CHAPTER 1

INTRODUCTION

Chapter 1

Introduction

1.1 Importance of clean cooking fuels and its status in India

Energy poverty is defined as the "absence of sufficient choice in accessing adequate, affordable, reliable, high-quality, safe, and environmentally benign energy services to support economic and human development" [1]. Access to clean cooking fuel at the household level is essential to successfully eradicate energy poverty in rural communities worldwide [2]. The provision of clean cooking fuels to households is one of the main objectives of the Sustainable Development Goals (SDG) especially SDG 7 which "ensures access to affordable, reliable, sustainable, and modern energy for all" [3,4]. Traditionally, rural Indian cooking relies on solid biomass fuel such as fuel wood, dung cake, and residues which leads to adverse consequences for health due to indoor air pollution [2]. The impact of the traditional fuels which emit particulate matter (PM) and carbon monoxide (CO) is also alarming. Because of this, the total number of deaths attributed to household air pollution in India in 2019 was 0.8 million, of which 3 % were children under 5 years [5].

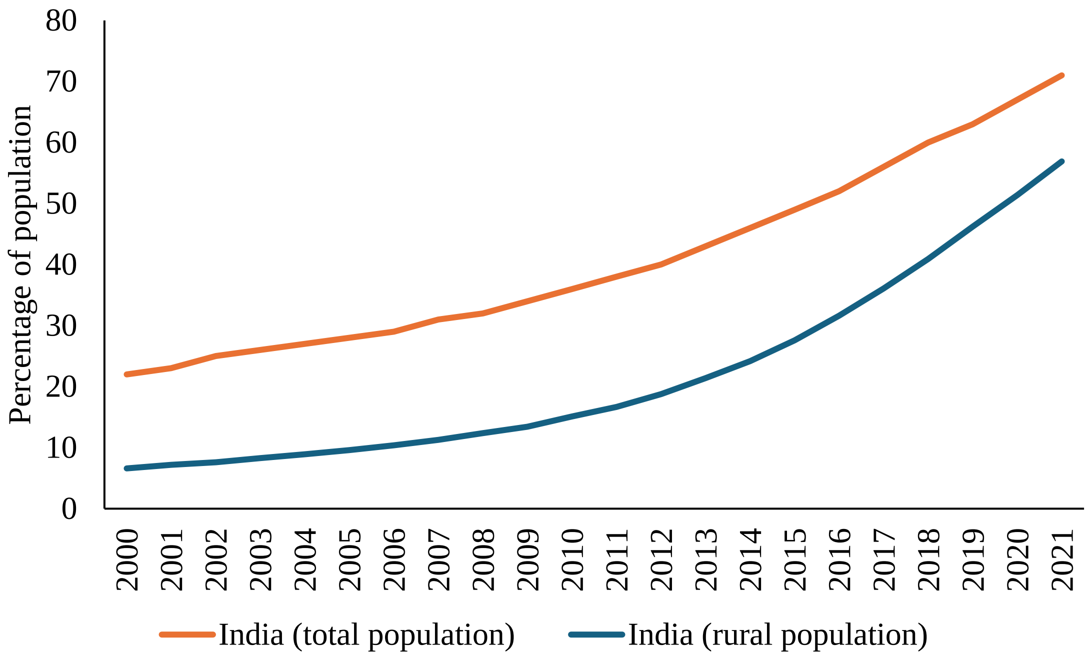

Fig 1.1: Access to clean cooking fuels and technologies in India and rural India [6]

Around 71 % of the total population and 57 % of the rural population in India have access to clean fuels and technologies for cooking as seen in **Fig 1.1**. There has been a 69% increase in the percentage of the total population of India with access to clean cooking. This is less compared to the access to clean cooking fuel for the rural population which is 88%. Although access to clean cooking fuel has increased drastically, a considerable population still does not have access to clean cooking options. The Government of India is encouraging the substitution of solid fuel for cleaner gaseous fuel *i.e.*, Liquefied Petroleum Gas (LPG), through promotional schemes like Pradhan Mantri Ujjwala Yojana (PMUY) [7]. The total number of domestic LPG connections released under the PMUY scheme as of February 2024 is 102 million [8]. Such an increase in the use of LPG in cooking is benefiting the users, mostly rural women, in different contexts including improving health and reducing drudgery [9]. The economically weaker sections have been provided subsidies as a part of the clean cooking policy by the Government of India. However, the supply of subsidized LPG results in a substantial fiscal burden on the national budget [10]. The subsidy on LPG provided by the Government of India for domestic connections has decreased by 81% from 2018-19 to 2022-23 as seen in **Fig 1.2**.

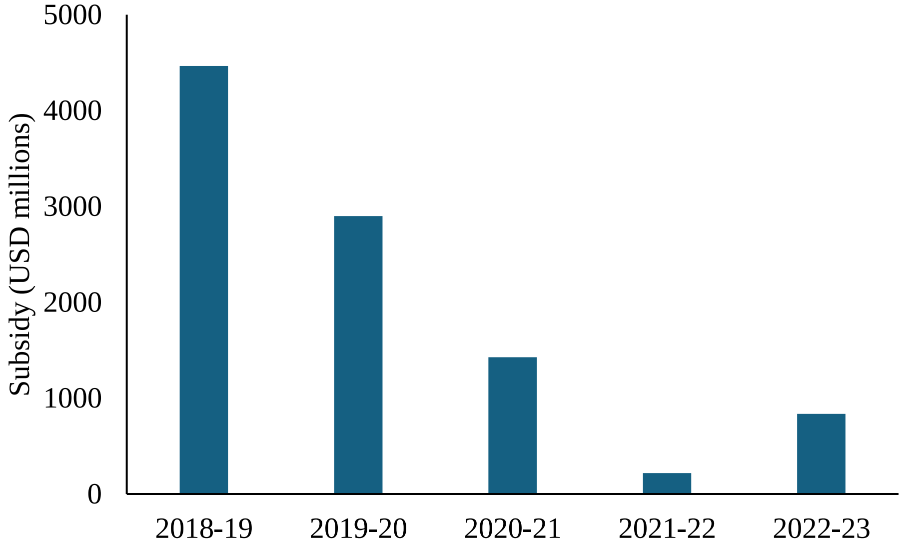

Fig 1.2: Subsidy on LPG given by the Government of India [11]

The shifting of fuel from solid fuel to LPG has necessitated the subsidy requirement. Thus, another fuel shifting is required to increase the penetration of clean cooking technology in rural India, decarbonizing the cooking sector along with LPG. It is imperative to focus on other alternative clean cooking fuels like biogas.

1.2 Biogas as a clean cooking fuel with multiple benefits

Based on the emission level of biogas reported in the literature [4], it can be considered a cleaner cooking fuel as compared to fuel wood. Biogas is obtained from the process of anaerobic digestion which is defined as the biodegradable degradation of organic materials by microorganisms such as animal manure, domestic sewage, and food wastes in the absence of oxygen which results in the formation of biogas and bio-slurry [12-14]. Both the outputs of anaerobic digestion are beneficial to people. Biogas can be used for cooking and bio-slurry is used as a biofertilizer as it is rich in nutrients and can improve crop yields by enhancing soil fertility [15].

Ideally, the use of biogas as a cooking fuel appears to provide more benefits compared to import-grade LPG in a country like India. Although there are differences in the fuel characteristics between LPG and biogas such as the average ignition temperature of biogas being (650–750)°C and that of LPG being (410-580)°C, a decentralized household biogas system (HBS) can potentially make users energy-independent [20].

Biogas serves as a clean-burning fuel alternative, and its adoption in rural areas enhances women's health, which is frequently compromised by the use of traditional cooking fuels. Women are frequently involved in collecting firewood for cooking fuel, which is a time-consuming and labour-intensive task. The adoption of biogas can lessen the workload for women and enhance energy availability for residents in rural regions [20-22]. Utilization of waste stream as biogas feedstock is expected to reduce uncontrolled atmospheric emissions and improve sanitation ensuring a cleaner environment. By the substitution of solid fuel in rural kitchens, biogas would contribute to mitigating indoor air pollution and thus reduce health risks. The use of biogas would also reduce pressure on forests due to fuel substitution [17-19]. Further, the biogas system also promises to contribute to a circular economy bringing the unused or sub-optimally used bio-resources such as cow dung, poultry litter, and crop residues into its value chain generating consumable energy. Therefore, the promotion of biogas as a cooking fuel alternative to LPG in rural areas of India has been strongly advocated as has been cited in several earlier instances [23,24]. The large-scale application of biogas has the potential to contribute to several SDGs, especially in regions like rural and semi-urban India. The objectives of the New National Biogas and Organic Manure Programme (NNBOMP) have been set on the three sustainable development goals 1,6 and 7 [16].

