CHAPTER 2

REVIEW OF LITERATURE

Chapter 2

Review of Literature

2.1 Introduction

In this Chapter, the review of literature on several aspects *viz.*, (i) assessing multifaceted benefits potential of the biogas system, (ii) status of research on biogas production (iii) challenges in the management of a household biogas system (HBS), (iv) status on biomass-based rural entrepreneurship and (v) technology advancement for management of household biogas system (HBS) is presented.

Research Methodology

To analyze the recent trends in biogas installation and to identify the barriers against its dissemination, a bibliometric analysis was conducted using publications indexed in the 'Web of Science' database. The following keywords were employed for the search: biogas, clean cooking fuel, alternative feedstocks, comparative cost analysis, rural India, sustainable development goals, business model opportunity, household biogas system, net present value, rural enterprises, annual decarbonization potential, affordable and clean energy. Publications from the past four years (2019- 2023) along with earlier works from before 2019 were considered to gain insight into both recent trends and long-standing issues. Additionally, annual reports from various Indian Government departments (dairy, piggery, fishery, and poultry) from 2021-2024 were reviewed wherever available. Information was also collected from NITI Aayog (the Government of India's apex public policy think tank) publications to align the study with national policy directions.

2.2 Assessing multifaceted benefits of the biogas system

The practice of production of a gaseous mixture that acts as a source of cooking fuel (biogas with methane as a major component), through anaerobic digestion of organic materials has been well-known since ancient times [1-3]. A typical HBS uses organic materials of a range of feedstock viz., animal manure, agricultural wastes, sludge, etc., to produce clean cooking fuel and digested slurry (organic fertilizer) through small-size reactors [4-6], especially for the rural communities in developing regions like India [7-10]. There has been several research demonstrating the multi-faceted benefits of the biogas system which includes using biogas as a primary cooking fuel. This is elaborated below and demonstrated in **Fig 2.1**.

Greenhouse gas reduction

As biogas is renewable and sustainable, it leaves a much smaller environmental footprint than traditional cooking fuels. Anaerobic digestion of organic matter recycles waste materials and keeps them from decomposing in landfills, which would otherwise result in the release of methane. Local production of biogas can eliminate the need for transportation and the resulting carbon emissions. Additionally, biogas also promotes energy independence, especially in remote and off-grid populations. Biogas is a fuel that is good for the environment because it produces a lot less greenhouse gas than fossil fuels. The carbon dioxide that is released during the combustion of biogas for cooking is mostly absorbed by the plants. On the other hand, burning fossil fuels release CO_2 that has been stored underground, raising the amount of CO_2 in the atmosphere [11].

Waste management

By turning waste into valuable resources, biogas technology for waste management provides a comprehensive solution to the problems associated with the disposal of organic waste. By keeping large volumes of waste out of landfills, this procedure lowers the emission of methane which is a powerful greenhouse gas. Methane is produced during the anaerobic digestion process and can be utilized to produce heat or power or refined into biomethane for fuel. Furthermore, the digestate that is produced can be used as an organic fertilizer that is rich in nutrients, improving soil health and lowering the need for chemical fertilizers. Biogas technology is an environmentally friendly, cyclical method of managing waste [12-14].

Economic and employment opportunities

In rural regions, the generation of biogas has the potential to greatly enhance economic development and sustainability by generating a variety of green jobs. Building biogas facilities calls for a variety of highly qualified workers, including general laborers, masons, plumbers, electricians, and engineers who can customize the plants to meet the needs of the local population. Biogas plants also require maintenance and there are professionals who make sure the equipment is operating safely and effectively, and plant operators for overseeing daily operations. Furthermore, quality control experts are essential in ensuring that biogas production satisfies regulations and that byproducts such as digestate are safe for application as fertilizers. Employment possibilities are also created by the collection and transportation of organic waste, with positions for workers to carry garbage to the biogas facilities, drivers and logistical staff collecting and sorting waste from farms, food processing facilities, restaurants, and homes. Moreover, professionals are needed to transform the leftover sludge into organic fertilizers, opening up yet another career opportunity. All things considered, the biogas sector not only promotes environmental sustainability but also creates local employment creation and brings economic stability in rural areas [15].

Clean Development Mechanism under the Kyoto Protocol

The Kyoto Protocol enables developed nations that accept carbon restrictions to fulfill their emissions targets in part by funding emission-reducing projects at locations where the work will be less expensive. The Kyoto Agreement promotes the establishment of a carbon emission trading mechanism. Every owner of a biogas plant should obtain a carbon credit from the trading system, and each biogas production unit should sell emission credits under the clean development mechanism (CDM), which industrial producers should pay for [11].

Biogas digestate can be used as a fertilizer

A sustainable way to preserve soil fertility and increase agricultural output is to use bio-slurry in place of chemical fertilizers. Bio-slurry is abundant in vital plant nutrients including potassium, phosphate, and nitrogen which are vital for crop growth. When used properly, bio-slurry improves soil health by offering a balanced supply of nutrients, which encourages strong plant growth and raises agricultural yields. In addition to providing nutrients, this organic fertilizer enhances soil microbial activity, water retention, and structure, all of which contribute to the development of healthier soil ecosystems. Optimizing the nutritional content of slurry is a critical stage in the separation process. By separating the slurry's liquid and solid components, the nutrient content can be adjusted to suit the unique requirements of various crops. While the liquid fraction can be sprayed directly on the plants, the solid fraction, which is rich in organic matter and nutrients, can be put directly into the soil. The liquid fraction is also more easily absorbed by plants. By ensuring that crops receive the precise amount of nutrients needed for optimum growth, this focused application lowers the possibility of overfertilization and nutrient runoff, both of which can be harmful to the environment. Furthermore, because bio-slurry recycles waste and lessens reliance on synthetic fertilizers, its usage as fertilizer is consistent with sustainable agriculture methods. Despite their effectiveness, chemical fertilizers can cause pollution, soil degradation, and an increase in greenhouse gas emissions with time. On the other hand, by converting organic waste into a useful agricultural input and therefore closing the nutrient loop and reducing environmental impact, bio-slurry supports a circular economy [16-19].

Net Zero emission

The IEA Net Zero Emissions by 2050 Scenario states that by 2030, biogas production should triple. Biogas technology may be used as a source of low-emission electricity generation, which will be more and more significant as the deployment of variable renewables like wind and solar develops apart from using it as a potential energy source for clean cooking [20].

