BIOGAS TECHNOLOGY IN BANGLADESH: A COMPREHENSIVE STUDY ON HISTORY, PRESENT SITUATION, TECHNOLOGIES AND ELECTRICITY GENERATION POTENTIAL

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ABSTRACT

In Bangladesh, biomass, encompassing organic materials of modern biological origin, plays a pivotal role in addressing energy scarcity. Bioenergy, harnessed from biomass, is crucial for national development. Rural communities in Bangladesh heavily rely on biomass fuels, including wood, crop residues, and animal dung, for domestic use. The Sustainable and Renewable Energy Development Authority (SREDA) anticipates a 25% increase in rural biomass fuel demand by 2041 due to population growth and changing cooking practices. Biogas-to-electricity initiatives gained momentum in the early 2000s, with organizations like IDCOL and Grameen Shakti leading the way. IDCOL's Biogas Program initiated in 2004 marked a turning point by providing electricity to off-grid rural areas. Subsequent integration with solar home systems in 2008 enhanced energy reliability. In the 2010s, IDCOL expanded its efforts, aiming to install 4,000 biogas plants, contributing to clean cooking fuel and electricity. The government's commitment to a 10% renewable energy share by 2021 further bolstered these initiatives. Biogas, generated through anaerobic digestion, has emerged as a cost-effective and sustainable solution, particularly small household-based fixed dome models. IDCOL's subsidy and support have driven the success of these renewable energy programs, achieving energy access and economic stability for rural households. The calorific value of biogas and its electricity potential hold promise for addressing energy demand challenges. Additionally, diverse biomass sources in Bangladesh exhibit varying sustainability and scalability scores, with agricultural residues showing high potential for both. Utilizing organic waste for biogas production in agricultural nations like Bangladesh holds promise for sustainable biogas technology and environmental impact reduction, contributing to the global transition towards cleaner energy sources. In summary, biogas-technology has emerged as a pivotal solution to combat energy scarcity, enhance sustainability, and promote economic stability in rural Bangladesh.

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CHAPTER 1
INTRODUCTION TO BIOMASS AND BIOENERGY

Organic material with a modern biological origin is defined as biomass. It contains all varieties of organic waste, including sewage sludge, trees, all kinds of plant remnants, timber, animal waste, municipal garbage, and agricultural crops. Bioenergy refers to the energy that is produced from biomass. Energy is remarkable and significant key factor for the advancement of a nation but the scarcity of the energy source has become an economic threat for the developing national around the world [Mofijur et al., 2013].

Globally, 2.5 billion people, or one-third of the world's population rely on the traditional use of solid biomass to cook their meals [IEA, 2017]. The worldwide domestic biomass supply in 2019 was 56.9 EJ. Solid biomass sources, such as wood chips, wood pellets, and traditional biomass sources, accounted for 85% of the domestic supply. 1.93 billion m^3 of wood fuel was produced globally in 2020. Asia had the highest share of wood fuel production with a contribution of 37% [WBA, 2021] practically all developing nations, biomass is the most popular fuel used for energy purposes in the residential, commercial, and industrial sectors. In developing countries, biomass is the dominant source of energy for cooking and heating in rural areas, accounting for over 90% of the total energy consumption in some countries [Madruga et al., 2012]. In South Asia, biomass accounts for a significant portion of the total energy consumption, ranging from 27% in Bangladesh to 87% in Nepal (FAO 2018). The FAO report also states that biomass is the primary source of energy for cooking and heating in rural areas of South Asia, accounting for over 80% of total energy consumption.

Biomass plays an important and complex role in Bangladesh, particularly in rural areas where approximately 74.5% of the population lives [FAO, 2009]. Currently the number is 60.29% (World Bank). Again, Bangladesh is one of the most densely populated countries in the world . Due to the rising growth of the population, the per capita energy consumption in Bangladesh increased from 5 GJ (gigajoules) in 1977 to 6.2 GJ and 8.98 GJ in 2009 and 2012 respectively [IEA, 2021, Kennes et al., 1984] . The per capita energy consumption in Bangladesh in 2021 was 9.9 gigajoules (GJ). This is the lowest of any country outside of Africa [Dettoni, 2022]. The largest energy consumers in Bangladesh are industries and the residential sector, followed by the commercial and agricultural sectors. Bangladesh will need an estimated 34,000 MW of power by 2030 to sustain its economic growth of over 7 percent [Rashid, 2018]. The rural people of Bangladesh depend mainly on biomass fuels, namely wood, leaves, twigs, bark, roots, bamboo, shell and coir of coconut, agricultural residues such as rice husk, straw, jute stick, bagasse, and cow dung for their domestic consumption [Mosaddek Hossen et al., 2017]. The majority of the arable land is cultivated for producing rice, wheat, jute, sugarcane, mustard, coconut and lentils. These crops produce a substantial amount of residues. These are the main sources of supplying bioenergy in Bangladesh. According to Sustainable and Renewable Energy Development Authority (SREDA), The average rural household in Bangladesh meets about 42% of its biomass fuel demand from wood fuels, 37% from crop residues, and 21% from animal dung [NACOM, 2019].
The SREDA report also states that the demand for biomass fuels in rural Bangladesh is expected to increase by 25% by 2041. This is due to a number of factors, including population growth, urbanization, and changes in cooking practices.