The following discussion delves into the historical progression of biogas development in India, aiming to identify and validate the existing gaps in research.

Biogas development in India

A Household Biogas System (HBS) has the capacity to meet the energy needs of a typical family in India of 4-5 members. It may be of different scales like small-scale biogas plants (1-25 m^3) and medium-size biogas plants (above 25 m^3).

There are various types of biogas digesters of different designs that are being used currently to meet the cooking fuel needs of people in India [25]. They are briefly introduced in **Appendix 1 A**.

Continuous efforts have been made for the development of biogas in India through various schemes and policy interventions. Significant highlights of the initiatives related to the development of biogas in India over the years are summarised in **Table 1.1** and discussed below. The promotion of household biogas plants by Khadi Village Industries Commission (KVIC) could be considered as the first formal and organizational program in India (1954) which was later taken over by the Department of Non-conventional Energy Sources (1960).

Integrated Rural Energy Programme (1980); National Project for Biogas Development (1981); Community, Institutional and Night Soil-based Biogas Plants Programme; Urjagram (decentralized village level energy program, 1989); National Biogas and Manure Management Program renamed from National Project on Biogas Development(2002-2003); Biogas Power Generation (off-grid) and Thermal Energy application programme (2017-18); New National Biogas and Organic Manure Program (2018) and GOBARDHAN (*Galvanizing Organic Bio-Agro Resources Dhan*, 2018) have been some notable biogas promotional programs in subsequent years in India. Again, SATAT (*Sustainable Alternative towards Affordable Transportation*, 2018) is a recent ambitious initiative of the Government of India to generate biogas through mega-scale plants to reduce dependency on fossil fuels used in the transport sector.

The journey of biogas development in India has been driven by several factors. The key factors that have been influencing the dynamism in the policy and programs of biogas in India are graphically presented in **Fig 1.3** and discussed below

The factors associated with the series of Government policies to promote biogas in India are shown in **Fig 1.3.**

Table 1.1: A brief historical overview of Government support for biogas development in India

Period	Sequence of events marking biogas development in	References
1960-78	• Launching of household biogas program in India initially by Khadi and Village Industries Commission (KVIC) and taken over by the Department of Non-conventional Energy Sources	[41]
1980-85	• Integrated Rural Energy Programme (IREP) launched with household biogas as a key component • Constitution of the National Biogas Development Board (NBDB) and the start of the National Project for Biogas Development (NPBD) • Community, Institutional & Night Soil based Biogas Plants Programme launched	[42]
1985-90	• Promotion of household biogas systems (decentralized)continued to meet the energy needs in rural areas • Household biogas remains a key component of *Urjagram*, a program for energy projects for rural areas	[43]
1992-97	• Reduction of subsidy support for household biogas system	[44]
1997-2007	• The NPBD was renamed as National Biogas and Manure Management Project (NBMMP) which was implemented at the national level at the household scale	[45]
2007-12	• Policy for the introduction of new materials and designs in place of traditional materials for household biogas plants	[46]

Period	Sequence of events marking biogas development in	References
2012-17	• The NBMMP scheme was continued for implementation in all the States and Union Territories • The Indian Standard for biogas (IS 16087: 2016) was adopted by the Bureau of Indian Standards for standard guidelines for biogas (biomethane) composition, quality parameters and for application in thermal, stationary engines, automotive applications, and supply through piped network	[47,48]
2017-24	• Focus on biogas extended with a new scheme "Biogas Power Generation (off-grid) and Thermal Energy Application Program (BPGTP)" which was implemented at the national level at an industrial scale. • NBMMP is updated to the New National Biogas and Organic Manure Program (NNBOMP) with special emphasis on organic fertilizer • Introduction of SATAT (Sustainable Alternative towards Affordable Transportation) at the national level at the industrial scale and GOBARDHAN (Galvanizing Organic Bio-Agro Resources Dhan) which was implemented at the national level at the community scale • The government also announced the PM-PRANAM (Programme for Restoration, Awareness, Nourishment, and Amelioration of Mother Earth) scheme to promote the use of organic fertilizers such as those obtained from biogas plants.	[49]

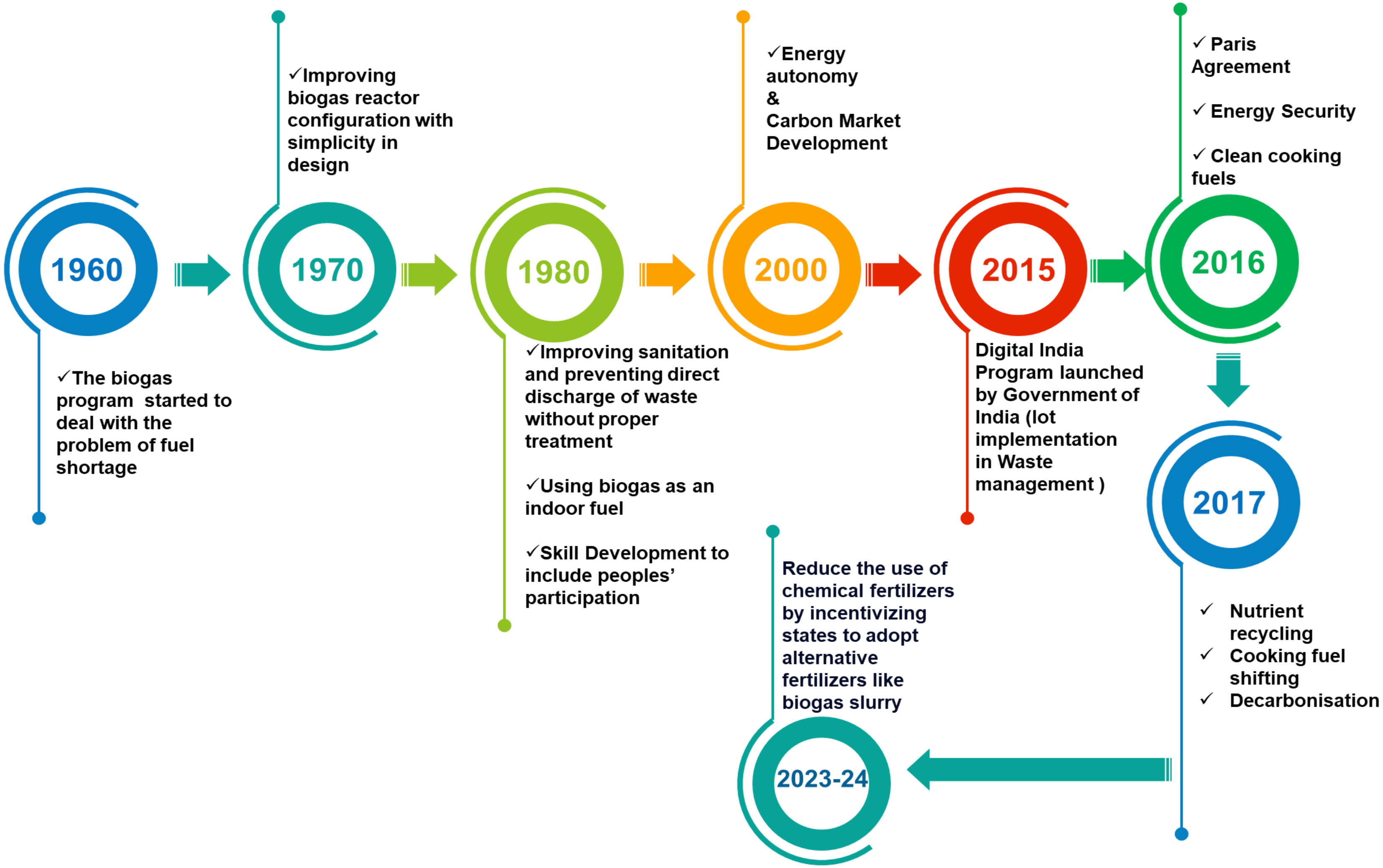

Fig 1.3 Key factors linked with the biogas promotional policies in India. [41-44]

1.3 Implementation and management of HBS in India

In India, the advancement of Household Biogas Systems (HBS) falls under the purview of the National Bioenergy Programme, which is managed by the Ministry of New & Renewable Energy's Biomass Division. (**Fig 1.4**). The implementing agencies are the State Programme Implementation Agency (PIA) and financial institutions. After the construction of the HBS is completed, the beneficiaries are provided with a Biogas User's Service-cum-Warranty Card. They are provided with free operation and maintenance services by the implementing agencies for five years. It is also the responsibility of the rural energy technicians (RETs) working for the implementing agencies to ensure the availability of spare parts for biogas stoves, burners, and other appliances as per the needs of the beneficiaries. There is a specified amount of time within which the complaints raised by the beneficiaries in the Biogas portal must be met by the RETs [54].