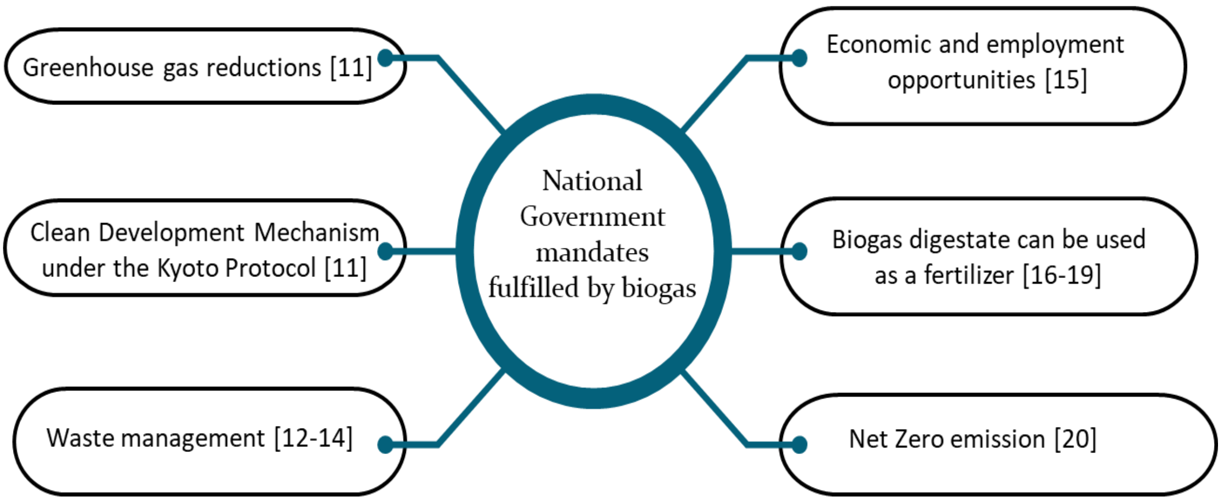

Fig 2.1: Multifaceted benefits of biogas programmes

(Source: Graphical representation based on Author's perception)

2.3 Status of research on biogas production

2.3.1 Factors influencing the production of biogas

The issues concerning the operational hassles of the biogas system have been extensively reported in the literature, high points of a review are presented in **Table 2.1**. The notable findings concerning feedstock, biological factors, and climate vis-à-vis ambiance are analyzed in detail below.

Feedstock-related factors

Extreme pH variations during the starting of the biogas plant and the digesting process can cause the whole system to fail because the pH stability of the decomposing material influences the stability of the process. The feedstock composition must be carefully chosen to reduce the necessity for artificial pH regulation. However, it can be difficult for an operator to plan because feedstock availability varies throughout the year [21-23]. The organic loading rate (OLR) is a key parameter in anaerobic digestion that can significantly affect biogas production and the overall process stability. Higher OLRs can improve the processing efficiency of anaerobic digestion, but they might also inhibit biogas production. Changes in the OLR impact the structure of the microbial community of the anaerobic digester. When exposed to a new OLR with the same feedstock, it takes time for the digester to return to its initial state of biogas quantity and quality. Overall, the OLR fluctuations produce a decrease in biogas and methane production [24-26]. Lignin is a complex aromatic polymer integral to the cell wall of lignocellulosic biomass. It is prohibitive to biogas production due to its intricate structure and resistance to degradation. The degradation of lignin depends on various microbial groups. Despite its potential, anaerobic digestion (AD) faces limitations in lignin valorization due to the sluggish rate of lignin depolymerization. Several pretreatment methods have been identified that enhance the anaerobic digestion process. The choice of feedstock also plays a crucial role, as higher lignin content corresponds to lower biomethane potential (BMP) and, consequently, decreased biogas production [27-31]. The production of biogas is also affected by the ratio of carbon to nitrogen (C/N). The optimal C/N ratio is in the range of 20-35 and a lower ratio can hamper the anaerobic digestion process. The biomethane potential and the rate at which methane is generated are both directly influenced by this ratio. If the C/N ratio increases, it can trigger the formation the ammonia which inhibits the formation of methane. If the C/N ratio decreases, it triggers the formation of nitrogen which again inhibits the formation of methane. In both cases, acidification occurs, so it is of optimum importance that the C/N ratio is maintained [32]. To ensure high methane production and process stability, the composition ratios of lipid, protein, and carbohydrates of the particular feedstock must be kept at a specific level. This ratio is a crucial measure of the effectiveness of the anaerobic digestion process [33]. Water is a critical factor in the anaerobic digestion process as it allows soluble nutrients and substrates to diffuse to bacterial sites. Anaerobic digestion can be classified into two types based on the amount of water in it: dry and wet. The moisture content of the feedstock in the dry anaerobic digestion process should be (60-75) %and (85-90) % in the wet anaerobic digestion [34]. The optimum particle size of the feedstock is another important parameter that has to be considered during the anaerobic digestion process. If the particle size of the feedstock is very fine, it leads to foaming in wet digestion and acidification in dry digestion [35]. Co-digestion with a secondary substrate should be done in an anaerobic digester to improve the digester's performance when feedstocks are not available [36].

Biological factors

The process of Chemical Oxygen Demand (COD) elimination involves breaking down the organic components in the feedstock, which lowers the overall organic load in the digester. This makes it easier for the microbial community to produce biogas from the leftover organic matter. The elimination of COD also lessens the possibility of substrate inhibition which impedes the activity of microorganisms inside the digester. This also leads to better digester performance and process stability [37]. The stability of the system could be determined by studying the relationship between volatile fatty acids (VFA) and pH changes of the feedstock fed to the digester. For example: the presence of meat in food waste increases the amount of VFAs produced which in turn affects the system's stability and balance by reducing methane production [38]. The production of anaerobic digestion may be hampered by excessive organic loading due to process instability such as foaming or acidity [39]. The anaerobic digestion process may also be hampered by reducing the Hydraulic Retention Time (HRT) which affects the microbial community inside the digestor and the overall health of the digestor [40,41]. The characteristics of the inoculum which is fed to the anaerobic digester at the beginning of the process also affect the stability of the overall digester [42].

Factors related to climate and others

The microbial community structure inside an anaerobic digester is affected by temperature fluctuations inside the digester. This could make it impossible for the digester to function properly until the right temperature is achieved inside the digester. Every stage of the anaerobic digestion process involves a different set of bacteria and the overall quality of biogas production is influenced by the temperature inside the digester. The biogas production increases when the temperature inside the digester rises to 50°C but decreases when the temperature reaches 55°C [43,44,45]. The efficiency of the biogas digester increases when the mixing or agitating of the feedstock and water takes place. Mixing or agitating feedstock and water minimizes scum formation, improves mass transfer, and promotes substrate uniformity. Mechanical mixing is the most efficient of all the many mixing processes [46].

Table 2.1: Brief review of the factors influencing the production of biogas

S. No.	*Factors influencing the production of biogas*	*References*
	I. Feedstock-related factors	
1	Extreme pH variations caused by improper composition of feedstock are reported to cause the whole system to fail.	[21-23]
2	Changes in the organic loading rate (OLR) were reported to impact adversely the structure of the microbial community of the anaerobic digester and hence its performance.	[24-26]
3	High lignin feedstock results in undesirable performance due to its poor biomethane potential.	[27-31]
4	Excessive acidification is reported while using feedstock with a C/N ratio out of the desirable range.	[32]
5	The composition of carbohydrate, protein and lipid of the feedstock is key for the performance (*i.e.*, high methane yield and process stability).	[33]
6	Water is reported as a critical factor in the digestion process which allows soluble nutrients and substrates to diffuse to bacterial sites.	[34]
7	The particle size of the feedstock is reported as a key parameter indicating that very fine particles lead to foaming in wet digestion and acidification in dry digestion.	[35]
8	Co-digestion using a secondary substrate provides encouraging results where there is a paucity of primary feedstock.	[36]
	II. Biological factors	
1	COD vis-à-vis control of the oxidation-reduction pathway is critical for the AD process particularly where the waste stream is used as feedstock.	[37]
2	The concentration of volatile fatty acids (VFA) vis-à-vis pH changes of the feedstock governs the operational stability of the biogas system.	[38]
3	Overloading is a common cause of volatile fatty acid (VFA) accumulation in anaerobic digesters and hence failure of the system.	[39]
4	HRT (hydraulic retention time) has an impact on the microbial community makeup and affects the health of the digester.	[40,41]
5	Characteristics of the inoculum fed to the digester influence the stability of the anaerobic digester and hence performance of the biogas system.	[42]