CHAPTER 2
LITERATURE REVIEW

2.1 Electricity Generation from Biogas: An Overview

Biogas can be used to generate electricity through various technologies and prime movers such as gas and steam turbines, diesel engines, fuel cells, and direct conversion in engines. Diverse conversion methods like gas and steam turbines, diesel engines, fuel cells, and direct engine conversion, offering insights into the technical aspects of biogas-driven electricity generation [Kabeyi and Olanrewaju, 2022]. Electrical Power Generation From Biogas Upgrading [Smith et al., 2022] delves into the critical biogas upgrading process, highlighting its significance in producing high-purity methane for electric generators. Use of Biogas for Electricity-Driven Appliances [Davarpanah, 2022] explores various renewable energy systems employed for electricity generation from biogas, including micro-gas turbines, combined heat and power systems, solid oxide fuel cells, and organic Rankine cycle systems, and addresses environmental considerations. Environmental Assessment of the Life Cycle of Electricity Generation from Biogas in Polish Conditions [Samson-Bręk et al., 2022] evaluates the environmental impact of biogas-based electricity generation in a specific context, shedding light on its environmental benefits and challenges. Green Electricity Generation from Biogas of Cattle Manure [Arshad et al., 2022] likely investigates the feasibility and potential of generating green electricity from cattle manure-derived biogas in Pakistan, potentially providing practical insights into biogas utilization. Experimental and Simulation Analysis of Biogas Production from Beverage Wastewater Sludge for Electricity Generation involves experimental and simulation analysis of biogas production from beverage wastewater sludge for electricity generation, offering valuable data on wastewater-derived biogas [Admasu et al., 2022]. The quality and quantity of biogas for small-scale electricity generation in off-grid settings is evaluated [Wasajja et al., 2021], providing practical insights into optimizing biogas systems for remote electricity production. These papers collectively contribute to a deeper understanding of biogas-based electricity generation, encompassing technical, environmental, and practical aspects, making them valuable resources for researchers and policymakers in the field.

2.2 Electricity Generation and Biogas in Bangladesh

The current discussion centers on the promising prospects of biogas production from diverse waste streams in Bangladesh, with particular emphasis on the country's potential to harness biogas from various sources, such as livestock and poultry waste, as an efficient means of sustainable energy generation [Parvez et al., 2023]. This theme is further developed by quantifying the substantial role that crop residues could play in enhancing energy security in Bangladesh. The potential to produce a staggering 42.560 TWh of electricity could greatly reduce the nation's reliance on natural gas for energy generation [Anand et al., 2021]. However, the adoption and impact of biogas technology suggest a complex relationship with poverty alleviation, without explicitly addressing electricity generation [Siddiki et al., 2021]. Theoretical calculations estimate that Bangladesh could produce a substantial 27,923.72 million m3/year of biogas from animal waste, highlighting its potential to mitigate greenhouse gas emissions and meet energy demands [Siddiki et al., 2021]. In terms of the urban environment, there is untapped biogas potential in Dhaka's slaughterhouse waste, estimating an annual generation of 2.15 Mm3 of biogas, which could serve as an innovative approach to both urban waste management and energy generation [Salehin et al., 2021].

Despite these advancements, Bangladesh's energy sector continues to face numerous challenges. The country is primarily reliant on fossil fuels, and its struggle to make substantial strides in renewable energy is evident, with only 1.23% of electricity generation originating from renewable sources [Bhuiyan et al., 2021]. However, a feasibility study advocates for biogas as a viable solution to meet energy needs in rural Bangladesh, albeit without delving into its role in electricity generation [Salam et al., 2020]. The drivers and barriers to implementing biogas technologies in the country are discussed in [Hasan et al., 2020]. An innovative "union-based biogas plant model" for electricity generation is introduced, but the specific challenges associated with its implementation are left unexplored [Zaman et al., 2019]. Finally, the potential of biogas technology adoption to enhance rural energy access and reduce fossil fuel dependency in Bangladesh is emphasized in [Sarker et al., 2020].

2.3 Key Challenges

The successful implementation of biogas-based electricity generation faces various challenges that impede progress. Inadequate infrastructures, insufficient capital, and inappropriate policy pose significant barriers to the widespread adoption of this technology [Patinvoh and Taherzadeh, 2019]. Moreover, biogas technology implementation requires advancement at all levels, including small-scale to large-scale implementation for energy generation, electricity generation, and transportation [Freitas et al., 2022]. Policy, funding, technical services, sustainability, awareness, and education are also critical factors in realizing the full potential of biogas in developing countries [Mensah et al., 2021]. The use of co-substrates and additives in the digestion process can also have significant environmental impacts, mainly due to the use of fossil fuels in the production chain [Zaman et al., 2019]. Additionally, the economic viability of biogas projects can be a challenge due to high implementation costs, requiring a mandatory energy rate to ensure a return on investment. Therefore, addressing these challenges through technical training, policy enforcement, public-private partnerships, record keeping, and advertisement of biogas programs can enhance biogas implementation and reduce the obstacles that hinder progress [Arshad et al., 2018].