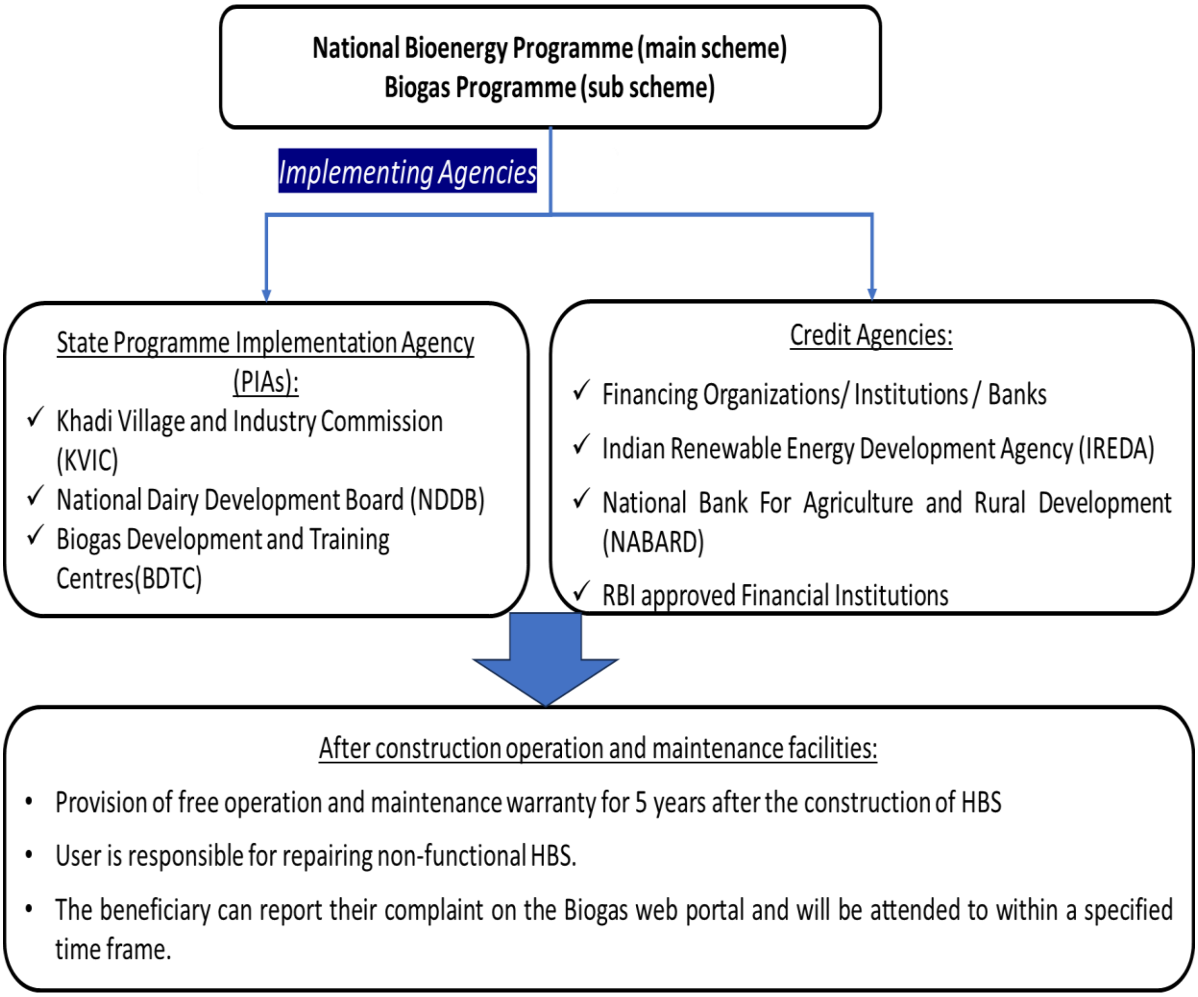

Fig 1.4: Prevailing biogas management system of HBS in India [54] *(Authors' perception)*

Owners of Household Biogas Systems (HBS) must keep their systems in good working order to prevent breakdowns, which allows them to appreciate the benefits over using fuelwood or LPG. Despite proven records of the usefulness of biogas as cooking fuel and subsequent claims about the soundness of its technical feasibility, the growth, as well as uses of biogas, has not remained as extensive as desired. The impact of the efforts of the Government to popularize the biogas system with policies and schemes is also not impressive. The underlying principle of the majority of the above-mentioned policies/schemes has been the welfare of rural people and to increase the share of renewable energy in the total energy mix of the country. Due to the inherent complexity of the process of biogas production which is chiefly influenced by the nature of feedstock and climate, the need for trained manpower has been realized since the beginning. Simultaneously, the efforts to improve the design of biogas plants and optimize the process parameters have also been continued resulting in improvement in conversion efficiency [26,27]. Diversification of feedstock has also been seen through the effort of research and development along with the utilization of digestate (by-product) [28-30]. Changes in the construction materials of the plants are also seen where the concrete and metal are substituted by FRP (Fiber-reinforced plastic) material [31,32].

However, despite the above efforts, accelerated growth of deployment of household biogas systems could not be seen in India. Key barriers against spontaneous growth of household biogas systems in India and particularly in Assam are identified such as competitive prices of alternative fuels, high capital cost, lack of knowledge about the utility of digestate and hence digestate is seen as a liability, diminishing interest due to seasonal variations of biogas production, uncertain supply of feedstock and unaffordable cost for management [33-36]. Human labour is involved in the collection of the biomass, and pre-treatment of the biomass including chopping and feeding the biomass to the biogas digester. These hardships are associated with biogas systems [37-40].

1.4 Global status of biogas development: a comparison with recent trends in India

Biogas is being produced all around the world using a variety of feedstocks (crop residue, animal manure, organic fraction of municipal solid waste, and wastewater sludge) as sources of heat and electricity, with about 90% of the global share by Europe, China, and the United States, whereas the contribution of India, Thailand, and Nepal is only about 10% [25]. The prominent use of biogas in Asian regions remains as a cooking fuel. An estimated

125 million people in China, Nepal, Vietnam, India, and Bangladesh use biogas as cooking fuel [50,51]. About 11% reduction in the volume of biogas produced for cooking was reported in Asia during the period from 2013 to 2022 (**Table 1.2 a**). There has been an increase in the volume of biogas produced for cooking in the regions of Africa, Central America and the Caribbean, and South America by 62%, 75%, and 9% respectively as seen from **Table 1.2 a**.

Incidentally, on studying the usage of biogas as a cooking fuel for prominent biogas-user countries in Asia, there has been a reduction in the volume of biogas production in countries like India, China, Myanmar, and Sri Lanka by about 35%, 8%, 47%, and 51% respectively during the same period of reference i.e., 2013 to 2022 (**Table 1.2 b**). Other countries like Bhutan, Cambodia, Indonesia, Nepal, Pakistan, Thailand, and Vietnam have reported an increase in the production of biogas. This requires a need for research to address the underlying issues that could be contributing to the reduction of the production of biogas for cooking in India and ultimately in Asia.

Table 1.2 a: Production of biogas for cooking (in terms of 10^6 cubic meters of biogas) among major regions around the world for the years 2013 and 2022 [52]

S.No.	Region	2013	2022
1	Africa	25.21	67.16
2	Asia	16719	14937.73
3	(Central America + Caribbean)	0.81	3.23
4	South America	0.18	0.19

Table 1.2 b: Production of biogas for cooking (in terms of 10^6 cubic meters of biogas) among prominent biogas user countries of Asia for the years 2013 and 2022 [52]

S. No.	Prominent biogas-user countries of Asia	2013	2022
1	Afghanistan	0	0.02
2	Bangladesh	62.86	65.73
3	Bhutan	0.46	4.56
4	Cambodia	11.53	16.07
5	China	14304.14	13103.93
6	India	1976.69	1290.44
7	Indonesia	9.79	16.63
8	Myanmar	0.15	0.08
9	Nepal	113.03	121.54
10	Pakistan	3.26	4.54
11	Sri Lanka	4.25	2.10
12	Thailand	0	0.25
13	Viet Nam	230.75	310.64

The reduction of biogas users in India (**Fig 1.5**) from 2013 to 2022 as well as a diminishing trend of fulfilling the target of installation of household biogas plants under schemes like NBMMP and NNBOMP (**Fig 1.6**) is a serious concern for India.

