in households that rely on wood, women and girls carry a disproportionate share of the workload in gathering it [14] There is evidence in the literature, based on a nationally representative sample from the second wave of the Indian Household Discourse Survey,

* Corresponding author.
E-mail address: s_balamurugan@cb.amrita.edu (S. Balamurugan).

https://doi.org/10.1016/j.sftr.2025.100856
Received 12 February 2024; Received in revised form 2 February 2025; Accepted 12 June 2025
Available online 14 June 2025
2666-1888/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

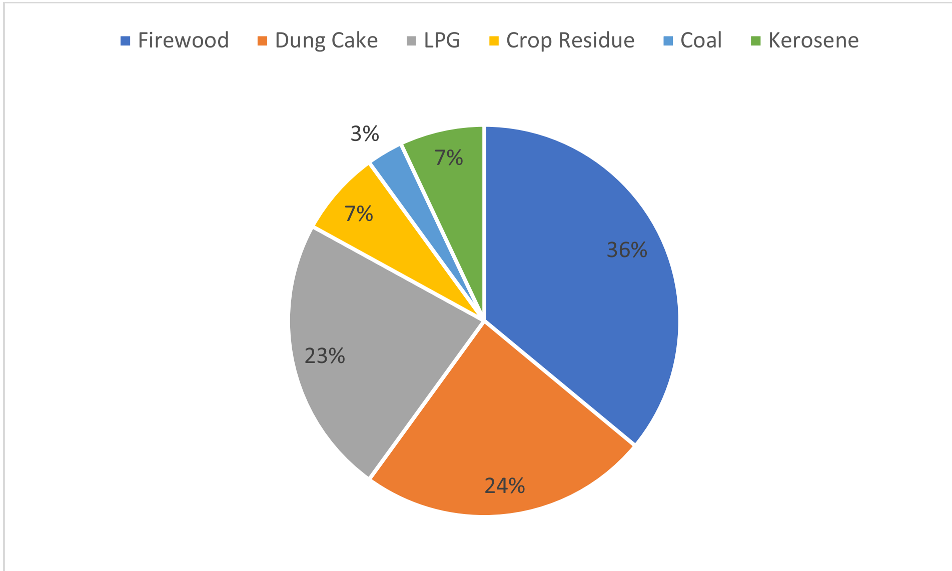

Fig. 1. Various Fuels Used for Cooking based on IHDS, 2011–12 [13] .

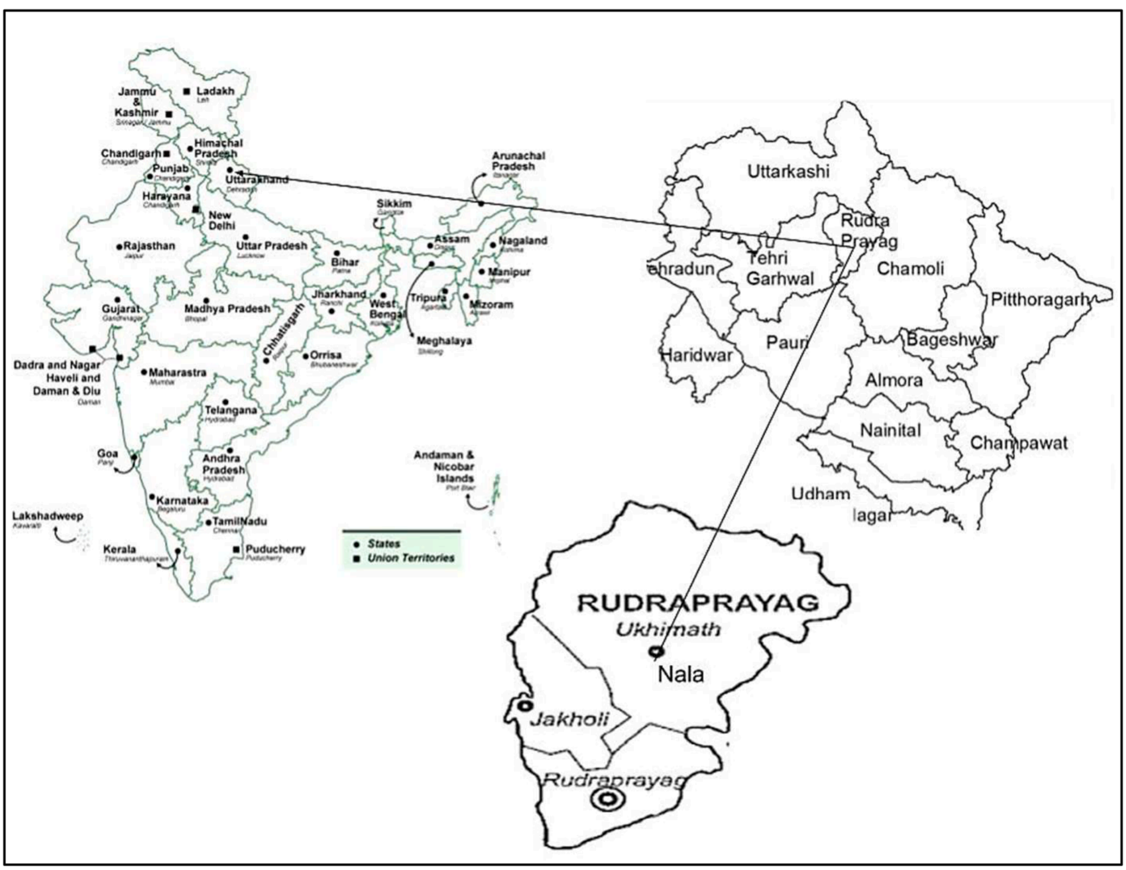

Fig. 2. Outline of community Nala, Ukhimath, Rudraprayag, Uttarakhand, India.

indicating household decisions about the purchase of clean fuel may be significantly influenced by gender inequality in Indian society. Indian households use a variety of fuels for cooking. Predicted on IHDS Fig. 1 shows how common place firewood and cow dung cakes are, with liquefied petroleum gas (LPG) also known as 'cooking gas', is widely used in many households coming in second.

Households' dependence on biofuel tends to rise when they have easier access to free alternative biofuel sources like wood or cow dung. This can be attributed to two factors: either they live close to a common property resource, like an open-access forest area, or they own livestock or agricultural land, which are more common in rural areas mostly in high-altitude villages of the Himalayas [15].

The viability and effects of biogas technology in high-altitude rural communities are assessed in this study, with a particular emphasis on

Nala, Rudraprayag, Uttarakhand. This work aims to optimize biogas system to replace conventional biomass fuels to achieve socio economic and environmental advantages. The study specifically seeks to evaluate the viability of biogas systems from a technical and economic point. Carbon emission reductions and other environmental benefits are calculated. Further, socioeconomic benefits including decreased labour burdens and improved energy security are examined.

This work makes an attempt to get answer to the adoption of biogas technology in rural communities to lower household waste, improve energy security, and lower carbon emissions through cow dung waste for biogas production assessment in community, and its impact on usage of firewood dung cakes and LPG.

The sections of this paper are organized as follows: Section 2 involves the status of SDG indicators aligned in the community. Section 3 includes the Methodology for Biogas Assessment calculation in the community. Section 4 gives us the impact of SDG indicators concerning biogas production. Thus, the comparison of SDG indicators in each different cases are analysed and further discussed in Section 5. Further, the conclusions are made for attaining sustainable development goals concerning the community oriented.

2. Materials and methods

2.1. Community outline

This study's emphasis was deliberately chosen to be the Nala community, which is situated in the Ukhimath tehsil of Rudraprayag district, Uttarakhand, India as shown in Fig. 2, because of its distinctive features and applicability to the study's goals [16,17]. The town offers unique potential and challenges for the adoption of sustainable energy solutions because it is in an area with low temperatures. The purpose of this study is to assess and resolve these issues, producing knowledge that can be widely applicable to comparable areas around the world.