2.4 Environmental and Sustainability Implications

he generation of electricity based on biogas has notable implications for both sustainability and the environment. This method provides a renewable means of producing electricity, which in turn reduces reliance on fossil fuels and decreases CO_2 emissions and energy consumption when compared to diesel-based electricity production [de Miranda and Kulay, 2023]. The conversion of biogas to electricity can be accomplished through a variety of technologies and prime movers, including gas and steam turbines, diesel engines, and fuel cells [Kabeyi and Olanrewaju, 2022]. Nevertheless, the use of co-substrates and additives in biogas production can have significant environmental impacts, especially with regards to the utilization of fossil fuels throughout the production chain [Freitas et al., 2022]. Life cycle analysis has indicated that the use of waste materials from the agricultural and agri-food industries as substrates for biogas production brings about environmental benefits, particularly in terms of human health and resources categories [Samson-Bręk et al., 2022]. Bio-gas generation from waste water [Admasu et al., 2022] is also an effective and sustainable model for electricity generation from bio-gas. In order to minimize the environmental impact of biogas-based electricity generation, it is essential to assess and optimize the biogas conversion technologies and take into account the emissions associated with the process [Davarpanah, 2022].

CHAPTER 3
BIOMASS RESOURCES AND USE IN BIO-GAS

3.1 Biomass Resources

Biomass resources for biogas, also referred to as anaerobic digestion feedstock or biogas feedstock, include various categories of organic materials. Biogas can be produced from various organic substrates, which all are in general suitable for anaerobic digestion. In Bangladesh, three major types of biomass fuel resources are in use: wood fuels, agricultural residues and animal dung. Wood fuels are obtained from different types of forests and tree resources grown in rural areas. Agricultural residues and animal dung contribute a substantial portion of biomass fuel in Bangladesh. A part of the total agricultural residues available during harvesting of crops and a part of total animal dung produced by animal resources are used as fuel [Islam, 2023].

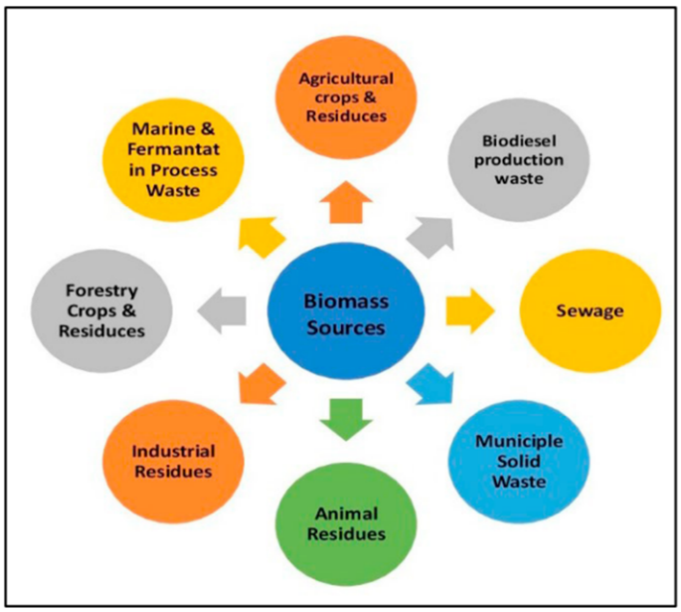

Figure 3.1: Biomass resources.

3.2 Biomass Feedstock

Biomass feedstocks include dedicated energy crops, agricultural crop residues, forestry residues, algae, wood processing residues, municipal waste, and wet waste (crop wastes, forest residues, purpose-grown grasses, woody energy crops, algae, industrial wastes, sorted municipal solid waste [MSW], urban wood waste, and food waste [Office of Energy Efficiency Renewable Energy, 2020].

1. **Ageiculural Crop Residue:** There are many opportunities to leverage agricultural resources on existing lands without interfering with the production of food, feed, fiber, or forest products. This includes agricultural waste products such as straw, husks, and stalks. Crop residues are a good source of biomass for biogas production, as they are relatively inexpensive and abundant [Office of Energy Efficiency Renewable Energy, 2020].

2. **Forestry Residues**: Forest biomass feedstocks fall into one of two categories: forest residues left after logging timber (including limbs, tops, and culled trees and tree components that would be

otherwise unmerchantable) or whole-tree biomass harvested explicitly for biomass. Dead, diseased, poorly formed, and other unmerchantable trees are often left in the woods following timber harvest. This woody debris can be collected for use in bioenergy [Office of Energy Efficiency Renewable Energy, 2020].

3. **Wood Processing Residues**: Wood processing yields byproducts and waste streams that are collectively called wood processing residues and have significant energy potential. For example, the processing of wood for products or pulp produces unused sawdust, bark, branches, and leaves/needles. These residues can then be converted into biofuels or bioproducts [Office of Energy Efficiency Renewable Energy, 2020].

4. **Animal manure and slurry**: This is the most common feedstock for biogas production, as it is readily available and has a high methane content. Manure and slurry can be collected from farms, slaughterhouses, and other livestock facilities. Bangladesh is an agricultural country and has a huge potentiality for energy production using animal manure. Animal manure contains a high amount of aerobic (carbon dioxide) and anaerobic (methane, carbon dioxide gas) constituents [Biosantech et al., 2013, Uddin et al., 2019].