The status of installation of household biogas plants under Government schemes like NBMMP and NNBOMP varies among the regions due to regionally varying factors. Assam which is one of the states of India apparently with favourable ambiance for household biogas systems (HBS), fulfilled the set target of installation till the year 2016 (**Fig 1.6**). However, there have been increasing gaps between the Government's set target and actual installation (only 46% in 2017, 28% in 2018, and 11% in 2021 could be achieved against the set target) as shown in **Fig 1.6**. A similar increasing gap between the Government of India's set target and installation can also be observed in several other states (Andhra Pradesh, Gujarat, Jharkhand, Gujarat, Meghalaya, Mizoram, Sikkim, and Tripura) as seen in **Fig 1.6**. The support of the Government to promote biogas and grow it as a prominent option of renewable energy source in India remains consistent. Despite such efforts, the progress is not encouraging as seen from the trends presented. There is a need to carry out a study that shows the ground information regarding the declining growth of HBS.

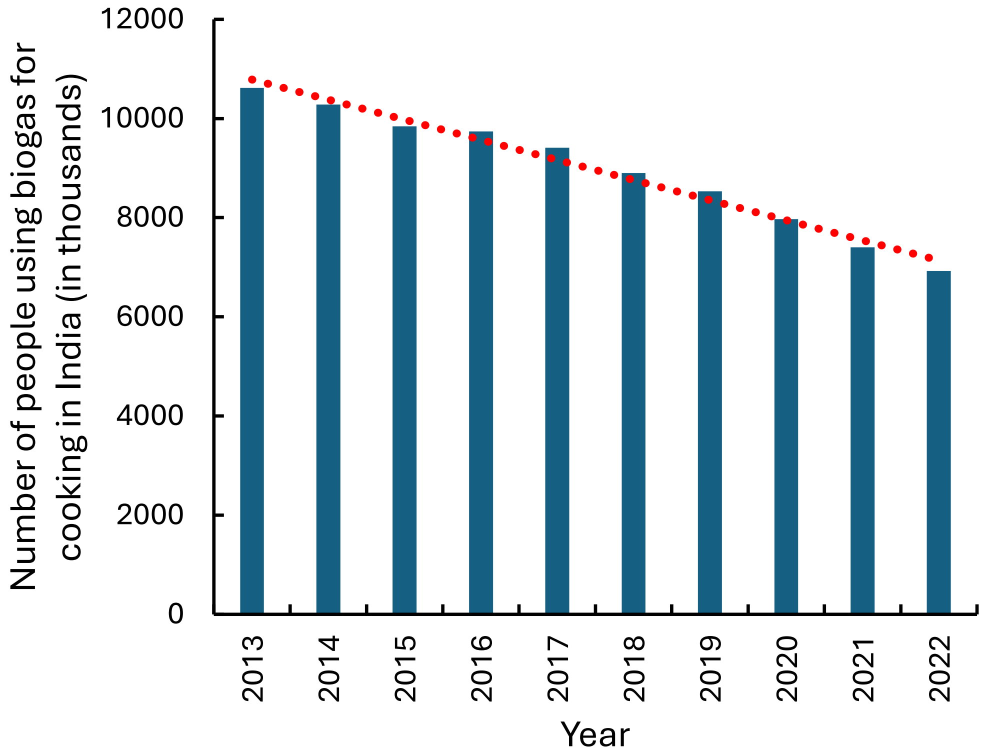

Fig 1.5 Trend of usage of biogas as a cooking fuel in India during 2013-2022 [52]

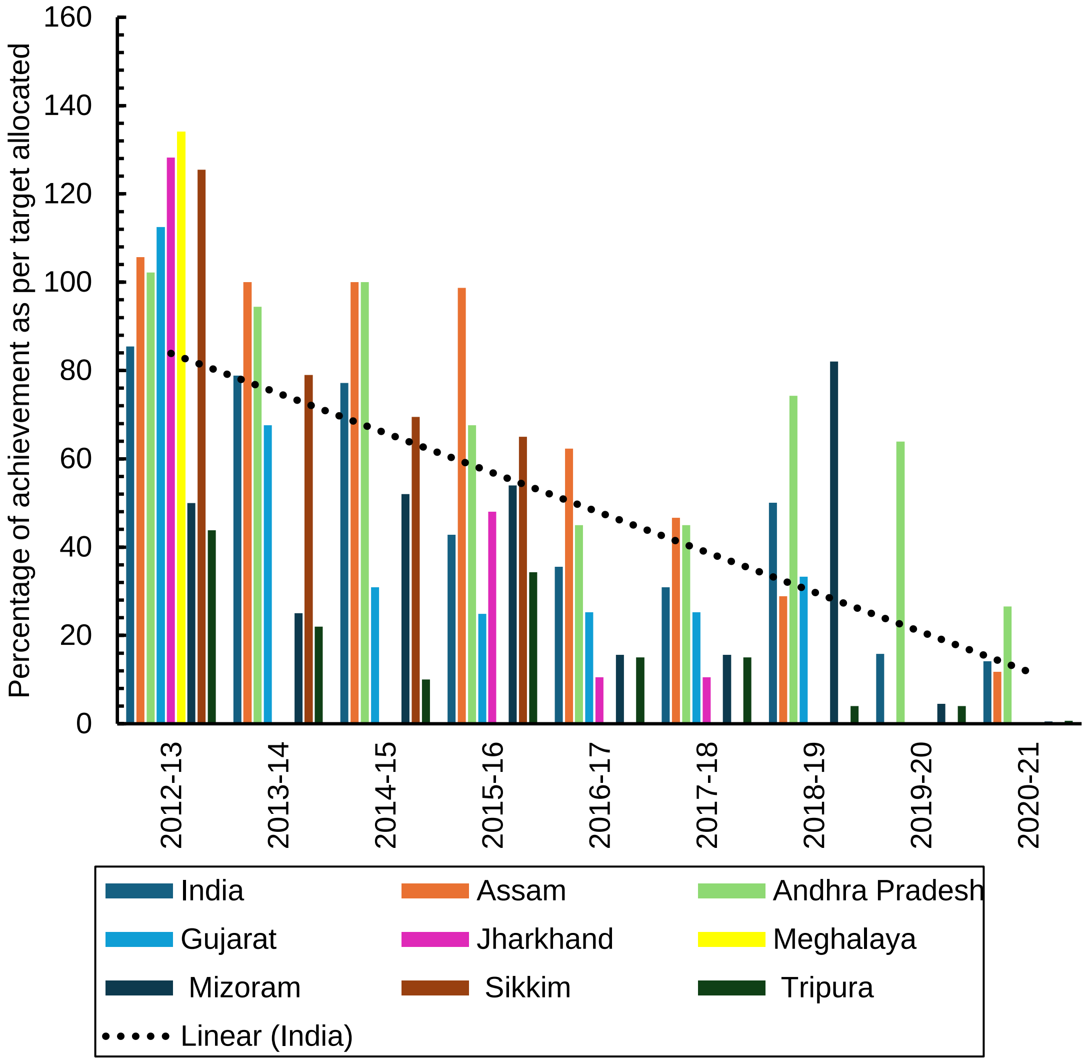

Fig 1.6: Percentage of biogas plants installed annually to the annual target set up by MNRE for some selected states and for India under the NNBMP and NNBOMP schemes [53]

The abundance of raw materials, soundness of technology, and economy of operations are three important areas to investigate to understand the reasons for the negative growth of biogas.

1.5 Management of biogas system

The management of a typical HBS depends broadly on the suitability of the feedstocks, knowledge of the parameters affecting the reaction kinetics, soundness of the technology and prospect of upgrading the technology.

Suitability of feedstocks

Cow dung and other surplus biomasses (animal droppings (cow dung, goat dropping, and poultry droppings) and crop residues (rice straw and maize stalk)) are predominantly used in typical Household Biogas Systems (HBS). One critical factor determining these raw materials' suitability is the carbon-to-nitrogen (C: N) ratio. This ratio influences the efficiency of biogas production, as an optimal C: N ratio ensures balanced microbial activity within the digester. **Table 1.3** provides the C: N ratios of commonly used feedstocks for biogas systems.

Table 1.3: C: N ratio of commonly used feedstocks for a biogas system [81]

S.No.	Feedstocks	C: N ratio
1	Rice husks	47:1
2	Sugar cane bagasse	53:1
3	Neem leaves	82:1
4	Grass silage	25:1
5	Rice straw	80:1
6	Potato	35:1
7	Wheat straw	50:1
8	Cow dung	16:1
9	Chicken manure	22:1
10	Pig excreta	15:1
11	Night soil	10:1
12	Sheep manure	25:1

Apart from the C: N ratio, other factors such as storage, handling, and pretreatment significantly influence the suitability and acceptability of the feedstock for biogas production. Proper storage of feedstock is crucial to maintain its quality and prevent the loss of volatile solids, which are essential for biogas production. Efficient handling practices are necessary to ensure that the feedstock is consistently available and can be easily processed. This involves using appropriate tools and equipment to reduce manual labor and potential contamination. Pretreatment processes, such as grinding, mixing, and moisture adjustment, enhance the digestibility of the feedstock. These processes help in breaking down complex organic materials, making them more accessible to the microorganisms in the digester.