Several considerations led to the Nala community's choosing. First, the cold environment of the area makes it a perfect place to test the feasibility and adaptation of green energy technology in cold climates. Designing solutions that work in similar situations requires an understanding of these dynamics. Second, the community's varied socioeconomic status provides a representative sample for analysing households' varied willingness and ability to implement sustainable energy practices.

The Nala community's strong reliance on conventional biomass fuels like firewood and dung cakes further emphasizes how urgent it is to make the transition to more efficient energy sources. The argument for sustainable solutions is important and strong because these traditional behaviors add to indoor air pollution, deforestation, and labour loads, particularly for women.

This study is unique in that it examines how socioeconomic factors, climate, and energy use interact in areas with low temperatures. Our goal is to create reproducible and scalable frameworks that tackle these interconnected elements by examining the Nala community. In addition to enhancing the community's quality of life, the knowledge acquired will help shape policies and initiatives aimed at facilitating the switch to renewable energy in other rural areas with cold climates.

2.2. Methodological approaches

A well-known methodology in rural development is the Participatory Rural Appraisal (PRA) approach, which emphasizes community interaction to obtain localized perspectives [13]. To gather qualitative information necessary for comprehending the socioeconomic and environmental background, the PRA technique was used during this study over a three-week period in the Nala village. The community's spatial distribution, resource availability, social dynamics, and seasonal agricultural patterns were all revealed by means of tools including resource mapping, transect walks, Venn diagrams, and seasonal calendars. To evaluate the livelihood and environmental factors impacting energy behaviours, health and crop cultivation data were also gathered. Qualitative data gathering techniques such focus groups, structured interviews, and direct observations were used in conjunction with these activities. By using these techniques to involve the community, it was made sure that the data collected represented local viewpoints and knowledge. It also encourages inclusivity and gives participants the ability to help identify and solve local problems. However, the community's active participation and the researcher's facilitation abilities determine the effectiveness.

2.3. Conversion of qualitative data to quantitative data using SPSS

In this study, the Statistical Package for the Social Sciences (SPSS) software was utilized to code, analyse, and interpret data collected through questionnaires. This enabled the transformation of qualitative data into quantitative data, providing a structured foundation for rigorous statistical analysis.

The process of data entry was meticulously planned to ensure the accuracy and reliability of the analysis. The data, collected via structured interviews and group discussions, was formatted for compatibility with SPSS for subsequent processing. The first step is defining and labelling variables. Each questionnaire item was assigned a unique variable name and an appropriate label within SPSS to maintain clarity and consistency.

Variables were categorized based on their measurement levels. Nominal variables represented categorical data without an intrinsic order, such as the gender of respondents (e.g., 1 = Male, 2 = Female). Ordinal variables captured ranked data, such as the levels of knowledge, attitudes, or awareness regarding waste management (e.g., 1 = Low, 2 = Medium, 3 = High). Scale variables included continuous data, such as the respondent's age or monthly income, allowing for detailed numerical analysis. These categorizations aligned with the study objectives, facilitating effective statistical computation.

Once variables were defined, responses from the questionnaires were systematically entered into SPSS, with each row representing an individual respondent and each column corresponding to a specific variable or questionnaire item. The data entry process was carefully monitored to minimize errors and maintain uniformity, and cross-verification was performed to ensure consistency between the original responses and the SPSS dataset.

Responses to closed-ended questions were directly coded into predefined numerical categories, such as awareness levels about biogas plants coded as 1 = Low, 2 = Medium, and 3 = High. This coding simplified the data analysis by standardizing responses. Data cleaning was conducted to address issues such as missing values, using methods such as mean substitution for scale variables or excluding incomplete cases if the level of messiness was minimal. Validation ensured the dataset was free from inconsistencies, enhancing its reliability.

The transformed dataset was analysed using SPSS to derive meaningful insights. Descriptive statistics were employed to summarize the data, including frequencies and percentages for categorical variables to highlight response patterns like awareness levels. For numerical variables, measures of central tendency (e.g., mean, median) and dispersion (e.g., standard deviation) were computed. These statistical measures provided insights into the data's overall distribution and variability, enabling a comprehensive understanding of the community's knowledge and attitudes toward waste management practices. SPSS facilitated data visualization through various graphical tools. Charts and graphs, such as bar charts, were utilized to depict the distribution of awareness about waste management. These visualizations complemented the numerical analysis.

Several assumptions underpinned the analysis. Normality was assumed for parametric tests on continuous data, verified using the Shapiro-Wilk test. According to studies by [18] & [19] many statistical tests, including ANOVA and regression, assume normality.

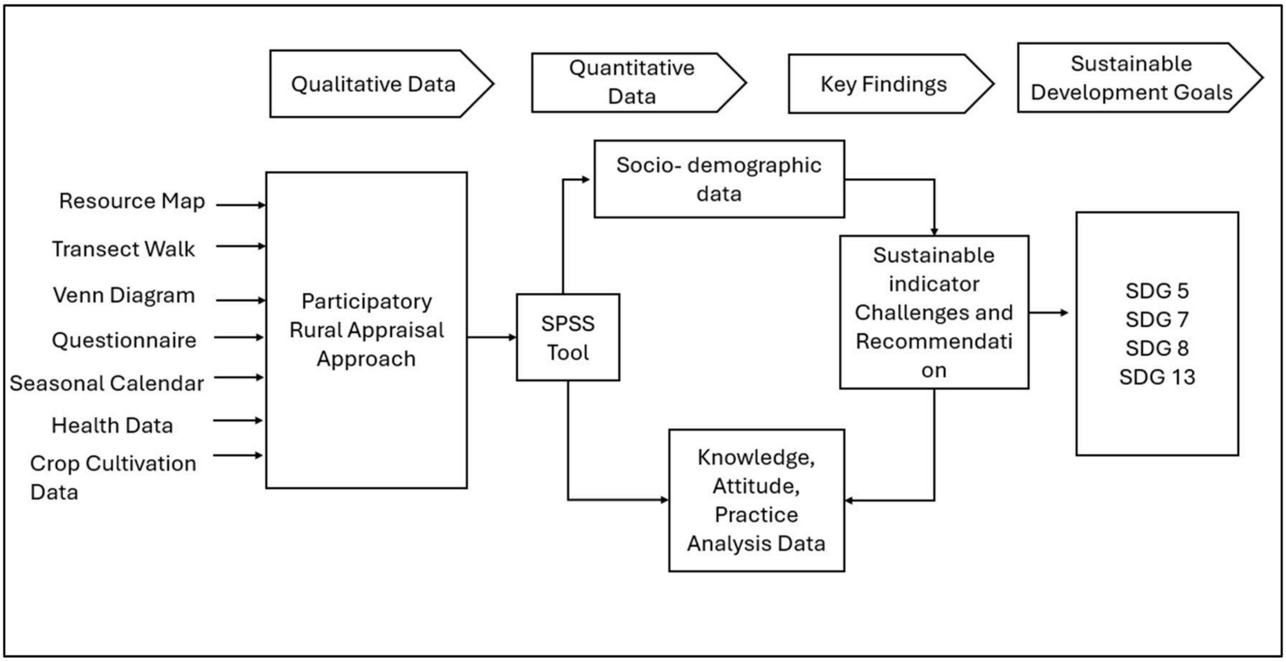

Fig. 3. Framework of identifying the community challenges.

Table 1
The population of Nala community ^{S}.

Size of the Family	No of Houses	No of Members	Percentage of Total Members
2 members	26	52	10 %
3 members	38	114	15 %
4 members	90	360	35 %
5 to 7 members	103	663	40 %
Total ($H^S{}_{total}$, C^S_{total})	257	1189(600 M, 589F)	
Avg size of family (AVGf ^{S})	1189/ 257 = 4.63		

where,
S: Survey data.
N: Number of members in the family.
AVGf ^{S}: Average size of the family.
C^S_{total}: Total members in a community.
$H^S{}_{total}$: Total number of households.

Independence of observations was ensured by conducting interviews individually in neutral settings to reduce external influence, a method validated in similar studies by [20].