5. **Energy crops**: These are crops that are grown specifically for biogas production. Energy crops include corn, sorghum, switchgrass, and miscanthus. Energy crops can have a higher methane yield than other biomass feedstocks, but they can also be more expensive to grow and harvest [Office of Energy Efficiency Renewable Energy, 2020].

6. **Food waste**: This includes food scraps, fruit and vegetable peels, and other organic waste from restaurants, grocery stores, and homes. Food waste can be a valuable feedstock for biogas production, as it can help to reduce food waste and greenhouse gas emissions [Zbiciak and Markiewicz, 2023].

7. **Industrial waste**: This includes waste from food processing, beverage production, and other industries. Industrial waste can be a good source of biomass for biogas production, as it can be relatively high in methane content [Biosantech et al., 2013].

8. **Algae**: Algae is a type of biomass that can be grown in water. Algae can be a good source of biomass for biogas production, as it has a high methane yield and can be grown in a variety of conditions [Office of Energy Efficiency Renewable Energy, 2020].

According to the International Energy Agency (IEA), the total supply of biomass in Bangladesh in 2023 is estimated to be 122.2 million tonnes of oil equivalent (Mtoe). This accounts for about 80% of the country's total primary energy supply. The main sources of biomass in Bangladesh are agricultural residues, wood, and animal waste [IEA, 2023]. Table 3.1 presents potential biogas yields of feedstock commonly used in anaerobic digestion.

The following are the sources and estimated supply of biomass in Bangladesh in 2023:

- Agricultural residues: 87.5 Mtoe (72%)
  - Rice husk
  - Straw
  - Bagasse
  - Coconut husk
  - Jute sticks

- Wood: 21.7 Mtoe (18%)
- Animal waste: 13 Mtoe (10%)
  - Cow dung
  - Poultry manure
  - Pig manure

Feedstock	Biogas Yield (m^3/t)	Feedstock	Biogas Yield (m^3/t)
Cattle slurry	15-25(10 % DM)	Potatoes	276-400
Pig slurry	15-25(8 % DM)	Rye grain	283-492
Poultry	30-100(20 % DM)	Clove grass	290-390
Grass silage	160-200(28 % DM)	Sorghum	295-372
Whole wheat crop	185(33 % DM)	Grass	298-467
Maize silage	200-220(33 % DM)	Red clover	300-350
Maize grain	560(80 % DM)	Jerusalem artichoke	300-370
Crude glycerine	580-1000(80 % DM)	Turnip	314
Wheat grain	610(85 % DM)	Rhubarb	320-490
Rape meal	620(90 % DM)	Triticale	337-555
Fats	Up to 1200	Oilseed rape	340
Nettle	120-420	Canary grass	340-500
Sunflower	154-400	Alfalfa	340-500
Miscanthus	179-218	Clover	345-350
Flax	212	Barley	353-658
Sudan grass	213-303	Hemp	355-409
Sugar beet	236-381	Wheat grain	384-426
Kale	240-334	Peas	390
Straw	242-324	Ryegrass	390-410
Oats grain	250-295	Leaves	417-453
Chaff	270-316	Fodder beet	160-180

Table 3.1: Potential biogas yields of feedstock commonly used in anaerobic digestion

3.3 Biomass Use

In bangladesh Biomass fuels is mainly used for domestic cooking, whereas it is partly used for other purposes. A study showed that biomass fuel is used more frequently as the cooking fuel in rural households than any other form of commercial fuel. The study also revealed that above 97% of biomass fuel is used for domestic cooking and 0.87% used for paddy parboiling [Zbiciak and Markiewicz, 2023]. Whereas, Another study found 92% of households use biomass for cooking, followed by rice parboiling and water heating [**?**]. Here are some of the additional key uses of biomass:

1. **Fuel**: Biomass can be burned directly to produce heat or converted into liquid or gaseous fuels, such as ethanol, biodiesel, and biogas. These fuels can be used to power vehicles, generate electricity, and heat homes and businesses [EIA, 2023].
2. **Electricity generation**: Biomass can be used to generate electricity in a variety of ways, including direct combustion, gasification, and pyrolysis. Direct combustion is the simplest method and involves burning biomass in a boiler to produce steam. Gasification and pyrolysis are more complex processes that convert biomass into gaseous fuels that can be used to generate electricity in a turbine [EIA, 2023].
3. **Heat production**: Biomass can be used to produce heat for a variety of purposes, such as space heating, water heating, and industrial process heat. Direct combustion is the most common method for producing heat from biomass.

4. **Materials**: Biomass can be used to produce a variety of materials, including paper, plastics, and textiles. It can also be used to make construction materials, such as lumber and bricks.

5. **Chemicals**: Biomass can be used to produce a variety of chemicals, including ethanol, biodiesel, and biopolymers. These chemicals can be used in a variety of products, such as fuels, plastics, and pharmaceuticals [EIA, 2023].

6. **Other uses**: Biomass can also be used for a variety of other purposes, such as composting, land reclamation, and water purification.