S. No.	*Factors influencing the production of biogas*	*References*
	III. Factors related to climate and other factors	
1	The optimum range required for maximum biogas yield is reported at 35ºC - 37ºC.	[43, 44, 45]
2	Mixing or agitating is identified as a critical requirement for the desirable performance of the biogas system.	[46]

2.3.2 Research advancement in biogas production

Traditionally, the know-how of the biogas production system is generated through laboratory experiments. However, with the increased knowledge of different aspects of the anaerobic digestion process, simulation tools have been successfully used to expand its research enabling it to provide a deeper understanding of the key factors.

Mathematical modeling

There are different microbial communities involved in the anaerobic digestion process and the process occurs in several steps. Each step is facilitated by specific bacterial groups that convert organic matter into simpler compounds like volatile fatty acids and ultimately methane. As discussed in Section 2.3.1, there are several factors that affect the formation of biogas in the anaerobic digestion process. Several mathematical models have been developed by researchers that partly understand and predict the behavior of the anaerobic digestion system [50]. The first mathematical model of the anaerobic digestion system took into account only the inhibition of methanogenesis caused by the volatile fatty acids (VFA). The three phases of the model are gas, liquid, and biological (solid) phase. It also incorporates a total ion balance. While the carbon dioxide generated is partially dissolved and partially escapes to the gas phase, methane is assumed to be insoluble in water. This model can forecast the failure of the anaerobic digester caused by a temporary accumulation of VFA, which reduces the pH and subsequently raises the concentration of un-ionized VFA inside the digester. It has also been used to simulate the starting of the digester and provide a response to an overload of organic matter inside the digester [51]. According to the Bryers model, the complex biodegradable particulate matter in wastewater is digested to produce protein, carbohydrates, and lipids, which are then converted to amino acids, simple sugars, and fatty acids. The model considers the lipids, proteins, carbohydrates, and particulate matter collectively, and the amino acids and simple sugars are combined. The model predicted the results in two distinct experimental systems that processed biomass particles anaerobically under optimized conditions of the bacterial composition inside the digester [52]. Another model was developed for anaerobic digestion that considered ammonia as a major inhibitor of the methanogenesis process especially when animal wastes such as piggery slurry, primary sewage sludge, and the organic fraction of municipal solid waste are being digested. The model consisted of two stages (hydrolysis/acidogenesis and methanogenesis) and considered unionized VFA inhibition of both steps and unionized ammonia inhibition for the methanogenesis step [53]. Better anaerobic system design and operation are now possible due to research that started with simple models in the 1970s and has progressed to more intricate and sophisticated models today. The ADM1 model is extensively utilized in the simulation of anaerobic digestion. It includes 24 chemicals with Monod-type kinetics for substrates and 29 processes. This model is further optimized by using methods like simulated annealing and artificial neural networks. These developments in simulation and modeling are essential for improving the efficiency of the anaerobic digestion system [54].

Biomethane potential estimation is another aspect of mathematical modeling that has been used to predict the methane generation potential for a variety of feedstocks. By leveraging the understanding of the chemical composition of waste materials, it becomes possible to forecast the methane yield using the stoichiometric formula originally formulated by Buswell and Hatfield [99, 100].

$$C_xH_yO_z + \left(x - \frac{y}{4} - \frac{z}{2}\right) H_2O \rightarrow \left(\frac{x}{2} + \frac{y}{8} - \frac{z}{4}\right) CH_4 + \left(\frac{x}{2} - \frac{y}{8} + \frac{z}{4}\right) CO_2 \quad (2.1)$$

Subsequent modifications by Boyle in 1952 to the chemical reaction, originally proposed by Buswell and Mueller, involved the inclusion of nitrogen and sulfur elements. This adjustment allowed for the determination of the fractions of ammonia and hydrogen sulfide within the resulting biogas.

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S \quad (2.2)$$

The theoretical biochemical methane potential (TBMP) of the material is calculated from [101]

$$TBMP\ (ml\ CH_4\ gVS^{-1}) = \frac{22.4 \times \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)}{12.017a + 1.0079b + 15.999c + 14.0067d + 32.065e} \quad (2.3)$$

Softwares utilised for the modeling of Anaerobic digestion

Anaerobic digestion (AD) is a complex biological process that is difficult to study and replicate. However, several software tools have been developed and used to simulate AD processes. Different software has been used to carry out the simulation studies on anaerobic digestion such as Aspen Plus, Aquasim, BioWin, Simba, STOAT (Sewage Treatment Operation Analysis over Time), and WEST (Worldwide Engine for Simulation, Training and Automation). Aspen Plus is one of the most used applications for AD simulation. Aspen Plus is a comprehensive process modeling application that lets the user build, optimize, and analyze chemical processes, including AD. Aspen Plus has been utilized in several research including the development of innovative process simulation models and the evaluation of co-digestion processes. Another popular software is BioWin, which is specifically developed for modeling wastewater treatment processes, including the AD component. BioWin has been demonstrated to accurately forecast different metrics in AD systems, such as biomass concentrations, hydrogen production, and nutrient removal when correctly calibrated. The Anaerobic Digestion Model No. 1 (ADM1), created by the International Water Association (IWA), has also been widely utilized as the foundation for AD simulations and is frequently implemented in software such as AQUASIM, MATLAB, and STOAT. WEST is another software platform that has been utilized for AD simulations, specifically to mimic the dynamic behavior of AD processes [47,48,49].

The modeling of a biological system is complicated when compared to a mechanical model because of a complete understanding of the system. Several uncertainties are involved in a biogas system, particularly for anaerobic digestion. With a deeper understanding of the biological process, uncertainties associated with the biogas system are reduced and this in turn contributes to the management of the biogas system. This understanding also motivates the development and use of IoT for the management of anaerobic digestion.

2.4 Challenges in the management of a Household Biogas System (HBS)

In rural areas, where access to advanced technology and expertise on the anaerobic digestion process may be limited, owners of HBS rely on daily monitoring and traditional methods to ensure the proper functioning of their systems. These methods passed down through generations or learned through experience, help address common issues that can arise during the operation of HBS. These are tabulated below in **Table 2.2**.

2.4.1 Managerial issues concerning design and construction

Cracks in the digester dome may arise as a result of local workers' lack of understanding of the HBS's structural behavior. A comprehensive structural testing methodology is used to confirm the structure's integrity before starting the feeding of HBS. This entails filling the fermentation chamber with water to the desired height and pressurizing the air in the gas storage portion. The system is then monitored for leakage for a full 24-hour period. Any obvious leaks are sealed with wax to prevent gas from escaping. In extreme circumstances, if extensive leakage is discovered, entire dome reconstruction may be required. This testing and repair process is critical to ensuring the biogas system's operational efficiency and safety. Proper training for local workers and strict adherence to these rules are required to avoid structural breakdowns and preserve the digester's lifespan [55-58].