Categorization simplified the analysis of continuous data, such as awareness scores categorized into Low, Medium, and High levels for easier comparison and interpretation. While this approach introduced simplifications, it aligned with the study objectives. The sample size of 100 respondents was sufficient for the study's scope but posed limitations in generalizability. According to [21], a sample size of 100 is considered adequate for exploratory research in social sciences. Despite these constraints, the methodological rigor ensured reliability and relevance within the study context.

This structured approach underscores the utility of SPSS in transforming qualitative insights into actionable quantitative findings, supporting the study's aim of evaluating community readiness for biogas-based waste management solutions. By the processes and methodology used for converting qualitative data to quantitative data with SPSS, a solid foundation is laid for subsequent discussions. This transparency helps to justify the reliability and validity of our findings, contributing to the overall robustness of our study. Thus, the framework of the process is discussed in Fig. 3.

By spending months in the village and getting to know the people there, a survey was gathered from the residents. There are 1189 people living in Nala overall, 600 of them are men and 589 are women. In Nala village, 74.43 % of people are literate, consisting of 85.33 % of men and 63.33 % of women. In Nala, there are about 257 dwellings. Table 1 presents the data gathered from the village survey.

3. Theory and calculations

3.1. SDG indicators in Nala community

One of the essential components for a nation's social and economic growth is energy and demand for it varies from place to place based on social and geographic factors. The dominant energy source for many developing nations is biomass, which includes traditional forms such as wood, crop residues, and animal dung, as well as more modern forms like biofuels [22,23]. Mountainous areas usually blend sociocultural diversity and ecological variability [24]. The four main elements of a hill agricultural system are meadows and forests, arable land, livestock, and people. These elements are all interconnected through several dynamic processes including the creation, transfer, and consumption of energy [25–29]. Since biomass accounts for about 90 % of energy consumption in the Himalayan region, the availability of food, fuel, and litter is crucial to the survival of rural settlements [30]. The main fuel source, firewood, was taken out all year long. As a result, the nearby forest ecosystem supplied a significant quantity of energy for human societies to survive in the form of fuelwood [31], and it remains the most important component for the survival of the hill agroecosystems [32].

Several authors have conducted in-depth studies on the fuelwood consumption pattern in the Himalayan regions, including migratory villages in Uttarakhand district [33], along altitudinal gradients in Garhwal Himalaya [35], various tribal communities in Northeast India [35], Pindar basin [36], Himachal Pradesh [37,38], and Tehri district in Uttaranchal [39]. Awasthi et al. [33] found that there was spatiotemporal variance in resource extraction among the Uttarakhand migrant villages. Research conducted using administrative boundary level data shows that the location's altitude and climate have an impact on firewood use.

Table 2
The Present status of Energy, Emission, Time consumption of Nala community [S].

Feedstock	Energy E_1 (MJ/unit)	Feedstock Requirement per Family FS^s	Energy Consumption (MJ)	Carbon Emission C_1 (kgCO2/unit)	Carbon Emission (kgCO2)	Time Spent by women T_1^S (min)	Cost involved (₹/year)
Biogas	E_{BG1}:39.96 MJ/m³	BG^S:0 m³	PE^S_{1BG} Family: 0 Community: 0 Percentage: 0 %	PC_{1BG}: 0.0725 kgCO2/m³	Family: 0 Community: 0 Percentage: 0 %	Single: 0 Family:0 Community:0	0
LPG	E_{LPG1}: 46.7 MJ/kg	LPG^S 0.15 kg (4 members/day	PE^S_{1LPG} Family: 8.10 Community: 2082.24 Percentage: 1.30 %	PC_{1LPG}: 0.74 kgCO2/kg	Family: 0.13 Community: 32.99 Percentage: 0.09 %	Single: 1.33 Family:3.08 Community:792.67	Family:6171 Community: 1345,424
Dung Cake	E_{DC1}: 15 MJ/kg	DC^S:1 kg (2 members/day)	PE^S_{1DC} Family: 34.70 Community: 8917.5 Percentage: 5.55 %	PC_{1DC}: 2.9119 kgCO2/kg	Family: 6.74 Community: 1731.12 Percentage: 4.60 %	Single: 60 Family:138.79 Community:35,670	0
Firewood (F)	E_{F1}: 18 MJ/kg	F^S: 14 kg (2 members/day)	PE^S_{1F} Family: 582.93 Community: 149,814 Percentage: 93.16 %	PC_{1F}: 4.3031 kgCO2/kg	Family: 139.36 Community: 35,814.70 Percentage: 95.31 %	Single: 540 (9 hrs) Family: 1249.14 Community: 321,030	0
Total	–	–	$PE^S_{1(F/DC/LPG/BG}$ Family: 625.73 Community: 160,813.74 Percentage: 100 %	–	Family: 146.22 Community: 37,578.82 Percentage: 100 %	Single: 10.02 hrs/day Family: 23.18 hrs/day Community: 5958.21hrs/day	–

where,
E_1: Energy value of feedstocks.
E_{F1}, E_{DC1}, E_{LPG1}, E_{BG1}: Energy value from different firewood, dung cake, LPG, Biogas.
FS^s: Feedstock requirement per day for N member family from Survey.
F^S, DC^S, LPG^S, BG^S: firewood, dung cake, LPG, Biogas requirement per day for N member family from Survey.
C_1: Carbon emission value from different feedstocks.
Energy per day for family ($PE^S_{1(F/DC/LPG/BG)}$).
where, T_1^S: Time spend by women in collecting different feedstocks.
Carbon emission per day for family ($PC_{1(F/DC/LPG/BG)}$).

In the hilly altitude regions, there are also significant regional variations in the consumption patterns of locally accessible energy and fuel mixtures. For their home energy demands, the rural residents of the hilly regions therefore rely on primary energy supplies such as fuel wood and agricultural leftovers, which are harvested using antiquated and ineffective methods. The main energy source for cooking and space heating in 85–90 % of rural families in steep terrain areas is biomass-based fuels [40]. Fuel wood accounted for 79–87 percent of all residential energy use, with 70 % going towards cooking [41].

The Sustainable Development Goals (SDGs) of energy access, environmental sustainability, and gender equality are among the many that are significantly impacted by using various cooking fuels. Making the right choice of cooking fuels is crucial for achieving SDG 7, which focuses on guaranteeing access to affordable and clean energy. Conventional resources such as firewood and dung cakes, which are frequently obtained through deforestation, impede the achievement of SDG 7′s universal access aim and worsen environmental degradation.

Carbon emissions from cooking are an important factor to consider, especially considering SDG 13, which calls for immediate measures to tackle climate change. Air pollution occurs both indoors and outdoors when firewood and dung cakes are burned because they discharge pollutants and carbon dioxide into the atmosphere. This directly affects climate action by emphasizing the necessity of switching to cleaner cooking methods.

The amount of time women spent on energy-related tasks, such as gathering firewood and dung cakes, has an impact on gender equality, which is a goal of SDG 5. Traditional cooking practices maintain gender roles in many communities, which restricts women's access to employment, education, and social opportunities. Low-income populations may find it difficult to adopt LPG due to affordability issues, which would keep them dependent on conventional biomass fuels thus SDG 8 gets affected.

3.1.1. Energy use pattern in the community

Many rural homes, like Nala village, rely on firewood and cow dung as key sources of fuel for cooking, heating, and mosquito repellent. These are traditional and biomass-based energy feedstock sources. They are frequently gathered from the surrounding area and burned for a variety of home purposes. This method of behaviour has been practiced for generations; however, it has been linked to environmental and health consequences.

Table 2. shows the energy value of different energy sources (feedstocks) [42,43] to calculate the community and family energy shared. Table 2. shows the feedstock requirement details collected for N-member family in the community. The different energy consumption patterns shared by the family and Community at Nala are also shown in Table 2.