Biomass provided 25% of the primary energy in Bangladesh in 2022. This is the highest share of any renewable energy source in the country [Islam, 2023, NACOM, 2019]. Here are some of the biomass uses in Bangladesh:

1. **Cooking**: Biomass is the main source of cooking fuel in Bangladesh, accounting for over 90% of the total cooking energy consumption. It is used to cook food in both rural and urban areas. The most common biomass fuels used for cooking are firewood, crop residues, and animal dung [Huda et al., 2014].

2. **Power generation**: Biomass can be used to generate electricity. This can be done through a variety of technologies, such as biogas plants, biomass-fired power plants, and micro-grids [Mosaddek Hossen et al., 2017].

3. **Fertilizer**: Biomass can also be used to produce fertilizer. This is done by anaerobic digestion, which converts biomass into biogas and digestate. The digestate can then be used as a fertilizer [Wazed and Islam, 2011].

4. **Industrial applications**: Biomass can also be used in a variety of industrial applications, such as brick making, paper production, and the production of bioethanol and biogas [Khan and Shamsuzzaman, 2022].

3.4 Biogas and Its Composition

Biogas constitutes a flammable blend of gases, with its primary constituents being methane (CH_4) and carbon dioxide (CO_2). It emerges as a result of the anaerobic bacterial breakdown of organic matter in the absence of oxygen. These decomposer microorganisms produce these gases as byproducts during their respiration process. The specific gas composition varies depending on the materials undergoing decomposition. Biogas shares similar combustion properties with natural gas and is approximately 20% lighter than air. Its calorific value falls within the range of 5000 to 7000 kcal per cubic meter. When used in a conventional biogas stove, it typically achieves an efficiency rate of around 60%. Detailed composition of biogas is given in Table 3.2.

Components	Percentage
Methane (CH_4)	$60 - 70$
Carbon dioxide (CO_2)	$30 - 40$
Hydrogen (H_2)	$2 - 2.5$
Nitrogen (N_2)	$1 - 1.5$
Oxygen (O_2)	$0.3 - 0.4$
Hydrogen Sulfide (H_2 S)	$0.1 - 0.2$

Table 3.2: Biogas and Its Composition

CHAPTER 4
HISTORY OF BIO-GAS GROWTH IN BANGLADESH

In recent years, there has been a significant expansion in the growth of biogas in Bangladesh. This upsurge can be attributed to the proactive policies and incentives implemented by the government, as well as an increasing awareness of the environmental benefits of this technology across rural areas. By installing over a million biogas plants, predominantly in households and farms, the country has effectively addressed energy access challenges, reduced its dependence on firewood and fossil fuels, and minimized indoor air pollution. This sustainable energy source has not only improved the quality of life for rural communities but has also contributed to the mitigation of climate change and the promotion of sustainable agricultural practices in Bangladesh.

4.1 Timeline of Bio-gas growth in Bangladesh

This year-wise history highlights the gradual growth of biogas technology in Bangladesh and its transformation into a vital source of clean energy and rural development over the past several decades.

- **1970s - Pioneering Efforts:**
  - 1972: Dr. M. A. Karim, a professor at Bangladesh Agricultural University (BAU), Mymensingh, set up the first biogas plant at the university campus. It was a floating-dome type plant with a $3m^3$ gas production capacity.
  - 1974: Another significant milestone was achieved when a biogas plant was constructed at the Bangladesh Academy for Rural Development (BARD) in Comilla. This demonstrated the technology's potential to provide sustainable energy solutions in rural areas.
  - 1976: The International Foundation for Research and Development (IFRD) contributed to biogas development by constructing a family-size biogas plant at the Bangladesh Council of Scientific and Industrial Research (BCSIR) campus in Dhanmondi [Gofran, 2007].
- **1980s: Slow Growth and Collaboration:**
  - The 1980s witness the gradual growth of biogas technology in Bangladesh, although the pace is hindered by challenges such as high construction costs and a lack of subsidies. Nevertheless, efforts continue to promote sustainable energy solutions.
  - 1986: The Local Government Engineering Department (LGED) contributes to biogas adoption by constructing its first floating-dome model biogas plant in Kurigram district. This initiative aims to address energy scarcity in rural areas [Chy, 2017].
- **1990s - Biogas Initiatives Expand:**
  - 1992: A pivotal moment occurs with the establishment of the Bangladesh Biogas Development Foundation (BBDF). This organization plays a vital role in creating awareness, providing training, and offering financial support to rural communities, fostering a culture of sustainable energy practices.
  - 1993: Memoranda of Understanding (MoUs) are signed between BCSIR, LGED, and the Department of Livestock (DLS), enhancing collaboration and coordination in biogas research, training, and dissemination efforts. These MoUs facilitate the exchange of knowledge and resources, accelerating biogas adoption.

- 1994: LGED supports the creation of an ecological village, Amgram, in Madaripur district, where 15 domestic biogas plants are installed using various organic materials, showcasing the versatility of biogas technology. This initiative not only provides clean energy but also demonstrates the sustainable use of bio-slurry in agriculture, further promoting biogas adoption.
- 1997: Infrastructure Development Company Limited (IDCOL) is established on May 14, 1997, by the Government of Bangladesh. IDCOL focuses on bridging the financing gap for medium to large-scale infrastructure and renewable energy projects, playing a significant role in advancing biogas technology and other sustainable energy solutions in the country [BSERT, 2018].