2.4.2 Managerial issues concerning feedstock

Insufficient biogas output is frequently caused by underfeeding the feedstock into the Household Biogas System (HBS). This issue can be addressed by checking feedstock quality, searching for clogs in gas outflow lines, and installing a gas flow meter. In contrast, excess biogas output may suggest overfeeding, which frequently results in the discharge of surplus gas into the environment. Poor biogas quality is usually caused by poor feedstock or inadequate digestion. To address this, traditional procedures include testing feedstock quality, monitoring for obstructions, and installing gas flow meters. Furthermore, utilizing carbon filters and hydrogen sulfide (H_2S) absorbents can also help detect changes in biogas quality. Implementing these activities guarantee optimal biogas output and quality [61,64-66].

2.4.3 Managerial issues concerning operation (biogas equipment)

Leakage in gas outflow pipes needs the replacement of the affected pipelines [67]. Water condensation in pipes can impede gas flow and cause corrosion in gas equipment. Inserting moisture traps can be a solution to this problem [68,69]. Biogas stove faults can be caused by obstructions, insufficient biogas supply, or corrosion of the air injection hole. These issues are normally addressed by utilizing H_2S filters or, in extreme circumstances, by replacement of the equipment [64, 65]. Blockages in the inlet pipe can arise due to poor feedstock pretreatment. To remove clogs from the inlet line, owners should use water or a long stick [62, 63]. Formation of a scum layer within the digester can impede gas production, clog pipe outputs, and severely impair HBS efficiency. This is usually avoided by checking for scum in the gas outlet pipe or, in extreme circumstances, complete cleaning of the plant is required[59,60].

2.4.4 Lack of technical knowledge

Maintenance concerns with household biogas systems (HBS) are frequently caused by users' lack of understanding of how they work. Frequently, there is a lack of maintenance services and operational understanding, which is increased by a lack of follow-up from biogas service providers. As a result, owners may be unaware of troubleshooting processes and fail to foresee probable malfunctions. This knowledge gap can cause frequent breakdowns of an HBS. In many circumstances, beneficiaries rely exclusively on their intuition to address problems, which can be insufficient and ineffective. In extreme cases, a lack of support and understanding may result in the abandonment of the HBS entirely. To address these concerns, it is critical to provide extensive training and resources to owners, ensuring they are well-equipped to operate and maintain their biogas systems. Regular follow-up services and readily available maintenance support from biogas service providers can considerably improve the sustainability and efficiency of HBS operations. Furthermore, having a sophisticated monitoring system can assist in forecasting and avoiding possible malfunctions, ensuring that biogas facilities operate continuously and optimally [70-74].

These prevailing practices may not always be as precise or scientific as modern techniques, and they are often not effective in addressing common issues and maintaining the functionality of biogas systems within resource-constrained environments like rural areas.

Table 2.2: Managerial issues faced in the management of a typical HBS (Fixed dome) and the prevailing practices of resolving these issues

S. No.	Managerial issues		Description or cause of issues	Remedy or notes for the concerned issues	References
	Sub-system	Issues faced			
1	Design and construction	Formation of cracks in the digester dome	Lack of understanding of the structural behavior of the HBS by local workers leads to deficiencies in the construction	• After construction before feeding has been started, structural testing of HBS is done by filling the fermentation chamber with water up to a suitable height and pressuring the air in the gas storage section to check for leakage for 24 hours • Sealing noticeable leaks with wax • Complete reconstruction of the dome	[62-65]
2	Feedstock	• Lack of quantity of biogas	• Underfeeding feedstock to the HBS	• Checking the quality of feedstock, checking for blockages in gas outflow pipes, installing a gas flow meter	[68,71-73]
		• Quantity of biogas more than that required	• Overfeeding feedstock to the HBS	• Biogas released into the environment	
		• Poor quality of biogas	• Poor quality of feedstock, incomplete digestion of the feedstock	• Checking the quality of feedstock, checking for blockages in gas outflow pipes, installing a gas flow meter • Use of carbon filter, H_2S absorbent	
3	Biogas equipment	Leakage in gas outflow pipe		Replacement of pipes	[68, 71, 72, 74]
		Water condensation can occur in the pipes	Can affect the flow of gas, corrosion in gas equipment	Attach moisture trap	[75, 76]

S. No.	Managerial issues: Sub-system	Managerial issues: Issues faced	Description or cause of issues	Remedy or notes for the concerned issues	References
		• Malfunctioning of biogas stove	• Blockage, not enough supply of biogas, corrosion of air injection hole	• Use H_2S filters • Replace equipment	[71, 72]
		• Blockage in the inlet pipe	• Blocking of inlet pipe during feeding	• Cleaning the inlet pipe with water or inserting a long stick	[69,70]
		• Formation of scum layer inside the digester	• Scum formation can hinder gas production, clog pipe outlets, and significantly reduce the HBS efficiency	• Checking of scum through the gas outlet pipe • Complete cleaning of the plant	[66-68]
4	Lack of technical knowledge		• Absence of maintenance services • Lack of operational knowledge • Lack of follow-up services by biogas service providers. • No awareness of trouble-shooting and inability to predict the breakdown of the plant	Beneficiaries mostly relied on their intelligence or sometimes in extreme cases HBS were abandoned	[74, 77, 73, 78-81]

2.5 Status of biomass-based rural entrepreneurship and its relevance to SDG

Several viable rural companies, such as dairy, poultry, piggery, and fishing, provide significant contributions to the Indian economy [75, 76]. For example, household-based milk producers, each with two to five cows, contribute significantly to India's thriving dairy sector [77]. Small-scale rural milk farmers account for 62% of all milk production in India [78]. This sector is critical to supplementary income creation for rural lives in India, with around 30 million farmers participating in backyard poultry [79]. Similarly, rural farmers raise 70% of the global pig population using traditional systems based on low-input, demand-driven production methods. Pig rearing generates greater cash for farmers than other livestock species [80]. India is the world's second-largest fish producer, after China [81]. All of these initiatives are input-intensive, and net income from the production system is a major motivator. Household Biogas Systems (HBS) can be considered an analogous production system because they require the same input (feedstock) and produce commercially valuable products (gas and digestate). As a result, a comparative assessment of HBS's economic performance with all other current rural companies is required to assess its viability and possible advantages. Small-scale aquaculture boosts rural incomes while requiring significant investment in ponds, feed, and fish stock. In contrast, HBS largely uses organic waste as a feedstock, transforming it into useful biogas and digestate. The biogas produced can be utilized to cook, heat, and generate electricity, while the digestate is an excellent organic fertilizer. This combined benefit makes HBS a potentially profitable and sustainable enterprise for rural communities and if effectively incorporated into the rural economy, results in long-term advantages for rural populations.