Addressing these factors can improve the overall efficiency and sustainability of the HBS, making biogas a more viable alternative to other energy sources like LPG or firewood.

Soundness of the technology and prospect of upgradation

The provision of regular monitoring enabling timely management of the biogas system is essentially required for a hassle-free operation. The design of the prevailing biogas systems has limited provision of monitoring and diagnostics. There are some research works targeting the modernization of biogas systems with the provision of online data capturing and diagnostics [31, 65].

There are several schemes, policies, and technologies as detailed in **Table 1.4**. Technological up-gradation and inclusive growth have been focal development points in rural India as 69 % of the population still resides here and has a literacy rate of 76.3% [55]. There has been substantial technological growth and development in the villages in general and also continuous efforts of the Government of India through different policies, schemes, and provisions which are noticeable as described in **Table 1.4**.

Table 1.4: Technological developments due to the implementation of policies in rural India by the Government of India [76]

S. No.	Name of the policy	Key technological developments	References
1	National e-Governance Plan – Agriculture (NeGP-A)	Information and communication technology tools to provide necessary information to the farmers	[56]
2	MKisan portal developed by the Department of Agriculture & Farmers Welfare, Government of India	It helps farmers to connect with experts and scientists from different departments and agricultural universities and get information on a variety of topics like weather, seed varieties, harvesting, and sowing time.	[56]
3	Farmers' portal (www.farmer.gov.in)	Providing information to the farmers on a range of topics including seeds, fertilizer, pesticides, credit, good practices, dealer network, and information related to individual developmental blocks is also available in this portal.	[56]
4	Digital India Land Records Modernisation Programme (DILRMP)	The hand-drawn maps of the villages are being scanned and digitized, which ensures that the geometry of the boundaries is kept intact and tied to their coordinates (latitude and	[56]

S. No.	Name of the policy	Key technological developments	References
		longitude) to keep the appropriate real-world location.	
5	Television and smartphones	During 2003, at the all-India level, about 40% of farmer households accessed information on modern agricultural technology from televisions. Presently, 90% of rural youth have access to a smartphone.	[57,58]
6	Opening accounts in a financial institution	The percentage of the rural population who have an account at a financial institution or a money service provider in India has increased from 35.23% in 2011 to 53.14% in 2014 to 77.53% in 2021.	[59]
7	Bharat Interface for Money (BHIM) mobile application	Information and communication technology tools have been used to provide financial services to rural regions across the country. The Government of India has also launched the Bharat Interface for Money (BHIM) mobile application which provides a fast, secure, reliable medium to make digital payments through mobile devices using the UPI (Unified Payment Interface) platform throughout the country.	[60]
8	E-learning platforms	DIKSHA (Digital Infrastructure for Knowledge Sharing and Sharing) and SWAYAM (Study Webs of Active Learning for Young Aspiring Minds) have been launched by the Government of India to facilitate e-learning among the rural population free of cost.	[58]
9	eShram	The Ministry of Labour & Employment, Government of India has developed a portal called "eShram" for creating a National Database of Unorganized Workers (NDUW) which has details of name, occupation, address, educational qualification, and skill for helping workers search for	[61]

S. No.	Name of the policy	Key technological developments	References
		work and derive benefits in an organized manner.	
10	Ayushman Bharat Health Account (ABHA)	Ayushman Bharat Health Account (ABHA) is a unique number allocated to users that contains information related to the health of the users and can be shared and accepted by healthcare providers.	[62]
11	Common Service Centres (CSC)	Common Service Centres (CSC) established across India help carry out public utility services related to healthcare, finance, education, and agriculture services for citizens living in the rural parts of the country. There are 4,68,773 CSCs in rural India as of December 2023.	[63]

The application of the Internet of Things (IoT) in various sectors like food waste management, environmental monitoring, etc. has been demonstrated on a large scale as discussed below. However, such use of IoT in anaerobic digestion systems has been mostly limited to research and development only. It is expected that shortly, biogas systems will be also managed by IoT systems. This is because extensive applications are seen in various other areas as seen in **Fig. 1.7**.

For the management of food waste in industries, the Internet of Things (IoT) was used to replace paper-based systems which improved overall operation and maintenance and produced a reliable database with enhanced instantaneous visibility of the hotspots creating food waste [64]. IoT tools have also been used to monitor the environment using real-time data and creating a database for environmental monitoring [65]. Real-time data monitoring of environmental conditions inside a greenhouse (air temperature, air humidity, soil temperature, wind velocity rainfall, and light intensity) have been also carried out [66]. Real-time monitoring has been done to carry out the management of municipal waste [67], collection and transportation of commercial food waste [68], smart waste management system [69-71], waste collected and kept for decomposition in a landfill [72], management of restaurant food waste [73].

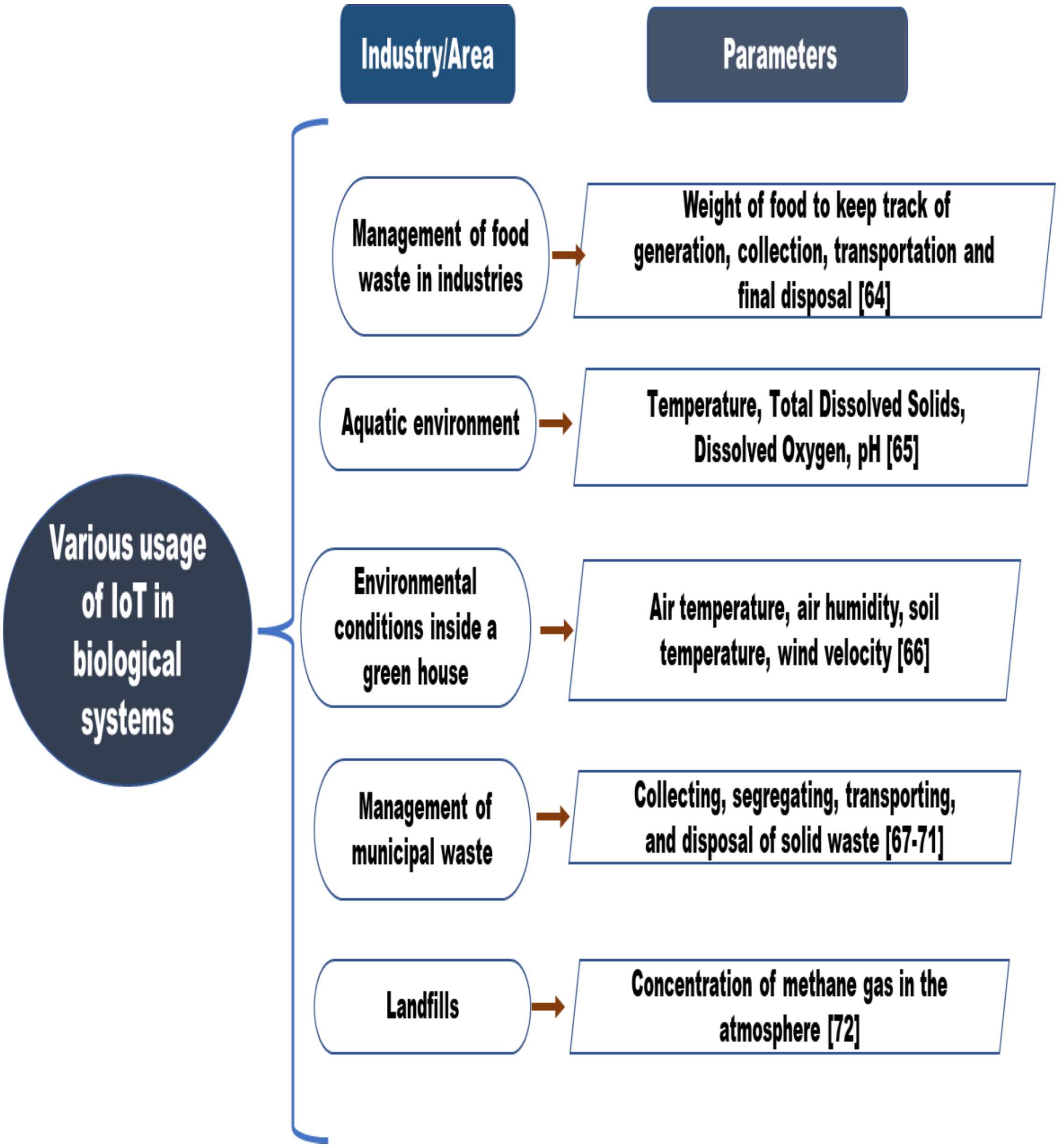

Fig 1.7: Current status of the application of IoT in different sectors

1.6 Potential of biogas as a rural entrepreneurship

Fuel wood and LPG are two options competing with biogas for cooking. In a typical rural household, fuel wood is either collected from its source or procured from the market. The size reduction and sun drying are required which involve costs. Thus, fuel wood is considered a commercial commodity. Similarly, LPG used as a cooking fuel also involves costs that vary depending upon the connection used. So, a comprehensive study is required considering the ground parameters to understand the comparisons between fuelwood, LPG, and biogas as a cooking fuel.