- **2000s - Rural Electrification Through Biogas:**
  - The significant expansion of biogas-to-electricity initiatives began in the early 2000s. Organizations and government agencies like the Infrastructure Development Company Limited (IDCOL) and Grameen Shakti took the lead in promoting the use of biogas for electricity generation in rural areas.
  - 2004 - IDCOL's Biogas Program: In 2004, IDCOL initiated a Biogas Program that aimed to provide electricity to rural households using biogas. This program focused on installing biogas plants equipped with electricity generation capabilities. It marked a crucial turning point in bringing electricity to off-grid communities.
  - 2008 - IDCOL's Solar Home System Integration: IDCOL integrated biogas electricity generation with solar home systems in 2008. This integration allowed rural households to have a more reliable and continuous supply of electricity by utilizing both solar and biogas energy sources.
- **2010s - Scaling Up Biogas Initiatives:**
  - 2010: IDCOL launches the "Renewable Energy for Rural Livelihoods" project, aiming to install 4,000 biogas plants with electricity generation capabilities, contributing to both clean cooking fuel and electricity for rural households.
  - 2015: The government of Bangladesh declares its commitment to achieving a 10% share of renewable energy in the national energy mix by 2021.
- **2020s: Advancements and Sustainability:**
  - Bangladesh made significant progress by converting biogas into electricity, enhancing technology, and connecting it to the power grid.
  - Bangladesh remained committed to biogas and sustainable energy in the 2020s, with the successful IDCOL Biogas Program serving as a model for other countries interested in renewable energy. Biogas gained popularity across the nation, benefiting rural areas, reducing pollution, and addressing climate change.

To summarize, Bangladesh's journey with biogas reflects their dedication to a cleaner and more sustainable energy future, aiming to improve people's lives and safeguard the environment for future generations.

CHAPTER 5
SUSTAINABLE BIOGAS PROCESSING

The growing concerns over the depletion of fossil fuels, energy security considerations, and concern over global warming, the world started taking a significant interest in renewable energy sources like biogas. The production of biogas from different biomass sources can actively involve farmers and institutions that deal with biomass in the worldwide shift toward sustainable energy. Hence, biogas presents a business opportunity for both farmers and those dealing with biomass waste. Utilizing locally available materials can boost the local industry, similar to the way homemade bricks, which are abundant and cost-effective, have become widely used. Furthermore, there are potential business prospects associated with the large-scale production and servicing of biogas plants and related equipment to support the growing biogas sector. As the demand for biogas facilities increases, there will be a market need for biogas-powered generators, gas valves and fixtures, gas pipelines, and various other small devices. To meet these demands, manufacturing companies will produce a variety of appliances for distribution to biogas producers. Additionally, companies specializing in plastic tank manufacturing can explore the development of user-friendly and cost-effective biogas plastic tanks, which can be buried in the ground like conventional biogas plants [Hahn, 2015]. The establishment of manufacturing standards for these tanks would ensure their suitability for widespread use and application. Figure 5.1 shows a simple ar-

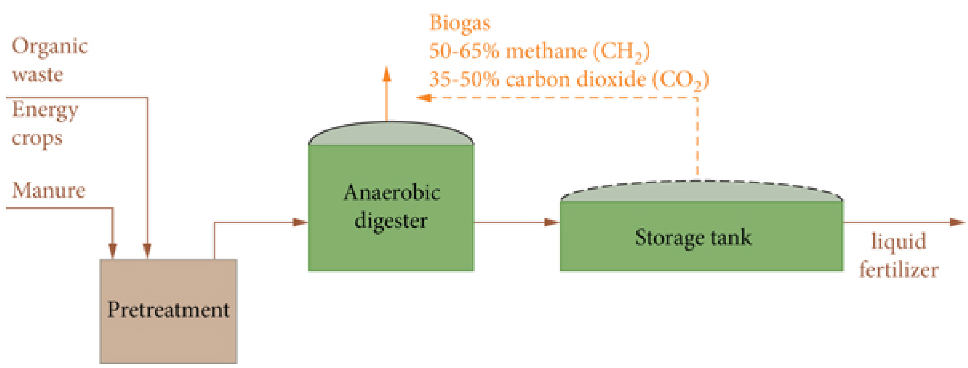

Figure 5.1: Biogas and fertilizer production

rangement where smallholder producers can generate biogas and fertilizer through anaerobic digestion. While the configuration is straightforward and cost-effective, its sustainability might be compromised by its restricted usage and its connection to the agricultural processes that provide organic materials. To ensure sustainability at the household level, it is essential to broaden the range of applications for biogas and diversify the sources of organic materials for biodigester [Kabeyi and Olanrewaju, 2022].
A diversified and more sustainable biogas system is demonstrated in Figure 5.2. It demonstrates a more diversified biogas system connecting upstream and downstream activities.This approach increases the diversity and sustainability of biogas systems, as all household activities are directly or indirectly linked to these systems, thereby significantly boosting their overall sustainability [Barasa Kabeyi and Olanrewaju, 2022]. Figure 5.2 illustrates the primary components necessary for a farm-level biogas system. These components include the biomass substrate source (comprising farm animal waste and plant waste), the gas storage system, the lighting and electricity generation system, and the fertilizer supply system, all interconnected with the biogas plant.