Several government programs connected to rural enterprises have had a significant impact on India's Sustainable Development Goals (SDGs). Policies promoting the installation of HBS for biogas are consistent with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) since they provide renewable energy sources while lowering carbon emissions. Initiatives in the poultry sector, such as subsidies for backyard poultry production, help to achieve SDG 1 (No Poverty) and SDG 2 (Zero Hunger) by improving food security and increasing income for rural people. Government dairy initiatives, such as the National Dairy Development Program, help to achieve SDG 8 (Decent Work and Economic Growth) by increasing milk production efficiency and providing new job possibilities. Fishery policies, particularly financial aid for small-scale aquaculture, contribute to SDG 14 (Life Below Water) by encouraging sustainable fishing methods and improving livelihoods. Piggery initiatives that focus on improved breeding and healthcare services help to achieve SDG 3 (Good Health and Well-being) and SDG 12

(Responsible Consumption and Production) by enhancing animal health and productivity. These policies promote long-term rural development by tackling economic, social, and environmental issues [82, 83].

2.6 Technology advancement for management of household biogas system

IoT has the potential to address challenges in the utilization of renewable and conventional energy resources by addressing the various technological gaps and limitations. It can improve sustainable energy research and innovation, contribute to solutions that benefit both the community and the environment, and promote a strong energy sector based-economy. IoT integrated into energy systems can help overcome challenges related to energy security without negatively impacting the environment. A typical IoT-integrated system can help ensure an uninterrupted and reliable flow of data and optimize connectivity among different parts of the system [84]. IoT in sustainable energy systems can apply to different sectors such as smart grids, precision agriculture, waste management, water conservation, environmental monitoring, smart cities, remote work and collaboration, circular economy, etc. The integration of IoT into sustainable energy systems provides diverse ways to achieve global energy access. This involves implementing clean and renewable energy methods in different sectors and contributing to the provision of affordable energy sources on a large scale in both urban and rural communities. IoT can also help in achieving Sustainable Development Goals (SDGs) because IoT-based technology is commercially viable, widely available, and easily accepted. Thus it can be said that the relationship between IoT and sustainability is multifaceted and IoT can play a significant role in promoting sustainability across various sectors.

2.6.1 IoT and Sustainability

IoT-based technology is employed to monitor and optimize energy consumption and reduce wastage of energy in buildings, industries, and homes through the use of thermostats, lighting, and appliances equipped with IoT sensors. This can also be extended to the monitoring and development of smart grids that help manage the distribution of electricity [85-88]. IoT-based sensors can be deployed by farmers in precision farming to monitor various soil conditions, crop health, and fertilization patterns and make irrigation decisions [89-90]. IoT-based technology can be used to improve waste management processes such as monitoring the waste level in bins, alerting users in the segregation of wastes, and optimization of waste collection routes [91,92]. IoT devices are used for environmental monitoring for various sectors such as monitoring the pollution levels of air and water, changes in the weather, warnings of natural disasters like earthquakes events, radiation monitoring, etc. [93,94]. IoT technologies play a crucial role in the development of smart cities in various areas such as infrastructure, smart streetlights, traffic management, smart parking and navigation, e-healthcare, etc. The integration of IoT with the modern workplace has reduced the need for physical traveling to offices in recent times. This can also help in reducing emissions during transportation and reducing building energy consumption [95,96].

From the above, it can be seen that IoT technologies contribute to more sustainable practices in various industries and aspects of daily life.

2.6.2 IoT and anaerobic digestion

The application of IoT in anaerobic digestion has already been discussed in **Chapter 1**. Here the examples of two such cases relevant to the current research have been elaborated.

A decentralized continuously stirred tank reactor made of stainless steel with a total volume of 942.4 liters and a working volume of 675.4 liters was created to process food waste generated by the Asian Institute of Technology (AIT) campus community. This reactor was outfitted with a remote monitoring system using the Internet of Things (IoT) to optimize process performance and supervise the operation and maintenance of the decentralized anaerobic digestion system. The pH, temperature, and Oxidation Reduction Potential (ORP) electrodes were connected to the anaerobic digester via a Programmable Logic Controller (PLC). The quality of the biogas produced was monitored using an online biogas analyzer device. The information gathered was recorded and subsequently communicated to a central server, which could be viewed from other devices. The PLC data might be monitored in real-time for every second at the centralized location. The composition of biogas was constantly analyzed by a biogas analyzer powered by solar PV (with battery backup) and outfitted with custom-programmed microcontrollers for data logging and remote transmission (GSM communications). A gas flowmeter was used to determine the amount of biogas produced by the digester. The digestate dewatering device included a stainless-steel tank and a sieve [97].

A distributed monitoring system to control and maintain household biogas appliances (stove and cooker) has been designed and developed to perform real-time monitoring of the biogas appliances, the amount of biogas consumed by consumers, biogas flow regulation, automatic start/stop, and pipe pressure monitoring throughout the setup. The distributed monitoring system included a local monitoring system for household biogas appliances (ZigBee) and a distant monitoring system (LoRa). The local monitoring terminal collected data from ZigBee

endpoints and transmitted it to the LoRa network. A real-time warning system was built within the LoRa gateway, which sent alarm messages to users via the GSM (global system for mobile communications) module.
The use of IoT (Internet of Things) technologies (ZigBee and LoRa) can improve the safety and dependability of a biogas plant by gathering data from sensors. The technology can be used to regulate biogas appliances remotely, provide alarm signals for biogas leaks, and prevent unintentional flameouts. The technology also serves as a foundation for gas production planning in biogas projects through centralized monitoring of the user's gas usage. The system is developed for rural areas, taking into account cellular network coverage and cost, and available technology [98].

2.7 Summary

This Chapter presents a comprehensive assessment of the literature on many essential features of biogas systems. First, it evaluates biogas systems' numerous benefits, emphasizing their potential to provide renewable energy, improve waste management, and contribute to environmental sustainability. Second, the present state of biogas production research is explored, including advances in biogas technology focusing on the mathematical modeling of anaerobic digestion and software used in this modeling. Third, the chapter delves into the obstacles to maintaining household biogas systems (HBS), including design and construction of the HBS, feedstock-related factors, factors related to the different biogas equipment, and the lack of technical knowledge among the users. Fourth, it examines the current state of biomass-based rural entrepreneurship, focusing on how biogas systems might promote rural economic development and also contribute to the SDGs. Finally, the chapter goes into technological improvements for managing a typical HBS by focusing on tools based on IoT for more effective operation and maintenance.

From the extensive literature review carried out, it was seen that although there has been a mapping of the barriers to the dissemination of biogas in India, there have been limited studies conducted to analyze the grassroots factors in rural areas of Assam. There exists a research gap in the area of biogas reactors because, though designed to function optimally under ideal conditions, these biogas reactors frequently face operational challenges when those conditions deviate in a typical rural area. The users of HBS often struggle to diagnose and address these issues due to a lack of technical support and the absence of dedicated service centers. This ultimately leads to diminished interest in HBS in rural India.

While improper management is a primary reason for HBS failures in rural Assam, the role of technology-driven support systems, such as IoT-based solutions, has not been thoroughly explored. The current work intends to investigate this gap in research on how information and communication technologies can help in real-time monitoring and support for HBS and hence address operational issues and improve overall performance thus ensuring a hassle-free operation and maintenance of HBS.

Furthermore, the potential of biogas systems to serve as a rural entrepreneurship model, similar to other rural enterprises like dairy, poultry, piggery, and fishery, has been largely overlooked. This study aims to explore whether IoT-integrated HBS can act as a catalyst for creating sustainable rural businesses while contributing to India's decarbonization efforts.