Present energy per day for family ($PE^S_{1(F/DC/LPG/BG)}$) is calculated for different feedstock using Eq. (1). The Present energy per day for the community ($PE^S_{C(F/DC/LPG/BG)}$) is calculated for different feedstock using Eq. (2). Further, the percentage of energy sources shared from a different feedstock for the family and community (% E) are computed using Eq. (3) and presented in Table 2

$$PE^S_{1(F/DC/LPG/BG)} = \left(AVGf^S * E_1 * FS^S\right)/N \tag{1}$$

$$PE^S_{(SCF/DC/LPG/BG)} = \left(C^S_{total} * E_1 * FS^S\right)/N \tag{2}$$

$$\%E = PE^S_{(F/DC/LPG/BG)}/PE^S_{(F)} + PE^S_{(DC)} + PE^S_{(LPG)} + PE^S_{(BG)} \tag{3}$$

Thus, the first indicator is to discuss the indicator SDG 7 (Affordable and Clean Energy) concerning the percentage of energy consumption patterns in the community. Both the % Family and % Community columns show identical values because they represent the same proportionate energy usage derived from the same total values.

3.1.2. Carbon emission from different energy sources in the community

There are intrinsic drawbacks to using biomass for energy in the traditional way, such as contamination and environmental damage. In conventional "chulhas," biomass is burned directly, which is inefficient in terms of heat and only extracts 9–12 % of the fuel's potential energy [9,14] . In addition to using 133 million tonnes of wood, it has been calculated that the 30 million "traditional chulhas" in use are one of the main sources of smoke production in rural Indian households [20,21].

Smoke builds up within the house in mountainous, high-altitude kitchens due to inadequate ventilation. For women who cook with biomass fuel for more than three hours a day, prolonged exposure to high levels of pollution is particularly harmful to their health. Furthermore, the breakdown of organic matter and animal excrement adds to the atmospheric build-up of greenhouse gases, such as methane, which has an absorption capacity for heat in the atmosphere that is more than 20 times greater than that of carbon dioxide [33,34]. The carbon emissions [44] from different energy sources to calculate the family and community contribution to emission are also included in Table 2 for comparison.

Present carbon emission per day for family ($PC_{1(F/\ DC/\ LPG/\ BG}$) is calculated for different feedstock using Eq. (4). The Present carbon emission per day for a community ($PC_{c(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock using Eq. (5). Further, the percentage of carbon emission sources shared from a different feedstock for the family and community (% C) are computed using Eq. (6) and presented in Table 2

$$PC_{1LF/CD/LPG/BG)} = \left(AVGf^S * C_1 * FS^S\right)/N \tag{4}$$

$$PC_{c(F/CD/LPG/BG)} = \left(C^S{}_{total} * C_1 * FS^S\right)/N \tag{5}$$

$$\%C = PC_{(F/DC/LPG/BG)}/PC_{(F)} + PC_{(DC)} + PC_{(LPG)} + PC_{(BG)} \tag{6}$$

Thus, the second indicator is to discuss the indicator SDG 13 (Climatic Action) concerning the percentage of energy consumption patterns in the community.

3.1.3. Time spent by women in the collection of different energy sources in the community

Women in high-altitude villages have a difficult time providing for the energy demands of the household, which requires a large time commitment. Because of the difficult terrain, gathering firewood takes a lot of time nearly three hours in the morning, afternoon, and evening. This statistic is based on observations and interviews conducted during our 3 week stay in the village, as part of the Participatory Rural Appraisal (PRA) approach. The information was gathered from local residents who detailed the time spent on firewood collection. This laborious procedure, which is carried out by women, emphasizes the daily time commitment and physical cost involved in obtaining conventional biomass fuels.

Besides, making dung cakes takes about an hour a day, this estimate was also obtained through direct observations and discussions with villagers during our field research. The PRA methodology facilitated detailed insights into daily tasks, including the time required to prepare dung cakes which increases their workload even more. In these tribes, dung cakes are frequently utilised for cooking as an alternative solid fuel. Making dung cakes requires physical labour, which adds to the time constraints placed on women and reduces their availability for other pursuits.

Even with these efforts, a household can only consume up to four LPG cylinders annually, this data was collected through household surveys and interviews during our village visit. The PRA approach allowed us to gather accurate information on LPG consumption patterns and constraints faced by the households. Because of the poor distribution and availability of LPG in hilly places, people are more likely to rely on conventional fuels. The lack of LPG in these areas highlights the ongoing difficulties women encounter in gaining access to healthier and more effective cooking options. The time spend by the women in village is tabulated in Table 2.

$$AVGwf^{\ S} : \text{Ratioofwomenincommunity} = 589/1189 = 0.5$$

Present time spend by women per day for family ($PT^S_{1(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock using Eq. (7). The Present time spend by women per day for a community ($PT^S_{c\ (F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock in Eq. (8). The time spend by women from different feedstock for the family and community are computed using Eqs. (7) and (8) presented in Table 2.

$$PT^S_{1(F/CD/LPG/BG)} = \left(AVGf^S * T^S_1\right) * AVGwf^S \tag{7}$$

$$PT^S_{c(F/CD/LPG/BG)} = \left(C^S_{total} * T^S_1\right) * AVGwf^S \tag{8}$$

In conclusion, women in hilly altitude communities bear a heavy burden due to the length of time they must spend gathering firewood, preparing dung cakes, and having restricted access to LPG. Targeted interventions are needed to address these issues by increasing access to clean and efficient energy sources, relieving the time and physical burden on women, and fostering inclusive and sustainable development in these communities. Thus, the third indicator is to discuss the indicator SDG 5 (Gender Equality) concerning the time spend by women per day in different energy sources.

3.1.4. Cost involved in different energy sources in the community

Households with low incomes in communities where collecting firewood is free and dung cakes serve as fuel and insect repellent. Even though gathering firewood takes a lot of time, it is a popular option because it does not cost money. Although they serve several purposes and add to home chores, dung cakes take an hour a day to prepare. For low-income families, the cost of LPG becomes a major burden, competing with scarce resources. Hilly terrain creates additional geographic barriers that drive up LPG prices and reduce affordability [44,45]. Women are frequently disproportionately impacted by the trade-offs between time, money, and alternative practices when deciding whether to adopt LPG. The cost involved in different energy sources in a family and community are calculated using Eqs. (9) and (10). The values are presented in Table 2.

$$PLPG^S_{cCost} = \left(L_2 * C^s_{total} * 365 * 950\right)/(4 * 14.2) \tag{9}$$

$$PLPG^S_{1Cost} = PLPG^S_c C_{Cost}\ /H^S_{total} \tag{10}$$

where,

PF^S_{Cost}: Cost spend on Firewood collection =0
PDC^S_{Cost}: Cost spend on dung cake= 0
PBG^S_{Cost}: Cost spend on biogas production =0
$PLPG^S_{Cost}$: Cost spend on LPG
LPG^S_{Cost} per cylinder = Rs. 950 [40]
Total number of days in a year =365
Number of cylinders used per day^S =4
Weight of an LPG cylinder = 14.2 kg

Thus, the fourth indicator is to discuss the indicator SDG 8 (Decent work and Economic growth) concerning the affordability of members living under low-income groups on spending on different energy sources.

3.2. Assessment of biogas potential in community

Evaluating the possibility of producing biogas from organic waste in this case, cow dung used as the feedstock for biogas assessment as they the community do not have a proper management of wastes especially the cow dung waste. The proposed formulas provide a methodical approach to calculating the biogas yield and energy output from a specific amount of cattle fodder.

Table 3
Determination of Biogas energy potential.