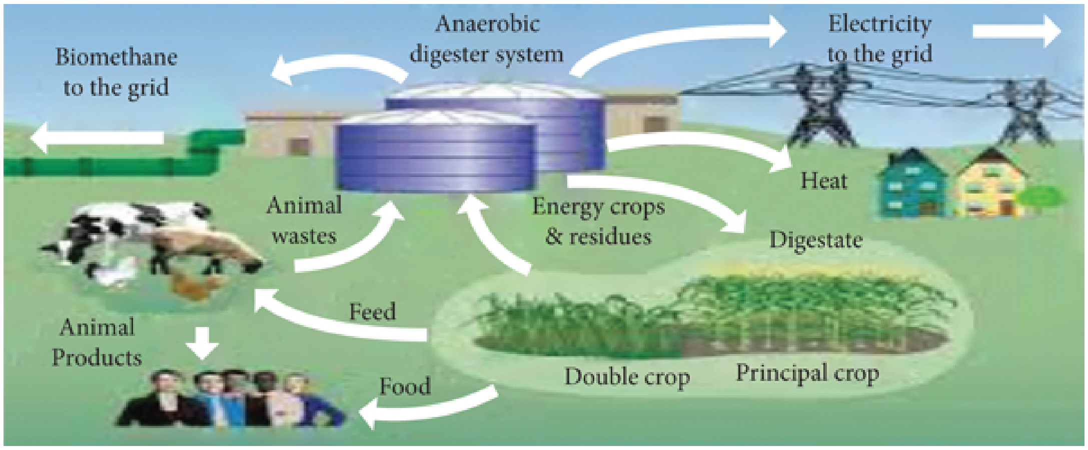

Figure 5.2: Diversified biogas production with fertilizer, lighting, and electricity applications

5.1 Biogas Generation and Processing

Basically Biogas is produced through the anaerobic activity of specific bacteria, under specific conditions. It serves as an environmentally friendly energy source, with a calorific value ranging from 21 to 24MJ/m3. In natural decomposition processes without regulation, organic matter naturally undergoes anaerobic biodegradation, releasing around 590–800 million tons of methane into the atmosphere. Conversely, biogas recovery systems use controlled conditions to decompose biomass, generating biogas for energy applications. Typically, biogas contains 50–70 % methane and 30–50 % carbon dioxide, with the exact composition influenced by the type of organic material used and the management of the process. Other elements like hydrogen sulfide and nitrogen may also be present. In larger biogas facilities, it's possible to enhance the biogas before it's supplied to gas networks. Anaerobic digesters are generally designed to operate within either the mesophilic temperature range (20–40°C) or the thermophilic temperature range (above 40°C) [Maria et al., 2023]. Some steps involved in biogas are given below:

Feedstock Preparation. Organic materials are collected and prepared as the feedstock for anaerobic digestion. This can include a variety of materials like manure, crop residues, kitchen waste, and wastewater sludge. It's crucial to ensure that the feedstock is well-prepared, with contaminants like plastics and non-organic materials removed.

Loading the Digestion System. The prepared organic feedstock is loaded into an anaerobic digester. This digester is typically a sealed, oxygen-free container or tank where the anaerobic microorganisms will carry out the digestion process.

Anaerobic Digestion Process.

1. **Hydrolysis:** In the initial phase of anaerobic digestion, complex organic compounds are broken down into simpler molecules through a process called hydrolysis. Enzymes secreted by microorganisms facilitate this breakdown, converting carbohydrates, proteins, and lipids into sugars, amino acids, and fatty acids.

2. **Acidogenesis:** The products of hydrolysis are then further broken down into volatile fatty acids (VFAs) during the acidogenesis stage. This step is characterized by the production of organic acids, hydrogen (H2), and carbon dioxide (CO2).

3. **Acetogenesis:** : In the acetogenesis phase, VFAs are converted into acetic acid, hydrogen, and CO2 by specific groups of microorganisms known as acetogens.

4. **Methanogenesis:** The final and most critical step is methanogenesis, where methane-producing archaea, known as methanogens, convert the products of the previous stages (acetic acid, hydrogen, and CO2) into methane (CH4). This methane is the primary component of biogas and can be captured for various applications [Karlsson et al., 2015].