References

1. Kougias, P.G. and Angelidaki, I. Biogas and its opportunities—A review. *Frontiers of Environmental Science & Engineering*, 12(3):1-12, 2018.
2. Sawyerr, N., Trois, C., Workneh, T. and Okudoh, V.I. An overview of biogas production: Fundamentals, applications, and future research. *International Journal of Energy Economics and Policy,* 2019.
3. Korbag, I., Omer, S.M.S., Boghazala, H. and Abusasiyah, M.A.A. *Recent advances of biogas production and future perspective*, IntechOpen, 2020.
4. Rajendran, K., Aslanzadeh, S. and Taherzadeh, M.J. Household biogas digesters—A review. *Energies*, 5(8):2911-2942, 2012.
5. Chen, L., Zhao, L., Ren, C. and Wang, F. The progress and prospects of rural biogas production in China. *Energy policy*, 51:58-63, 2012.
6. Garfí, M., Martí-Herrero, J., Garwood, A., and Ferrer, I. Household anaerobic digesters for biogas production in Latin America: A review. *Renewable and sustainable energy reviews*, 60:599-614, 2016.
7. Suhag, M. and Sisodia, A. Study Regarding Domestic Biogas Plants in Selected Villages of Kurukshetra, Haryana (India). *Journal of Environment and Earth Science*, 6:5, 2016.

8. Bhol, J., Sahoo, B.B. and Mishra, C.K. December. Biogas digesters in India: A review. In *National Conference on Renewable and New Energy Systems,* pages 1-6, Odisha, 2011.

9. Patinvoh, R.J. and Taherzadeh, M.J. Challenges of biogas implementation in developing countries. *Current Opinion in Environmental Science & Health*, 12:30-37, 2019.

10. Nevzorova, T. and Kutcherov, V. Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. *Energy Strategy Reviews*, 26:100414, 2019.

11. Pathak, H., Jain, N., Bhatia, A., Mohanty, S. and Gupta, N. Global warming mitigation potential of biogas plants in India. *Environmental monitoring and assessment*, 157(1):407-418, 2009.

12. Singh, A., Tiwari, R., Chandrahas and Dutt, T. Augmentation of farmers' income in India through sustainable waste management techniques. *Waste Management & Research*, 39(6):849-859, 2021.

13. Soni, A., Patil, D. and Argade, K. Municipal solid waste management. *Procedia Environmental Sciences*, 35:119-126, 2016.

14. Apte, A., Cheernam, V., Kamat, M., Kamat, S., Kashikar, P. and Jeswani, H. Potential of using kitchen waste in a biogas plant. *International Journal of Environmental Science and Development*, 4(4):370, 2013.

15. Chakrabarty, S., Boksh, F.M. and Chakraborty, A. Economic viability of biogas and green self-employment opportunities. *Renewable and Sustainable Energy Reviews*, 28:757-766, 2013.

16. Chen, G., Zhao, G., Zhang, H., Shen, Y., Fei, H. and Cheng, W. Biogas slurry use as N fertilizer for two-season Zizania aquatica Turcz. in China. *Nutrient cycling in agroecosystems*, 107(3):303-320, 2017.

17. Kumar, S., Malav, L.C., Malav, M.K. and Khan, S.A. Biogas slurry: source of nutrients for eco-friendly agriculture. *International Journal of Extensive Research*, 2(2):42-46, 2015.

18. Yu, F.B., Luo, X.P., Song, C.F., Zhang, M.X. and Shan, S.D. Concentrated biogas slurry enhanced soil fertility and tomato quality. *Acta Agriculturae Scandinavica Section B–Soil and Plant Science*, 60(3):262-268, 2010.

19. Kataki, S., Hazarika, S. and Baruah, D.C. By-products of bioenergy systems (anaerobic digestion and gasification) as sources of plant nutrients: scope of processed application and effect on soil and crop. *Journal of Material Cycles and Waste Management*, 21(3):556-572, 2019.
20. Bumbiere, K., Pubule, J. and Blumberga, D. What Will Be the Future of Biogas Sector?. *Rigas Tehniskas Universitates Zinatniskie Raksti*, 25(1):295-305, 2021.
21. Akunna, J.C., Abdullahi, Y.A. and Stewart, N.A. Anaerobic digestion of municipal solid wastes containing variable proportions of waste types. *Water Science and Technology*, 56(8):143-149, 2007.
22. Panigrahi, S. and Dubey, B.K. A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste. *Renewable Energy*, 143:779-797, 2019.
23. Appels, L., Baeyens, J., Degrève, J. and Dewil, R. Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in energy and combustion science*, 34(6):755-781, 2008.
24. Ferguson, R.M., Coulon, F. and Villa, R. Organic loading rate: A promising microbial management tool in anaerobic digestion. *Water research*, 100:348-356, 2016.
25. Nakasaki, K., Kwon, S.H. and Takemoto, Y. An interesting correlation between methane production rates and archaea cell density during anaerobic digestion with increasing organic loading. *Biomass and Bioenergy*, 78:17-24, 2015.
26. Mu, L., Zhang, L., Zhu, K., Ma, J. and Li, A. Semi-continuous anaerobic digestion of extruded OFMSW: Process performance and energetics evaluation. *Bioresource technology*, 247:103-115, 2018.
27. Brown, D., Shi, J. and Li, Y. Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. *Bioresource technology*, 124:379-386, 2012.
28. Buffière, P., Loisel, D., Bernet, N. and Delgenes, J.P. Towards new indicators for the prediction of solid waste anaerobic digestion properties. *Water science and technology*, 53(8):233-241, 2006.
29. Liew, L.N., Shi, J. and Li, Y. Methane production from solid-state anaerobic digestion of lignocellulosic biomass. *Biomass and Bioenergy*, 46:125-132, 2012.
30. Xu, F., Wang, Z.W. and Li, Y. Predicting the methane yield of lignocellulosic biomass in mesophilic solid-state anaerobic digestion based on feedstock characteristics and process parameters. *Bioresource technology*, 173:168-176, 2014.