Biogas has a similarity to some other economic activities. In a typical rural Indian context, cooking fuel and organic fertilizer are commercial commodities, and a biogas system has the potential to generate both at the household level. Thus, a biogas system should be accepted as a viable business venture. However, in the existing venture of household biogas system, there is inadequate business sense despite the involvement of funds, operating expenses, manpower, and usable outputs (*viz*., renewable fuel and organic fertilizer). Such a lack of business sense could be a reason for the failure of the biogas system. On the other hand, there are various viable rural enterprises including dairy, poultry, piggery, and fishery contributing considerably to the Indian economy [74,75]. For example, millions of small and marginal milk producers, with two to five animals, contribute significantly to India's successful dairy sector [76]. Small-scale rural milk farmers generate 62% of the total milk production in India [77]. The poultry sector in India is broadly divided into two sub-sectors – the organized commercial sector and the unorganized backyard poultry sector. The unorganized sector plays a key role in supplementary income generation for rural livelihoods in India and there are around 30 million farmers engaged in backyard poultry as per the 19th Livestock Census [78]. Similarly, 70% of the pig population is reared under the traditional system by rural farmers using a low-input demand-driven production system. In comparison to other livestock species, pig rearing has a higher contribution to the income of farmers [79]. India is the second largest fish-producing nation in the world after China. Fish production is also dominated mostly by small-scale aquaculture farmers which contributes to their income and provides some employment for a small sector of society [80]. All the above ventures are input intensive where net income from the production system is the key motivating factor. HBS can be considered as an equivalent production system as it is also input (feedstock) intensive and products (gas and digestate) have commercial importance. Therefore, a comparative investigation of household biogas systems with other successful enterprises is required to understand the current discouraging status of its deployment.

1.7 Problem Statement

1.7.1 Preamble

Biogas is a clean source of energy that has the potential to replace commonly used solid fuels, reducing indoor air pollution and lowering associated health risks [17-19]. The usage of biogas also supports a circular economy in rural India by helping the utilization of underutilized bio-resources, such as cow dung, poultry litter, and crop residues to produce usable cooking fuel. Thus, promoting biogas as a cooking fuel substitute for LPG in rural India is strongly recommended as indicated by several studies [24].

1.7.2 Motivation

Despite the distinct benefits of biogas in the rural cooking energy sector, there has been no significant increase in the deployment of household biogas systems in India. Several factors (viz., favorable competitive prices of alternative fuels, the high capital cost of biogas installation, underutilization of digestate, uncertain supply of feedstock, labor-intensive for operation of biogas system) [33-36, 40] identified as barriers require verification and validation especially, for regions like Assam where growth of HBS installation has been negative. The support of the Government to promote biogas and grow it as a prominent option of renewable energy source in India remains consistent [52,53]. The above considerations are a motivation to take up this research aiming to find practical solutions for the promotion of HBS.

1.7.3 Research Gap

Ideally, the biogas system should serve as a self-sustaining business model to create income and employment for the users. Contrary to this expectation, retarded or negative growth of dissemination of HBS in India is noticed. This concern has to be investigated considering grassroots factors [52,53]. The potential role of technology-driven support services for hassle-free operation and maintenance of HBS in India also requires investigation. Under optimal conditions, the biogas reactor works properly and is expected to generate an adequate quantity of gas as per the needs of a rural household. However, digesters cease to operate favorably when operating conditions deviate from the desired levels, leaving minimum clues for the users to diagnose and address. Lack of support and services in the form of dedicated service centers to address the faults have led to diminishing interest in biogas in rural India. Therefore, providing technical support to the owners of HBS using information and communication-based tools is also a part of the current investigation [33,34,35]. Entrepreneurship cannot emerge endogenously in a rural region. There must be a catalyst that is provided by an intermediary that ignites the processes leading to the emergence of entrepreneurs. Whether the catalyst for the rural entrepreneurship model can be based on IoT-integrated HBS and if it can be a tool to improve the existing biogas model should also be investigated [41,42].

1.8 Objectives of the research

The following objectives have been set for the research work:

1. To undertake a contemporary investigation of the future of household biogas systems in rural areas.
2. To carry out a feasibility analysis of IoT for the management of household biogas systems.
3. To assess the potential of the biogas system as a viable rural entrepreneurship option and its prospect to decarbonize the rural Indian cooking sector.

1.9 Organization of the Thesis

The text of the thesis is organized as below:

Chapter 1: Introduction

This Chapter highlights the importance of clean cooking fuels and their current status in India, the context of biogas as a clean cooking fuel, the global status of biogas development and the status of such development in India, implementation, propagation, and management of HBS in India, possible scope for upgradation of biogas technology in India, and transforming the products of a typical biogas plant, such as cooking fuel and organic fertilizer, into revenue-generating ventures, motivation of the research and objectives of the research.

Chapter 2: Review of Literature

This chapter provides a review of the literature on the relevant aspects of the current research work. The Chapter provides an overview of the factors concerning the operational hassles of the biogas system (feedstock, biological, climatic, and others). Mathematical and

Simulation models for anaerobic digestion have also been reviewed. Prevailing practices of the management of HBS have also been reviewed, with the inclusion of the management of HBS by utilizing the Internet of Things (IoT) along with its contribution to sustainability.

Chapter 3: Household Biogas Systems in rural areas: a contemporary investigation

In this Chapter, the investigation of the slow or negative growth in the adoption of household biogas systems (HBS) in India has been made using ground-level data collected from a cross-section of people living in rural areas who are either existing/past users or prospective users of biogas as a clean cooking fuel. Various aspects have been considered for the field study addressing concerns for lack of interest in biogas as a cooking fuel, the current status of HBS installation, the need for HBS as a sustainable source of cooking fuel (from the perspective of operational issues, technological intervention, and slurry management). Analysis based on the affordability and reliability of biogas as clean cooking fuel for people in rural areas against the use of existing cooking fuels like LPG and fuel wood is discussed in this Chapter. The prospect of technology-integrated management support to revive the interest in household biogas systems in rural India is also introduced in this Chapter.

Chapter 4: IoT for management of household biogas system: a feasibility analysis

In this Chapter, the experience of the application of an IoT system for accessing the data of a biogas system is presented. The shortcomings of this IoT-based management system have also been discussed briefly in this Chapter along with the economics of the developed system.

Chapter 5: Investigation of the scope of the biogas system as a viable rural entrepreneurship and its prospect to decarbonize the rural Indian cooking sector

In this Chapter, the prospect of HBS as a viable rural business model has been investigated by comparing it to four household-based rural enterprises (piggery, fishery, dairy, and poultry). A comparative economic analysis of the enterprises has been carried out and the ranking of the profitability of the enterprises is done by calculating the Net Present Value (NPV) of the enterprises. Analysis of the relative contributions of five selected enterprises on Sustainable Development Goals (SDGs) has been done. The decarbonization potential of the surveyed villages has also been demonstrated by factoring in the average consumption of LPG among the villagers and checking the potential of substitution of this cooking fuel with HBS.

Chapter 6: Summary and Conclusions

This Chapter enlists a general summary of overall findings and conclusions including new directions which have emerged from this work to address in future work. The Thesis ends with an Appendix and a List of Publications.

References:

1. Reddy, A.K., Annecke, W., Blok, K., Bloom, D., Boardman, B., Eberhard, A. and Ramakrishna, J., 2000. Energy and social issues. *World energy assessment*, pp.39-60.
2. International Energy Agency. *ENERGY POVERTY: How to make modern energy access universal?* Retrieved on 26 February 2024 from https://iea.blob.core.windows.net/assets/fdbdd604-de2c-4977-8a3f-20f93e68e738/HowtoMakeModernEnergyAccessUniversal.pdf.
3. United Nations, Department of Economic and Social Affairs, Sustainable Development. *Ensure access to affordable, reliable, sustainable and modern energy for all.* Retrieved on 16 Feb 2023 from https://sdgs.un.org/goals/goal7.
4. World Health Organisation. *Defining clean fuels and technologies.* Retrieved on 23 February 2024 from https://www.who.int/tools/clean-household-energy-solutions-toolkit/module-7-defining-clean.
5. World Health Organisation. *The Global Health Observatory. Explore a world of health data.* Retrieved on 26 Feb 2024 from https://www.who.int/data/gho/data/themes/air-pollution/household-air-pollution.
6. The World Bank. *Access to clean fuels and technologies for cooking (% of population) – India.* Retrieved on 16 Feb 2024 from https://data.worldbank.org/indicator/EG.CFT.ACCS.ZS?locations=IN.
7. Ministry of Petroleum and Natural Gas, Government of India. *Pradhan Mantri Ujjwala Yojana 2.0.* Retrieved on 27 May 2021 from https://www.pmuy.gov.in/.