Parameters	Value
Total number of cattle (C^S_T)	514
Amount of cow dung per cattle per day (C^S_A)	10 kg
Total amount of cow dung per day (C^S_{TA})	5140 kg
Cow dung: Water ratio	1: 1
Total amount of water per day (C_w)	5140 kg
Total amount of slurry (S_T)	10,280 kg
Hydraulic Retention Time (HRT)	35 days
Total Dry matter (T_{DM})	1456.24
Total Biogas production per day (V_{total})	206 m^3/day
Energy from Biogas produced per day (E_b)	8114 MJ/day

The anaerobic digestion of organic matter has evolved for the biogas production, there must be enough moisture in the air. The slurry is produced when water and cow faeces are mixed. This combination facilitates the production of biogas by providing the right environment for anaerobic bacteria to flourish. The number of solids in fresh manure is gauged by the dry matter percentage. It stands for the organic material that biogas can be produced. The total amount of cow dung, Slurry, Dry matter, Total Biogas production, and energy from biogas per day are calculated using Eqs. (11) – (15) and presented in Table 3.

$$C^S_{TA} = C^S T * C^S A \quad (11)$$

$$S_T = C^S_{TA} + C_W \quad (12)$$

$$T_{DM} = T_{FM} * \%DM \quad (13)$$

$$V_{total} = T_{DM} * V \quad (14)$$

$$E_b = V_{total} * E_1 BG \quad (15)$$

where,
T_{DM}: Total Dry matter (DM),% DM =0.24 [46],
T_{FM}: Total Fresh manure
V: Biogas produced per day =0.24 [46]

The process of evaluating biogas is systematic and involves knowing the inputs (water, cow dung), as well as how anaerobic digestion transforms them into biogas. The last stage measures the biogas's potential for energy. For communities looking to turn their agricultural waste into biogas as a clean energy source, this will be helpful. Transitioning to cleaner energy sources, such as dung biogas, can lower emissions, save time, and improve the environmental and economic sustainability of cooking practices.

4. Results of biogas production

4.1. Contribution of biogas to SDG indicators: impacts

This section explains how biogas contributes to the economic, social, and environmental pillars of sustainable development as in Fig 4. It explains how biogas specifically fits into the SDGs and sustainable development dimensions through SDG indicators.

4.1.1. Increasing energy production (SDG 7: affordable and clean energy)

By reducing the community's reliance on traditional biomass fuels like firewood, biogas, a clean fuel, helps SDG Indicator 7.1 [45] which measures the proportion of the population with primary reliance on clean fuels and technology. Indicator 7.2.1[45] adds to the Renewable Energy Share in the Total Final Energy Consumption: By boosting the percentage of renewable energy in the community's energy consumption, biogas adoption assists in the community's overall goal of switching to sustainable energy sources.

In line with Sustainable Development Goal 7 (SDG 7) to guarantee

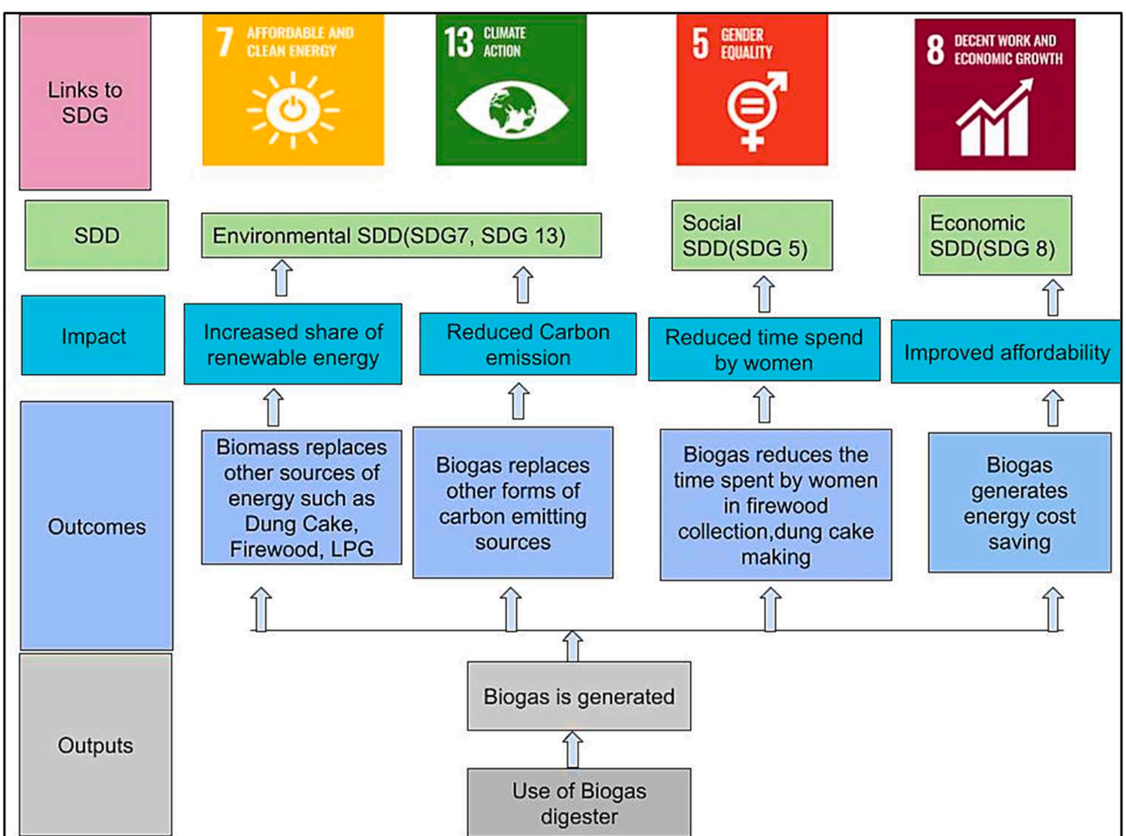

Fig. 4. The potential of Biogas to contribute towards SDG and SDD in the Nala community.

Table 4
The Targeted status of Energy, Emission, Time consumption of Nala community [S].

Feedstock	Feedstock Requirement TFS	Energy Consumption (MJ)	Carbon Emission (kgCO2)	Time Spent by women (min/day)	Cost involved (₹/yr.)
Biogas	TBG: 206 m^3/day/2 member	Family: 32.03 Community: 8231.76 Percentage: 5.12 %	Family: 0.11 Community: 29.3 Percentage: 0.08 %	Single: 5 Family:27.27 Community:5945	Family: 4094.53 Community:892,600
LPG	TLBG:0.15 kg/day/4 member	Family: 8.1 Community: 2082.24 Percentage: 1.30 %	Family: 0.13 Community: 32.99 Percentage: 0.09 %	Single: 1.33 Family:1.818 Community:396.33	Family: 6171.67 Community:1345,424
Dung Cake	TDC: 1 kg/day/2 member	Family: 34.70 Community: 8917.50 Percentage: 5.55 %	Family: 6.74 Community: 1731.13 Percentage: 4.85 %	Single: 60 Family:138.79 Community:35,670	Family:0 Community:0
Firewood	TF: 13.23 kg/day/2 member	Family: 550.90 Community: 141,582.24 Percentage: 88.04 %	Family: 131.70 Community: 33,846.81 Percentage: 94.9 %	Single: 510 min (8.5 hrs) Family: 1180.44 Community: 303,373.35	Family:0 Community:0
Total		Family: 625.73 Community: 160,813.74 Percentage: 100 %	Family: 138.67 Community: 35,640.24 Percentage: 100 %	Single: 9.61 hrs/day Family: 22.3 hrs/day Community: 5756.411 hrs/day	

access to contemporary, reasonably priced, and sustainable energy, the adoption of biogas technology in a community greatly reduces reliance on firewood. Reducing reliance on conventional biomass fuels and raising the community's proportion of renewable energy sources are two ways that biogas, as a clean and sustainable fuel, satisfies SDG 7 indicators. In addition to reducing the amount of firewood used, the switch to biogas benefits the environment enhances community economic stability and improves health by lowering indoor air pollution. This change helps achieve the more general objectives of environmental preservation, health enhancement, and economic development by fostering a more equitable and sustainable approach to energy access. Thus, if Biogas of 206 m^3 is added to the 2-member family in the community as discussed in Section 3, the feedstock quantity is calculated and presented in Table 4.

Table 4 shows the new targeted energy consumption patterns from different energy sources in a family and community. The Targeted energy per day for community ($TE_{C(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock using Eqs. (16), (17), (18). Targeted energy per day for family ($TE_{1(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock using Eqs. (19), (20), (21). Further, percentage of energy source shared from different feedstock for the family and community (% TE) are computed using Eq. (22) and presented in Table 4.