31. Pokój, T., Bułkowska, K., Gusiatin, Z.M., Klimiuk, E. and Jankowski, K.J. Semi-continuous anaerobic digestion of different silage crops: VFAs formation, methane yield from fiber and non-fiber components and digestate composition. *Bioresource technology*, 190:201-210, 2015.
32. Kong, X., Wei, Y., Xu, S., Liu, J., Li, H., Liu, Y. and Yu, S. Inhibiting excessive acidification using zero-valent iron in anaerobic digestion of food waste at high organic load rates. *Bioresource technology*, 211:65-71, 2016.
33. Li, Y., Jin, Y., Borrion, A., Li, H. and Li, J. Effects of organic composition on mesophilic anaerobic digestion of food waste. *Bioresource technology*, 244:213-224, 2017.
34. Luning, L., Van Zundert, E.H.M. and Brinkmann, A.J.F. Comparison of dry and wet digestion for solid waste. *Water science and technology*, 48(4):15-20, 2003.
35. Motte, J.C., Escudié, R., Hamelin, J., Steyer, J.P., Bernet, N., Delgenes, J.P. and Dumas, C. Substrate milling pretreatment as a key parameter for solid-state anaerobic digestion optimization. *Bioresource technology*, 173:185-192, 2014.
36. Matheri, A.N., Sethunya, V.L., Belaid, M. and Muzenda, E. Analysis of the biogas productivity from dry anaerobic digestion of organic fraction of municipal solid waste. *Renewable and Sustainable Energy Reviews*, 81:2328-2334, 2018.
37. Dhar, H., Kumar, P., Kumar, S., Mukherjee, S. and Vaidya, A.N. Effect of organic loading rate during anaerobic digestion of municipal solid waste. *Bioresource Technology*, 217:56-61, 2016.
38. Yong, Z., Dong, Y., Zhang, X. and Tan, T. Anaerobic co-digestion of food waste and straw for biogas production. *Renewable energy*, 78:527-530, 2015.
39. Regueiro, L., Lema, J.M. and Carballa, M. Key microbial communities steering the functioning of anaerobic digesters during hydraulic and organic overloading shocks. *Bioresource technology*, 197: 208-216, 2015.
40. Ziganshin, A.M., Schmidt, T., Lv, Z., Liebetrau, J., Richnow, H.H., Kleinsteuber, S. and Nikolausz, M. Reduction of the hydraulic retention time at constant high organic loading rate to reach the microbial limits of anaerobic digestion in various reactor systems. *Bioresource technology*, 217:62-71, 2016.
41. Jain, S., Jain, S., Wolf, I.T., Lee, J. and Tong, Y.W. A comprehensive review on operating parameters and different pretreatment methodologies for anaerobic digestion of municipal solid waste. *Renewable and Sustainable Energy Reviews*, 52:142-154, 2015.

42. Pavi, S., Kramer, L.E., Gomes, L.P. and Miranda, L.A.S. Biogas production from co-digestion of organic fraction of municipal solid waste and fruit and vegetable waste. *Bioresource technology*, 228: 362-367, 2017.
43. Kettunen, R.H. and Rintala, J.A. The effect of low temperature (5–29 C) and adaptation on the methanogenic activity of biomass. *Applied microbiology and biotechnology*, 48(4):570-576, 1997.
44. Chae, K.J., Jang, A.M., Yim, S.K. and Kim, I.S. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. *Bioresource technology*, 99(1):1-6, 2008.
45. Arikan, O.A., Mulbry, W. and Lansing, S. Effect of temperature on methane production from field-scale anaerobic digesters treating dairy manure. *Waste management,* 43:108-113, 2015.
46. Wu, B. (2012). CFD simulation of mixing for high-solids anaerobic digestion. *Biotechnology and Bioengineering*, 109(8):2116-2126.
47. Rajendran, K., Kankanala, H.R., Lundin, M. and Taherzadeh, M.J. A novel process simulation model (PSM) for anaerobic digestion using Aspen Plus. *Bioresource technology*, 168:7-13, 2014.
48. Aguilar, M.C., Wang, Y.D., Roskilly, T., Pathare, P.B. and Lamidi, R.O. Biogas from anaerobic co-digestion of food waste and primary sludge for cogeneration of power and heat. *Energy Procedia*, 142:70-76, 2017.
49. Inayat, A., Ahmed, S.F., Djavanroodi, F., Al-Ali, F., Alsallani, M. and Mangoosh, S. Process simulation and optimization of anaerobic co-digestion. *Frontiers in Energy Research*, 9:764463, 2021.
50. Gavala, H.N., Angelidaki, I. and Ahring, B.K. Kinetics and modeling of anaerobic digestion process. *Biomethanation I*, 57-93, 2003.
51. Graef, S.P. and Andrews, J.F. Mathematical modeling and control of anaerobic digestion. *Water Research*, 8:261-289, 1974.
52. Bryers, J.D. Structured modeling of the anaerobic digestion of biomass particulates. *Biotechnology and bioengineering*, 27(5):638-649,1985.
53. Kiely, G., Tayfur, G., Dolan, C. and Tanji, K. Physical and mathematical modelling of anaerobic digestion of organic wastes. *Water research*, 31(3): 534-540, 1997.
54. Batstone, D.J., Keller, J., Angelidaki, R.I., Kalyuzhny, S.V., Pavlostathis, S.G., Rozzi, A., Sanders, W.T.M., Siegrist, H., Vavilin, V.A. The IWA Anaerobic Digestion Model

No 1 (ADM1). In *Proceedings of 9th World Congress Anaerobic Digestion, Antwerpen – Belgium*, 2001.

55. Amaratunga, M. Structural Behaviour and Stress Conditions of Fixed Dome Type of Biogas Units. *Biogas Technology, Transfer and Diffusion*, 295-30, 1986.
56. Deng, L., Liu, Y., Wang, W., Deng, L., Liu, Y. and Wang, W. Construction Materials and Structures of Digesters. *Biogas Technology*, 157-199, 2020.
57. Roy, A.D., Prakash, O., Kumar, A., Kaviti, A.K. and Pandey, A. Design and Selection Criteria of Biogas Digester. *Low Carbon Energy Supply: Trends, Technology, Management*, 91-112, 2018.
58. Pérez, I., Garfí, M., Cadena, E. and Ferrer, I. Technical, economic and environmental assessment of household biogas digesters for rural communities. *Renewable energy*, 62:313-318, 2014.
59. Raman, P., Rao, V.R. and Kishore, V.V.N. A static scum-breaking net for fixed-dome biogas plants. *Biological wastes*, 30(4):261-273, 1989.
60. Afridi, Z.U.R. and Qammar, N.W. Technical challenges and optimization of biogas plants. *ChemBioEng Reviews*, 7(4):119-129, 2020.
61. Cheng, S., Li, Z., Mang, H.P., Neupane, K., Wauthelet, M. and Huba, E.M. Application of fault tree approach for technical assessment of small-sized biogas systems in Nepal. *Applied Energy*, 113:1372-1381, 2014.
62. Arora, S., Busch, L., Snyder, S. and Kilian, R. A Simple and Energy Efficient Approach to Cleaning Biogas. *Residuals and Biosolids,* 570-578, 2018.
63. Paolini, V., Petracchini, F., Carnevale, M., Gallucci, F., Perilli, M., Esposito, G., Segreto, M., Occulti, L.G., Scaglione, D., Ianniello, A. and Frattoni, M. Characterisation and cleaning of biogas from sewage sludge for biomethane production. *Journal of environmental management*, 217:288-296, 2018.
64. Roubík, H., Mazancová, J., Banout, J. and Verner, V. Addressing problems at small-scale biogas plants: a case study from central Vietnam. *Journal of Cleaner Production*, 112:2784-2792, 2016.
65. Hewitt, J., Holden, M., Robinson, B. L., Jewitt, S., & Clifford, M. J. Not quite cooking on gas: Understanding biogas plant failure and abandonment in Northern Tanzania. Renewable and Sustainable Energy Reviews, 165, 112600, 2022.
66. Khan, E.U. and Martin, A.R. Review of biogas digester technology in rural Bangladesh. *Renewable and Sustainable Energy Reviews*, 62:247-259, 2016.