8. Ministry of Petroleum & Natural Gas, Government of India. *Report of the Expert Group on A Viable and Sustainable System of Pricing of Petroleum Products, New Delhi*. Retrieved on 27 June 2021 from http://www.indiaenvironmentportal.org.in/files/reportprice.pdf.
9. Sharma, A., Parikh, J. and Singh, C. Transition to LPG for cooking: A case study from two states of India. Energy for Sustainable Development, 51:63-72, 2019.
10. Anand, R., Coady, M.D., Mohommad, M.A., Thakoor, M.V.V. and Walsh, M.J.P. *The fiscal and welfare impacts of reforming fuel subsidies in India*. International Monetary Fund, 2013.
11. Ministry of Petroleum and Natural Gas, Government of India. *Price and subsidies in LPG.* Retrieved on 20 March 2024 from https://sansad.in/getFile/annex/262/AU144.pdf?source=pqars
12. Chen, Y., Cheng, J.J. and Creamer, K.S., 2008. Inhibition of anaerobic digestion process: a review. *Bioresource Technology*, *99*(10), pp.4044-4064.
13. Madsen, M., Holm-Nielsen, J.B. and Esbensen, K.H., 2011. Monitoring of anaerobic digestion processes: A review perspective. *Renewable and sustainable energy reviews*, *15*(6), pp.3141-3155.
14. Gavala, H.N., Angelidaki, I. and Ahring, B.K., 2003. Kinetics and modeling of anaerobic digestion process. *Biomethanation I*, pp.57-93.
15. Obileke, K., Nwokolo, N., Makaka, G., Mukumba, P. and Onyeaka, H., 2021. Anaerobic digestion: Technology for biogas production as a source of renewable energy—A review. *Energy & Environment*, *32*(2), pp.191-225.
16. Ministry of New and Renewable Energy, Biogas Technology development Division. *Request for Expression of Interest (EOI) for Third Party Evaluation Study of New National Biogas and Organic Manure Programme (NNBOMP), Implemented during the 3-year period from 2017-18 to 2019-20*. Retrieved on 7 July 2021 from https://avantiscdnprodstorage.blob.core.windows.net/legalupdatedocs/7419/MNRE.pdf.
17. Singh, B., Szamosi, Z., Siménfalvi, Z. and Rosas-Casals, M. Decentralized biomass for biogas production. Evaluation and potential assessment in Punjab (India). *Energy Reports*, 6:1702-1714, 2020.
18. Mottaleb, K.A. Biogas adoption and elucidating its impacts in India: Implications for policy. *Biomass and Bioenergy*, 123:166-174, 2019.

19. Destek, M.A., Sarkodie, S.A., and Asamoah, E.F. Does biomass energy drive environmental sustainability? An SDG perspective for top five biomass consuming countries. *Biomass and Bioenergy*, 149:106076, 2021.
20. Adhikari, R., Shrestha, A., Ghimire, S., Shrestha, K., Ghimire, R., & Ghimire, B. Impact of biogas on health and well-being of women in Nepal: A case study of Chitwan district. *Renewable and Sustainable Energy Reviews*, 41:1177-1183, 2015.
21. Dutta, S., & Ghosh, S. Impact of biogas technology on women's health and well-being: A case study from rural India. *Energy for Sustainable Development*, 20:10-17, 2016.
22. Njuguna, M., Muchiri, M., & Kimani, M. Impact of biogas on women's health and well-being in Kenya. *Journal of Sustainable Development*, 7(1):117-127, 2014.
23. Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S.S., Vijay, V., Kumar, V., Vijay, V.K. and Pant, D. Valorization of agricultural waste for biogas based circular economy in India: A research outlook. *Bioresource Technology*, 304:123036, 2020.
24. de Jesus, R.H.G., Barros, M.V., Salvador, R., de Souza, J.T., Piekarski, C.M. and de Francisco, A.C. Forming clusters based on strategic partnerships and circular economy for biogas production: A GIS analysis for optimal location. *Biomass and Bioenergy*, 150:106097, 2021.
25. Ministry of New and Renewable Energy (Biogas Divison). *Allocation of physical targets for setting up small biogas plants under Biogas Programme during FY 2023-24-reg*. Retrieved on 22 March 2024 from https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2023/06/2023062748-1.pdf, 2023.
26. Kothari, R., Vathistha, A., Singh, H.M., Pathak, V.V., Tyagi, V.V., Yadav, B.C., Ashokkumar, V. and Singh, D.P. Assessment of Indian bioenergy policy for sustainable environment and its impact for rural India: Strategic implementation and challenges. *Environmental Technology & Innovation*, 101078, 2020.
27. Divya, D., Gopinath, L.R. and Christy, P.M. A review on current aspects and diverse prospects for enhancing biogas production in sustainable means. *Renewable and sustainable energy reviews*, 42:690-699, 2015.

28. Vijay, V., Subbarao, P.M. and Chandra, R. Study on interchangeability of seed based feedstocks for biogas production in multi-feeding mode. *Cleaner Engineering and Technology*, 1:100011, 2020.
29. Ajay, C.M., Mohan, S. and Dinesha, P. Decentralized energy from portable biogas digesters using domestic kitchen waste: A review. *Waste Management*, 125:10-26, 2021.
30. Mishra, A., Kumar, M., Bolan, N.S., Kapley, A., Kumar, R. and Singh, L. Multidimensional approaches of biogas production and up-gradation: Opportunities and challenges. *Bioresource Technology*, 338:125514, 2021.
31. Baredar, P., Khare, V. and Nema, S. *Design and optimization of biogas energy systems*. Academic Press, 2020.
32. Cheng, S., Li, Z., Mang, H.P., Huba, E.M., Gao, R. and Wang, X. Development and application of prefabricated biogas digesters in developing countries. *Renewable and sustainable energy reviews*, 34:387-400, 2014.
33. Raha, D., Mahanta, P. and Clarke, M.L. The implementation of decentralised biogas plants in Assam, NE India: The impact and effectiveness of the National Biogas and Manure Management Programme. *Energy Policy*, 68:80-91, 2014.
34. Mittal, S., Ahlgren, E.O. and Shukla, P.R. Barriers to biogas dissemination in India: A review. *Energy Policy*, 112:361-370, 2018.
35. Malakar, Y. Studying household decision-making context and cooking fuel transition in rural India. *Energy for Sustainable Development*, 43:68-74, 2018.
36. Gould, C.F., Urpelainen, J. and Sais, J.H. The role of education and attitudes in cooking fuel choice: Evidence from two states in India. *Energy for Sustainable Development*, 54:36-50, 2020.
37. Feiz, R., Metson, G.S., Wretman, J. and Ammenberg, J. Key factors for site-selection of biogas plants in Sweden. *Journal of Cleaner Production*, 354:131671, 2022.
38. Ma, J., Scott, N.R., DeGloria, S.D. and Lembo, A.J. Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass and Bioenergy*, 28(6):591-600, 2005.
39. Silva, S., Alçada-Almeida, L. and Dias, L.C. Biogas plants site selection integrating Multicriteria Decision Aid methods and GIS techniques: A case study in a Portuguese region. *Biomass and Bioenergy*, 71:58-68, 2014.