Community:

$$TEC(TDC\,/\,TLPG) = \left(\mathrm{E}_1 * TFS^S * \mathrm{H}^S \text{ total }\right)/\mathrm{N} \tag{16}$$

$$TEC(TBG) = TFS^S * \mathrm{E}_1 \tag{17}$$

$$TEC_{(TF)} = \sum PEC\_TE_{(TDC)} - TE_{(TLPG)} - TE_{(TBG)} \tag{18}$$

Family:

$$TE_{1(TDC/TLPG)} = \left(\mathrm{E}_1 * TFS^S * AVGf^S\right)/\mathrm{N} \tag{19}$$

$$TE_{1(TBG)} = TEC(TBG)/\mathrm{H}^S_{\mathrm{total}} \tag{20}$$

$$TE_{1(TF)} = \sum PE_1 - TE_{(TDC)} - TE_{(TLPG)} - TE_{(TBG)} \tag{21}$$

$$\%TE = TE_{(F/DC/LPG/BG)}/TE_{(F)} + TE_{(DC)} + TE_{(LPG)} + TE_{(BG)} \tag{22}$$

where,

TFS: Feedstock requirement per day for N member family from Survey

TF, TDC, TLPG, TBG: firewood, dung cake, LPG, Biogas requirement per day for N member family from Survey While biogas can be a cost-effective and sustainable energy source, it also has drawbacks. These include the greenhouse gas contribution of methane, impurities that can damage or even destroy devices, low energy density, and variations in composition and amount.

4.1.2. Reduce climate change impacts (SDG 13: climate action)

Although not a direct indicator, Indicator 13.1 [41] helps to Adoption of biogas reduces carbon emissions and promotes climate resilience, which may lessen the frequency and intensity of climate-related disasters. Adoption of biogas can be part of a community plan to lower risks related to climate change by promoting sustainable energy usage, as indicated by Indicator 13.2 [45,46].

The adoption of biogas is essential for lowering carbon emissions in a community and is consistent with SDG 13, which addresses climate action. Biogas considerably reduces the carbon footprint of the community by acting as a cleaner substitute for fossil fuels and conventional biomass. This carbon decrease helps local and global climate resilience and advances global climate goals, such as the Paris Agreement. The adoption of biogas addresses SDG 13 indicators, demonstrating its ability to fight climate change and advance sustainable energy practices, ultimately resulting in a future that is more resilient and climate friendly. Due to the Biogas adoption of 206 m3, the new carbon emission from different energy sources is presented in Table 4. where, C_1: Carbon emission value from different feedstocks

Present carbon emission per day for family ($TC_{1(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock using Eq. (4). The Present carbon emission per day for a community ($TC_{c(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock using Eq. (5). Further, the percentage of carbon emission source shared from different feedstock for the family and community (% TC) are computed using Eq. (6) and presented in Table 4.

4.1.3. Reduction in time spend by women in collecting different feedstock energy sources

The introduction of a biogas plant significantly reduces the time women spend collecting various feedstock energy sources. According to [41], this measure is directly impacted by the reduction in time required to gather traditional fuel sources such as firewood and dung cakes.

Contribution of Indicator 5.4.1 [45]**:** The reduction in time spent on collecting fuel directly contributes to Indicator 5.4.1, which measures the amount of time women allocate to unpaid domestic and care work. By decreasing the time spent on these tasks, women can engage more in productive activities, thereby improving their overall quality of life. Moreover, Indicator 5.1.1, which assesses women's empowerment and gender equality, is positively influenced as women have more opportunities for education, employment, and participation in community activities. This measure is directly impacted by less time spent on gathering traditional fuels, allowing for greater participation in economic and social activities. Favourable outcomes include improved health, increased educational opportunities for women and children, and enhanced economic productivity.

The adoption of biogas relieves women of the labour-intensive duty of gathering firewood, which has historically fallen on their shoulders. Women's economic empowerment can be further enhanced by diverting their time to other income-generating pursuits when they are less dependent on firewood. The community's social and economic dynamics are positively impacted by women's growing involvement in the economy. The time spend by the women after biogas production is presented in Table 4.

Targeted time spend by women per day for family ($TT_{1(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock using Eqs. (23) and (24), The targeted time spend by women per day for a community ($TT_{C(F/\ DC/\ LPG/\ BG)}$) is calculated for different feedstock in Eqs. (25) and (26), are presented in Table 4.

$$TT_{1(F/C_{D/LPG})} = \left(AVGf^S * T_1^S\right) * AVGwf^S \tag{23}$$

$$TT_{1(BG)} = TT^S_{c(BG)} / H^S total \tag{24}$$

$$TT_{c(F/CD/LPG)} = \left(C^S_{total} * T_1^S\right) * AVGwf^S \tag{25}$$

$$TT_{c(BG)} = TT_1^S * C^S total \tag{26}$$

where, TT_1: Time spend by women in collecting different feedstocks

$AVGwf^S$: Ratio of women in community = 589/1189=0.5

4.1.4. Improving affordability, economic development, and adding value to products (SDG 8: decent work and economic growth)

According to Indicator 8.1.12 [45], the utilization of biogas has the potential to create local economic opportunities that could increase the growth rate of the real GDP per employed person, a measure of economic productivity. Additionally involved as Indicator 8.5.12 [45] The utilization of biogas has the potential to impact this figure by creating jobs that increase the mean hourly wage and potentially narrow the gender pay disparity.

The adoption of biogas lowers the cost of energy for communities, ensuring that everyone has access to reasonably priced and sustainable energy (SDG 7). This reduces household financial burdens and promotes economic growth. The adoption of biogas reduces the need to gather LPG at higher elevations where accessibility may be difficult. One way to support SDG 8′s goal of encouraging full and productive employment is to transfer the time saved by not needing to collect LPG or traditional fuels to other productive and income-generating activities. The switch to biogas encourages self-sufficiency in energy production, which strengthens local resilience. This is consistent with the notion of constructing robust, resilient, and sustainable. The cost involved in LPG in a family and community are calculated using Eqs. (9) and (10) already. The values are presented in Table 4. Moreover, cost involved in Biogas in a family and community are calculated using Eqs. (27) and (28) where,

$$TBG_c Cost = B_{maintenancecost} + B_{labourcost} \tag{27}$$

$$TBG_1 Cost = B_2 \mathit{Cost}_{community} / H_{total} \tag{28}$$

5. Discussion

The overall discussion involves the current situation in the community without biogas adoption and the new status with Biogas adoption:

The adoption of biogas presents a transformative opportunity for the community. Currently, traditional biomass fuels, such as firewood (93.1 %) which contribute the primary energy sources. This heavy reliance of firewood results in substantial carbon emissions, calculated at 35,814.7 kg CO_2e annually. Women in the community spend approximately 9 h per day collecting firewood, which is a significant time burden.

The shift to biogas is anticipated to reduce firewood consumption to 88 %, which would lower carbon emissions of firewood to 33,846.8 kg CO_2e. This reduction aligns with SDG 13 (Climate Action) by mitigating greenhouse gas emissions. Additionally, the time spent by women in collecting firewood is expected to decrease to 8.5 h per day, directly contributing to SDG 5 (Gender Equality) by alleviating the time burden on women.

Thus, with the Biogas adoption, the following contribution towards SDG5, SDG 7, SDG 13, SDG 8, and corresponding Social, economic, and Environmental Sustainable Development Dimension (SDD) can be attained as shown in Table 5.

Table 5
The SDG and SDD Attained on the Contribution of Biogas Adoption in the Community.

SDG	Contribution of Biogas	SDD
SDG 5: Gender Equality	Reduces the time spent by women in collecting firewood from 9 h per day to 8.5 h per day	Social
SDG 7: Affordable and Clean Energy	Biogas reduces firewood consumption from 93 % to 88 %.	Environment
SDG 8: Decent Work and Economic Growth	The cost involved in the operation and maintenance of biogas is around 892,600/ yr added to 134,5425.34/ yr for LPG.	Economic
SDG 13: Climate Action	Reducing Total GHG emissions from 37,578.82 kg CO_2e to 35,640.24 kg CO_2e.	Environment

5.1. Comparison of biogas assessment in different scenarios

This section presents a detailed comparison of biogas assessments across four different scenarios. These scenarios are designed to evaluate strategies for optimizing biogas production and their subsequent impact on energy consumption, carbon emissions, and socio-economic factors within the Nala community. Each scenario is grounded in resource availability, technological improvements, and shifts in energy consumption patterns.