67. Bensah, E. C., & Brew-Hammond, A. Biogas technology dissemination in Ghana: history, current status, future prospects, and policy significance. International Journal of Energy and Environment, 1(2), 277-294, 2010.
68. Ullrich, G. Second supervisor training on biogas plant construction, promotion of Private Sector Development in Agriculture. Technical Report, Nairobi, Kenya, 2008.
69. Ryckebosch, E., Drouillon, M. and Vervaeren, H. Techniques for transformation of biogas to biomethane. *Biomass and bioenergy*, 35(5):1633-1645, 2011.
70. De Alwis, A. Biogas–a review of Sri Lanka's performance with a renewable energy technology. *Energy for Sustainable Development*, 6(1):30-37, 2002.
71. Limmeechokchai, B. and Chawana, S. Sustainable energy development strategies in the rural Thailand: The case of the improved cooking stove and the small biogas digester. *Renewable and Sustainable Energy Reviews*, 11(5):818-837, 2007.
72. Surendra, K.C., Takara, D., Hashimoto, A.G. and Khanal, S.K. Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, 31:846-859, 2014.
73. Lewis, J.J., Hollingsworth, J.W., Chartier, R.T., Cooper, E.M., Foster, W.M., Gomes, G.L., Kussin, P.S., MacInnis, J.J., Padhi, B.K., Panigrahi, P. and Rodes, C.E. Biogas stoves reduce firewood use, household air pollution, and hospital visits in Odisha, India. *Environmental science & technology*, 51(1):560-569, 2017.
74. Audit Report Report of the Comptroller and Auditor General of India on Renewable Energy Sector in India, Technical Report No. 34, New Delhi, India, 2015.
75. Department of Animal Husbandry and Dairying Ministry of Fisheries, Animal Husbandry and Dairying Government of India. *Annual Report, 2021-22*, , 2021.
76. Chand, R. Doubling Farmers' Income: Rationale, Strategy, Prospects and Action Plan. Technical Report, National Institution for Transforming India, Government of India, New Delhi, 2017.
77. Morgan, N. Smallholder dairy development: Lessons learned in Asia. Technical Report, Animal Production and Health Commotion for Asia and the Pacific and FAO of the United Nations regional office for Asia and the Pacific, Bangkok, 2009.
78. Sinha, O.P. Agro-industries characterization and appraisal: dairy in India. Technical Report, AGSF Working Document (FAO), 2007.

79. National Action Plan for Egg & Poultry-2022 For Doubling Farmers' Income by 2022, Technical Report, Department of Animal Husbandry, Dairying & Fisheries Ministry of Agriculture & Farmers Welfare Government of India, 2022,
80. Overview of the Piggery Sector, Department of Animal Husbandry and Dairying. Retrieved from https://dahd.nic.in/sites/default/filess/NAP%20on%20Pig%20.pdf on 23 May, 2022).
81. Annual Report, Fisheries, 2021-22, Department of Fisheries, Ministry of Fisheries, Animal Husbandry and Dairying, Government of India, 2021.
82. FAO Livestock and SDGs, Technical Report, Food and Agriculture Organization of the United Nations (FAO), Synthesis—Livestock and the Sustainable Development Goals: Global Agenda for Sustainable Livestock, FAO-AGAL Livestock Information, Sector Analysis and Policy Branch, 2023,
83. NITI Aayog, Government of India. *The Indian Model of SDG Localisation, Part one, United Nations High-Level Political Forum on Sustainable Development* 2022. Retrieved from https://www.niti.gov.in/sites/default/files/2022 08/The_Indian_Model_of_SDG_Localisation_13072022.pdf on 21/03/2023.
84. Khatua, P.K., Ramachandaramurthy, V.K., Kasinathan, P., Yong, J.Y., Pasupuleti, J. and Rajagopalan, A. Application and assessment of internet of things toward the sustainability of energy systems: Challenges and issues. *Sustainable Cities and Society*, 53:101957, 2020.
85. Al-Turjman, F., Altrjman, C., Din, S. and Paul, A. Energy monitoring in IoT-based ad hoc networks: An overview. *Computers & Electrical Engineering*, 76:133-142, 2019.
86. Chooruang, K. and Meekul, K. November. Design of an IoT energy monitoring system. In *2018 16th International Conference on ICT and Knowledge Engineering (ICT&KE)* (pp. 1-4). IEEE. 2018,
87. Shahinzadeh, H., Moradi, J., Gharehpetian, G.B., Nafisi, H. and Abedi, M. IoT architecture for smart grids. In *2019 International Conference on Protection and Automation of Power System (IPAPS),* pages 22-30, 2019. IEEE.
88. Siozios, K., Anagnostos, D., Soudris, D. and Kosmatopoulos, E. *IoT for smart grids*. Cham, Switzerland: Springer, 2019.
89. Chehri, A., Chaibi, H., Saadane, R., Hakem, N. and Wahbi, M. A framework of optimizing the deployment of IoT for precision agriculture industry. *Procedia Computer Science*, 176:2414-2422, 2020.

90. Singh, R.K., Berkvens, R. and Weyn, M. AgriFusion: An architecture for IoT and emerging technologies based on a precision agriculture survey. *IEEE Access*, 9:136253-136283, 2021.
91. Misra, D., Das, G., Chakrabortty, T. and Das, D. An IoT-based waste management system monitored by cloud. *Journal of Material Cycles and Waste Management*, 20(3):1574-1582, 2018.
92. Malapur, B.S. and Pattanshetti, V.R. August. IoT based waste management: An application to smart city. In *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, pages 2476-2486, 2017. IEEE.
93. Shinde, S.R., Karode, A.H. and Suralkar, S.R. Review on-IoT based environment monitoring system. *International Journal of Electronics and Communication Engineering and Technology*, 8(2):103-108, 2017.
94. Floris, A., Porcu, S., Girau, R. and Atzori, L. An IoT-based smart building solution for indoor environment management and occupants prediction. *Energies*, 14(10):2959, 2021.
95. Zanella, A., Bui, N., Castellani, A., Vangelista, L. and Zorzi, M. Internet of things for smart cities. *IEEE Internet of Things journal*, 1(1):22-32, 2014.
96. Mehmood, Y., Ahmad, F., Yaqoob, I., Adnane, A., Imran, M. and Guizani, S. Internet-of-things-based smart cities: Recent advances and challenges. *IEEE Communications Magazine*, 55(9):16-24, 2017.
97. Logan, M., Safi, M., Lens, P. and Visvanathan, C. Investigating the performance of internet of things based anaerobic digestion of food waste. *Process Safety and Environmental Protection*, 127: 277-287, 2019.
98. Huo, P., Yang, F., Luo, H., Zhou, M. and Zhang, Y. Distributed monitoring system for precision management of household biogas appliances. *Computers and electronics in agriculture*, 157:359-370, 2019.
99. Buswell, A.M. Anaerobic fermentations. *Bulletin (Illinois State Water Survey),* 32, 1939.
100. Murphy, J.D. and Thamsiriroj, T. Fundamental science and engineering of the anaerobic digestion process for biogas production. In *The Biogas Handbook*, pages 104-130. Woodhead Publishing, 2013.
101. Feng, L., Li, Y., Chen, C., Liu, X., Xiao, X., Ma, X., Zhang, R., He, Y. and Liu, G. Biochemical methane potential (BMP) of vinegar residue and the influence of feed to inoculum ratios on biogas production. *Bioresources*, 8(2):2487-2498, 2013.