40. Soha, T., Papp, L., Csontos, C. and Munkacsy, B. The importance of high crop residue demand on biogas plant site selection, scaling and feedstock allocation–A regional scale concept in a Hungarian study area. *Renewable and Sustainable Energy Reviews*, 141:110822, 2021.
41. Mital, K.M. *Biogas systems: policies, progress and prospects*. Taylor & Francis, 1997.
42. Kharbanda, V.P. and Qureshi, M.A. Biogas Development in India and the PRC. *The Energy Journal*, 6(3), 1985.
43. *Seventh Five-Year Plans (1985-90) for Rural Development*. Retrieved on 20 March 2020 from http://www.yourarticlelibrary.com/agriculture/seventh-five-year-plans-1985-90-for-rural-development/44517.
44. Bhattacharya, S.C. and Jana, C. Renewable energy in India: historical developments and prospects. *Energy*, 34(8):981-991, 2009.
45. Ministry of New and Renewable Energy, Government of India. *Annual Report, 2015-16, Renewable Energy for Rural Applications, International Solar Alliance*. Retrieved on 7 July 2021 from http://164.100.94.214/file-manager/annual-report/2015-2016/EN/Chapter%205/chapter_5.htm#:~:text=5.6%20The%20programme%20is%20being,during%20the%20year%202002%2D03.
46. Cheng, S., Li, Z., Mang, H.P., Huba, E.M., Gao, R. and Wang, X. Development and application of prefabricated biogas digesters in developing countries. *Renewable and sustainable energy reviews*, 34: 387-400, 2014.
47. Renewable Energy Sector in India , Report No. 34 of 2015 *,Chapter - VIII, National Biogas and Manure Management Programme* Retrieved on 20 March 2020 from https://cag.gov.in/uploads/download_audit_report/2015/Union_Civil_Performance_Renewable_Energy_Report_34_2015_chap_8.pdf.
48. Bureau of Indian Standards, Government of India. *Indian Standard Biogas (Biomethane)-Specification, IS 16087: 2016*. Retrieved on 20 March 2020 from https://law.resource.org/pub/in/bis/S11/is.16087.2013.pdf, 2013.
49. Ministry of New and Renewable Energy, Government of India. *Biogas Schemes, 2021.* Retrieved on 20 March 2021 from https://mnre.gov.in/bio-energy/schemes.
50. World Energy Outlook, International Energy Agency. *Outlook for biogas and biomethane: Prospects for organic growth.* Retrieved on 20 March 2021 from

https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth

51. REN21 Renewables Now. *Renewables 2021 Global Status Report*. Retrieved on 20 March 2021 from https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf.
52. International Renewable Energy Agency. *Off-grid renewable energy statistics 2023.* Retrieved on 25 February 2024 from https://www.irena.org/Publications/2023/Dec/Off-grid-Renewable-Energy-Statistics-2023, 2023.
53. Ministry of New and Renewable Energy, Government of India. *Annual reports*. Retrieved on 25 February 2024 from https://mnre.gov.in/annual-report/.
54. Ministry of New and Renewable Energy, Biogas Divison, Government of India. *Administrative approval for implementation of Biogas Programme under the Umbrella scheme of National Bio Energy Programme for FY 2021-22 to 2025-26-(Phase-I) regarding.* Retrieved on 25 February 2024 from https://biogas.mnre.gov.in/public/downloadables/MNRE%20Biogas%20Prog%202021%20to%202026%20%20dated%2002_11_2022.pdf.
55. Ministry of Statistics and Programme Implementation, National Sample Survey Office, Government of India. *Periodic Labour Force Survey (PLFS). Annual Report 2021-22*. Retrieved on 25 February 2023 from https://www.mospi.gov.in/sites/default/files/publication_reports/AnnualReportPLFS2021-22F1.pdf.
56. Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. ANNUAL REPORT, 2022-23. Retrieved on 25 February, 2023 from https://agriwelfare.gov.in/en/Annual.
57. National Sample Survey Organisation Ministry of Statistics and Programme Implementation, Government of India. *Situation Assessment Survey of Farmers, Access to Modern Technology for Farming, NSS 59th Round (January–December 2003).* Retrieved on 25 February, 2024 from https://mospi.gov.in/sites/default/files/publication_reports/Report_587m_0.pdf, 2005.
58. PRATHAM, *Annual Status of Educational Report (Rural), Beyond Basics, 2023*. Retrieved on 25 February, 2024 from https://asercentre.org/.

59. Global Findex Database, World Bank. Retrieved on 16 Feb, 2023 from https://data.worldbank.org/indicator/FX.OWN.TOTL.ZS?name_desc=false&locations=IN
60. Cashless India, Government of India. *BHARAT INTERFACE FOR MONEY (BHIM).* Retrieved on 16 Feb 2023 from http://cashlessindia.gov.in/bhim.html.
61. Ministry of Labor and Employment, Government of India. *About eShram Portal.*Retrieved on 17 Feb, 2024 from https://eshram.gov.in/e-shram-portal.
62. National Health Authority, Government of India. *ABHA - Ayushman Bharat Health Account - Key to your digital healthcare journey.* Retrieved on 17 Feb, 2024 from https://abha.abdm.gov.in/abha/v3/.
63. Common Services Centre, Ministry of Electronics and Information Technology, Government of India. *Common Services Centre (CSC).*Retrieved on 16 Feb, 2023 from https://csc.gov.in/#:~:text=Common%20Services%20Centres%20are%20the,effort%20in%20visiting%20government%20offices.
64. Jagtap, S. and Rahimifard, S. The digitisation of food manufacturing to reduce waste–Case study of a ready meal factory. *Waste Management*, 87:387-397, 2019.
65. Okafor, N.U. and Delaney, D. Considerations for system design in IoT-based autonomous ecological sensing. *Procedia Computer Science*, 155:258-267, 2019.
66. Wang, J., Chen, M., Zhou, J. and Li, P. Data communication mechanism for greenhouse environment monitoring and control: An agent-based IoT system. *Information Processing in Agriculture*, 7(3):444-455, 2020.
67. Fatimah, Y.A., Govindan, K., Murniningsih, R. and Setiawan, A. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *Journal of Cleaner Production*, 269:122263, 2020.
68. Wen, Z., Wang, Y. and De Clercq, D. What is the true value of food waste? A case study of technology integration in urban food waste treatment in Suzhou City, China. *Journal of Cleaner Production,* 118:88-96, 2016.
69. Van Fan, Y., Lee, C.T., Lim, J.S., Klemeš, J.J. and Le, P.T.K. Cross-disciplinary approaches towards smart, resilient and sustainable circular economy. *Journal of cleaner production*, 232:1482-1491, 2019.

70. Velvizhi, G., Shanthakumar, S., Das, B., Pugazhendhi, A., Priya, T.S., Ashok, B., Nanthagopal, K., Vignesh, R. and Karthick, C. Biodegradable and non-biodegradable fraction of municipal solid waste for multifaceted applications through a closed loop integrated refinery platform: Paving a path towards circular economy. *Science of the Total Environment*, 731:138049, 2020.
71. Gopikumar, S., Raja, S., Robinson, Y.H., Shanmuganathan, V., Chang, H. and Rho, S. A method of landfill leachate management using internet of things for sustainable smart city development. *Sustainable Cities and Society*, 66:102521, 2021.
72. Venkatesan, G., Mithuna, R. and Gandhimathi, S. IOT-based monitoring of lab scale constitutive landfill model of food waste. *Materials Today: Proceedings*, 33:2729-2734, 2020.
73. Wen, Z., Hu, S., De Clercq, D., Beck, M.B., Zhang, H., Zhang, H., Fei, F. and Liu, J. Design, implementation, and evaluation of an Internet of Things (IoT) network system for restaurant food waste management. *Waste management*, 73:26-38, 2018.
74. Department of Animal Husbandry and Dairying Ministry of Fisheries, Animal Husbandry and Dairying Government of India. *Annual Report, 2021-2022*. Retrieved on 23 November, 2022 from https://dahd.nic.in/sites/default/filess/AnnualEnglish.pdf.
75. Chand, R. Doubling Farmers' Income: Rationale, Strategy, Prospects and Action Plan, *Indian Journal of Agricultural Economics,* 2017.
76. Food and Agriculture Organization of The United Nations Regional Office for Asia and the Pacific. *Smallholder dairy development: Lessons learned in Asia.* Retrieved on 24 Nov, 2021 from https://www.fao.org/3/i0588e/I0588E00.htm, 2009.
77. Sinha, O.P., 2007. *Agro-industries characterization and appraisal: dairy in India.* Retrieved on 13 Nov, 2021 from https://www.fao.org/3/ap299e/ap299e.pdf.
78. Department of Animal Husbandry, Dairying & Fisheries Ministry of Agriculture & Farmers Welfare Government of India. *National Action Plan for Egg & Poultry-2022 For Doubling Farmers' Income by 2022*. Retrieved on 14 Nov, 2023 from

https://www.dahd.nic.in/sites/default/filess/Seeking%20Comments%20on%20National%20Action%20Plan-%20Poultry-%202022%20by%2012-12-2017.pdf.

79. Department of Animal Husbandry and Dairying. *Overview of the Piggery Sector.* Retrieved on 12 Nov, 2021 from https://dahd.nic.in/sites/default/filess/NAP%20on%20Pig%20.pdf.

80. Department of Fisheries, Ministry of Fisheries, Animal Husbandry and Dairying, Government of India. *Annual Report 2021-22*. Retrieved on 12 Nov, 2021 from https://dof.gov.in/sites/default/files/2022-04/Annual_Report_2021_22_English.pdf.

81. Lallement, A., Peyrelasse, C., Lagnet, C., Barakat, A., Schraauwers, B., Maunas, S. and Monlau, F. A Detailed Database of the Chemical Properties and Methane Potential of Biomasses Covering a Large Range of Common Agricultural Biogas Plant Feedstocks. *Waste*, 1(1):195-227, 2023.