Scenario 1. Complete Biomass Conversion to Biogas

This scenario evaluates the maximum potential for biogas production if all available biomass resources in the community, such as firewood and dung cakes, are entirely converted to biogas. This scenario is derived from an analysis of the community's total biomass availability. It serves as a baseline, demonstrating the upper limit of biogas production and providing a foundation for comparison with other scenarios. It highlights the feasibility of using biogas as a primary energy source if all biomass is utilized efficiently.

Scenario 2. Engineering Enhancements to Increase Biogas Production by 10 %

This scenario explores the impact of technological advancements in improving biogas production efficiency. It is based on hypothetical improvements in the efficiency of biogas digesters or optimized anaerobic digestion processes. A 10 % increase in biogas production is considered a realistic and achievable target through engineering innovations. This scenario investigates the resulting improvements in energy production and reductions in carbon emissions, demonstrating the role of technology in advancing renewable energy systems.

Scenario 3. Doubling Dung Cake Production by Reducing Firewood Usage

This scenario considers shifting a portion of the community's energy reliance from firewood to dung cakes, thereby increasing dung cake production. The scenario is based on a feasibility assessment of reallocating energy resources within the community. Doubling dung cake production leverages an abundant yet underutilized resource. This scenario evaluates the environmental and socio-economic benefits of reduced firewood usage, including its impact on biogas production and carbon emissions.

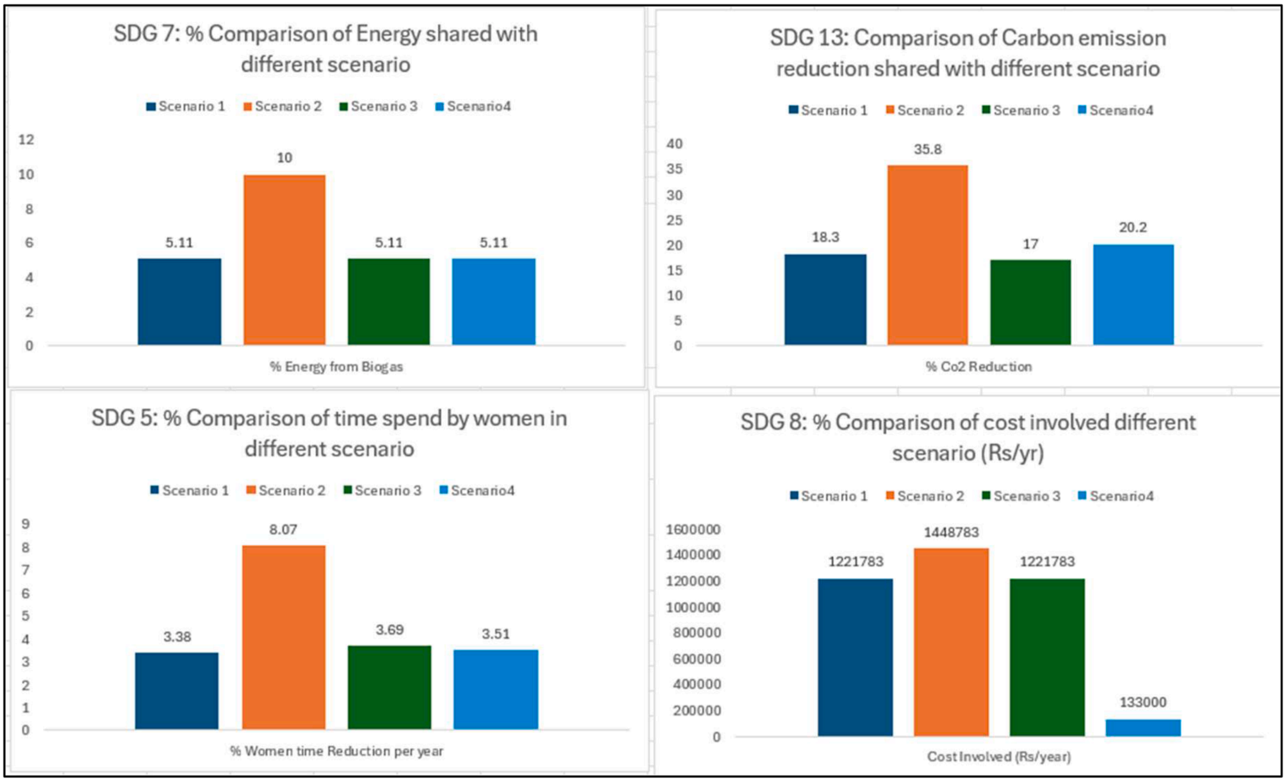

Fig. 5. Comparison of four different cases concerning SDG 7, 13, 5, and 8.

Scenario 4. Simultaneous Compensation of Firewood and LPG

This integrated scenario combines efforts to reduce both firewood and LPG usage, providing a holistic approach to the community's energy transition. It is derived from a combined analysis of reducing reliance on multiple energy sources. By simultaneously addressing firewood and LPG consumption, this scenario assesses the overall impact on biogas yield, carbon footprint, and energy sustainability. It provides a comprehensive view of the community's transition toward cleaner and more sustainable energy systems, considering environmental, social, and economic dimensions.

The initial and new values of biogas production for each scenario are presented in Fig. 5. It compares the scenarios with respect to their contributions to Sustainable Development Goals (SDG) 7 (Affordable and Clean Energy), 13 (Climate Action), 5 (Gender Equality), and 8 (Decent Work and Economic Growth).

Out of all the options, Scenario 2 is the most advantageous since it strikes a balance between producing more energy, reducing emissions, and improving gender equality. The constraint of inadequate cattle feedstock, however, presents a difficulty. Even if Scenario 3 and 4 increase women's time efficiency, they could not have the same overall beneficial effect as Scenario 2. To realize the full benefits of increasing biogas production and make it the most sustainable option for the community, it is important to consider the feedstock constraint. Moreover, by compensation LPG as in Scenario 4, the cost of expenditure is reduced and thus biogas is a form of energy that can improve affordability which leads to SDG 8 contribution.

6. Conclusions

Communities benefit much from Biogas technology, especially when it comes to fostering Sustainability. Adoption of Biogas can cut firewood use from 93 % to 88 %, according to our quantitative research. This would result in a significant decrease in total Carbon Emissions, from 37,578.82 kg CO2e to 35,640.2 kg CO2e. This modification highlights the contribution of biogas to climate change mitigation and is consistent with the attainment of SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action). Adoption of Biogas also helps achieve SDG 5 (Gender Equality) by lowering the amount of time women spend gathering firewood. To ease gender-specific constraints and improve women's access to more productive activities, the Time spent on each collection has been reduced from 9 h per day to 8.5 h per day i.e., 15 h per month. Biogas systems provide a significant economic benefit by reducing operating and maintenance expenses. Along with the community's present LPG expenditure of 1345,425.34/ yr, biogas operations expense of Rs 892,600/ yr gets added. SDG 8 (Decent Work and Economic Growth) may directly gets supported for cost reduction, if the community increases the biogas adoptability. In summary, biogas technology is a crucial part of sustainable community development because it not only offers an eco-friendly substitute for conventional energy sources but also promotes gender equality, economic growth, and climate action.

CRediT authorship contribution statement

Sreevidhya C: Writing – original draft, Software, Investigation, Funding acquisition, Formal analysis, Data curation. **S. Balamurugan:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

"This project has been funded by the E4LIFE International Ph.D. Fellowship Program offered by Amrita Vishwa Vidyapeetham. We extend our gratitude to the Amrita Live-in-Labs® academic program for providing all the support".

Data availability

Data will be made available on request.

References

[1] IEA Global Energy, Available online, Review: CO2 Emissions in 2021. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2, 2022 (accessed on 3 July 2023).
[2] K. Abbass, M.Z. Qasim, H. Song, M. Murshed, H. Mahmood, I. Younis, A review of the global climate change impacts, adaptation, and sustainable mitigation measures, Env. Sci. Pollut. Res. 29 (2022) 42539–42559.
[3] https://wmo.int/news/media-centre/climate-change-indicators-reached-record-levels-2023-wmo [accessed 13 February 2024].
[4] B. Vujic, J. Pekez, V. Mihajlovic, L. Radovanovic, U. Marceta, I. Palinkas, Public perception and awareness on climate changes and the importance of renewable. energy sources, Appl. Eng. Lett. J. Eng. Appl. Sci. (2020).
[5] https://www.iea.org/reports/world-energy-outlook-2021 [accessed 13 February 2024].
[6] Energy, Global. "Net Zero by 2050".
[7] Balakrishnan Kalpana, Ramaswamy Padmavathi, Sambandam Sankar, Thangavel Gurusamy, Ghosh Santu, Johnson Priscilla, Mukhopadhyay Krishnendu, Venugopal Vidhya, Thanasekaraan Vijayalakshmi, Air pollution from household solid fuel combustion in India: an overview of exposure and health related information to inform health research priorities, Glob. Health Action (2011).
[8] A. Chafe Zoë, Brauer Michael, Klimont Zbigniew, Mehta Sumi Van Dingenen Rita, Rao Shilpa, Riahi Keywan, Frank Dentener, Smith Kirk R. 'Household cooking with solid fuels contributes to ambient PM2.5 air pollution and the burden of disease, Env. Health Perspect. (2014).
[9] Chowdhury Sourangsu, Dey Sagnik, Guttikunda Sarath, Pillarisetti Ajay, Smith Kirk R, Di Girolamo Larry, 'Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources, in: Proc. Natl. Acad. Sci. Unit. States Am, 2019.
[10] Desai Sonalde, Dubey Amaresh, B.L. Joshi, Sen Mitali, Shariff Abusaleh, Vanneman Reeve, Human Development in India: Challenges for a Society in Transition, Oxford University Press, New Delhi, 2010.
[11] Jyoti. Parikh, Hardships and health impacts on women due to traditional cooking fuels: a case study of Himachal Pradesh, India, Energy Pol. (2011).
[12] N. Kumar, V. Bheemreddyvalla, Role of Fuelwood and Its Substitute, e magazine, 2021.
[13] Martin Kofi Kanyagui, et al., Livelihood challenges faced by women in rural India: exploration of solutions using participatory action research, Dev. Pr. 34 (4) (2024) 512–526.
[14] Christophe Muller, Yan Huijie, Household fuel use in developing countries: review of theory and evidence, Energy Econ. (2018).
[15] K. Chandrasekhar, K.S. Rao, R.K. Maikhuri, K.G. Saxena, Ecological implications of traditional livestock husbandry and associated land use practices: a case study from the trans-Himalaya, India, J. Arid Env. 69 (2007) 299–314, https://doi.org/10.1016/j.jaridenv.2006.09.002.
[16] C. Sreevidhya, S. Balamurugan, Optimization of methane yield for a low temperature region based on hydraulic retention rate and temperature control, in: Materials Today: Proceedings, 2023.
[17] C. Sreevidhya, S. Balamurugan, Determination of methane yield and suitable microbial activity at different operating temperature and hydraulic retention time, in: 2022 1st International Conference on Sustainable Technology for Power and Energy Systems (STPES), IEEE, 2022.
[18] Field, Andy. "Discovering statistics using IBM SPSS statistics." (2013): 115–21.
[19] B.G. Tabachnick, L.S. Fidell. Using multivariate statistics (6. Baskı), Pearson, MA, 2013.
[20] Jacob Cohen, et al., Applied Multiple Regression/Correlation Analysis For the Behavioral Sciences, Routledge, 2013.
[21] Z. Dornyei, Research Methods in Applied Linguistics, Oxford University Press, 2007.
[22] https://www.iea.org/reports/world-energy-outlook-2021 [accessed 12 February 2024].
[23] https://www.worldenergy.org/[12 February 2024].
[24] M.F. Price, M. Thompson, The complex life: human land uses in mountain ecosystems. The Institutional Dynamics of Culture, Volumes I and II, Routledge, 2018, pp. 908–921.
[25] J.S. Singh, Uma Pandey, A.K. Tiwari, Man and forests: a central Himalayan case study, Ambio 13 (2) (1984) 80–87.
[26] P.C. Tiwari, Land-use changes in Himalaya and their impact on the plains ecosystem: need for sustainable land use, Land. Use Policy 17 (2) (2000) 101–111.
[27] M. Ashish, Agricultural economy of Kumaon hills: threat of ecological disaster, Econ. Polit. Wkly. (1979) 1058–1064.
[28] W. Whittaker, The ecology and economy of Himalayan agriculture and labour migration: a case study of Garhwal District, Dimens. Dev. Plan. 2 (1989) 509–550.
[29] Anand Sharma, et al., Micro-level sustainable biomass system development in central Himalaya: stress computation and biomass planning, Sustain. Dev. 7 (3) (1999) 132–139.
[30] Paul J. Martins, Jagdish C. Nautiyal, Population-supporting capacities a case study in the central himalayas, Interdiscip. Sci. Rev. 13 (4) (1988) 312–330.
[31] Marcus Moench, Jayant Bandyopadhyay, People-forest interaction: a neglected parameter in himalayan forest management, Mt. Res. Dev. (1986) 3–16.
[32] K.K. Sen, et al., Patterns and implications of land use/cover change, Mt. Res. Dev. 22 (1) (2002) 56–62.
[33] Anjali Awasthi, et al., Forest resource availability and its use by the migratory villages of Uttarkashi, Garhwal Himalaya (India), For. Ecol. Manage. 174 (1–3) (2003) 13–24.
[34] B.P. Bhatt, M.S. Sachan, Firewood consumption along an altitudinal gradient in mountain villages of India, BioMass BioEnergy 27 (1) (2004) 69–75.
[35] B.P. Bhatt, M.S. Sachan, Firewood consumption pattern of different tribal communities in Northeast India, Energy Policy 32 (1) (2004) 1–6.
[36] Vishwambhar Prasad Sati, Traditional intramontane mobility in Garhwal Himalaya: a survey of subsistence practices in the Pindar basin, Uttaranchal, Singap. J. Trop. Geogr. 29 (2) (2008) 173–185.
[37] A.K. Negi, B.P. Bhatt, N.P. Todaria, Local population impacts on the forests of Garhwal Himalaya, India, Environmentalist 19 (1999) 293–303.
[38] Anjali Awasthi, et al., Forest resource availability and its use by the migratory villages of Uttarkashi, Garhwal Himalaya (India), For. Ecol. Manage. 174 (1–3) (2003) 13–24.
[39] T.M.V Kumar, District energy planning and management for integrated development of Himalaya: issues and approaches, Stud. Himal. Ecol. Himal. (1980) 256–260.
[40] Priya Nair, Jaideep Menon, Role of Amrita Vishwa Vidyapeetham in integrated holistic health policy actions of civil 20 India 2023, Amrita J. Med. 19 (4) (2023) 204–208.
[41] A. Adams, E.T. Jumpah, H.S. Dramani, Dynamics of clean and sustainable households' energy technologies in developing countries: the case of improved cookstoves in Ghana, Sustain. Futur. 5 (2023) 100108, https://doi.org/10.1016/j.sftr.2023.100108.
[42] https://en.wikipedia.org/wiki/Energy_density [accessed 12 February 2024].
[43] Pokharel Tika Ram, Rijal Hom Bahadur, Hourly firewood consumption patterns and CO2 emission patterns in rural households of Nepal, Designs 4 (4) (2020) 46.
[44] https://www.petroldieselprice.com/lpg-gas-cylinder-price-in-Rudraprayag [accessed 13 March 2023].
[45] https://sdgtoolkit.org/what-is-it/indicators-and-goals/[accessed 12 February 2020].
[46] D.M. Teferra, W. Wubu, Biogas for clean energy. Anaerobic Digestion 1, 2018, pp. 149–168, https://doi.org/10.5772/intechopen.79534.