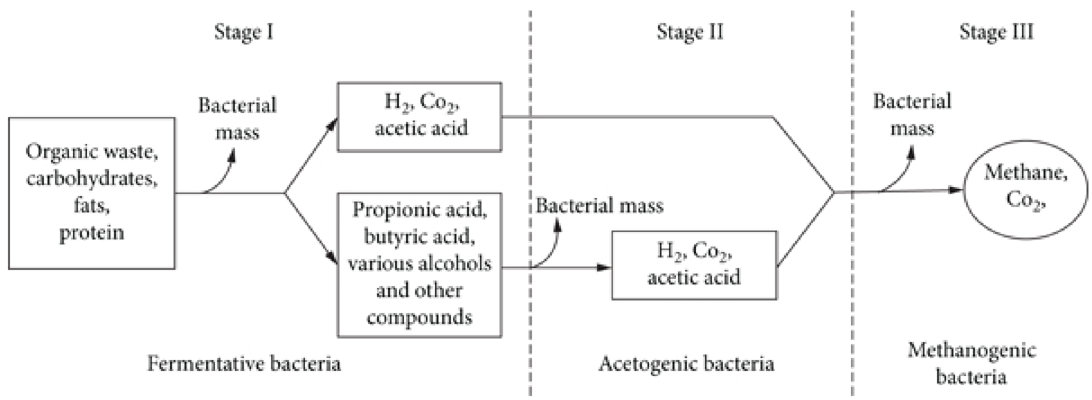

Figure 5.3: Summarizes the process into three stages with hydrolysis and acidogenesis combined [Eggeling and Sasse, 1986]

Biogas Collection. Biogas produced during methanogenesis accumulates in the digester's headspace or a separate collection system, where it can be collected and stored.

Gas Utilization. The collected biogas can be utilized for various purposes, such as electricity generation, heating, or as a fuel source for vehicles. It can also be upgraded and purified to increase its methane content for injection into natural gas pipelines.

Digestate Handling. After the digestion process is complete, the remaining solid material, known as digestate, is rich in nutrients and can be used as a fertilizer or soil conditioner.

Sustainable biogas processing is of utmost importance in tackling the current environmental and energy challenges. This process involves utilizing organic waste materials, including agricultural residues, sewage, and food scraps, and transforming them into biogas through anaerobic digestion. The outcome of this process not only helps in mitigating greenhouse gas emissions but also provides a renewable source of energy. Biogas produced can be put to various uses such as generating electricity, heating, and functioning as a clean fuel for transportation. This, in turn, reduces our dependence on fossil fuels and helps in promoting a circular economy. Additionally, the byproduct of nutrient-rich digestate can be utilized as an organic fertilizer, thus, closing the nutrient loop and enhancing soil health. Therefore, sustainable biogas processing is a critical step towards creating a more sustainable and greener future by tackling waste management, energy production, and agricultural sustainability simultaneously.

CHAPTER 6
EXPLORING ELECTRICITY GENERATION POSSIBILITIES

The use of biogas for electricity generation is still relatively new on a global scale, but it's more prevalent in industrialized nations. As the environmental consequences of fossil fuels become increasingly apparent, the utilization of biogas for electricity production is gaining traction. This includes its use in various capacities with gas turbines and as a fuel source for internal combustion engines, sparking growing interest and adoption [V. Quaschning, 2019].

An extensive study on the application of biogas systems proposes that the use of biogas can be divided into four subgroups according to its ultimate purpose, which are [Hakawati et al., 2017]:

1. Electricity generation from power plants, CHP units, and fuel cells.
2. Production of heat using a boiler
3. Heat from power plants, CHP systems, and fuel cells.
4. Transportation fuel via internal combustion engines (for ICE vehicles), and electricity station (for electric vehicles).

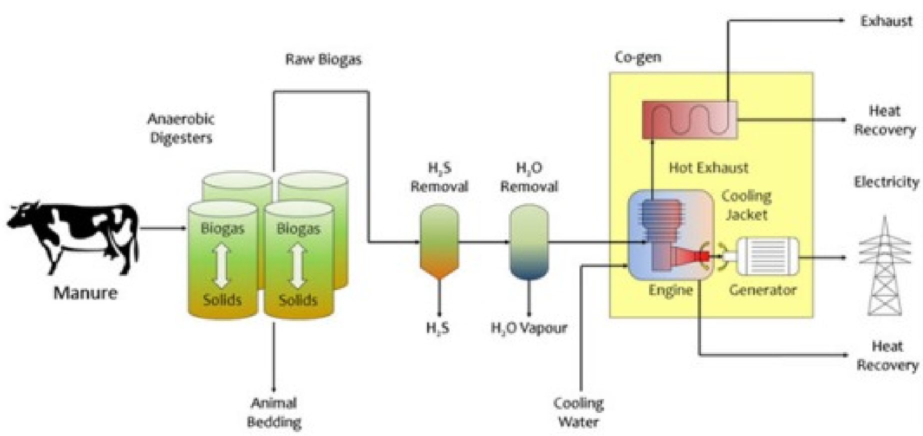

Figure 6.1: Electricity Generation from Biogas: A General Overview.

6.1 Micro Gas Turbine System

A micro gas turbine system is a type of electricity generator that can be used to convert biogas into electricity. A micro gas turbine system can be used to generate electricity from biogas by converting the chemical energy in the biogas into mechanical energy, which is then used to drive an electrical generator. The efficiency of this process can vary depending on factors such as the composition of the biogas and the power load of the generator.

The feed biogas for the micro gas turbine electricity generator primarily consists of CH_4, H_2S, H_2, and CO_2. Figure 6.4 illustrates the entire process of converting biogas into electricity, which involves desulfurization, drying, compression, combustion, and the actual generation of electricity. The commonly used micro gas turbine electricity generator is the CR-30 model, which has a maximum rated power load (PWL) of 30 kW. This micro gas turbine, with dimensions measuring 0.76 meters in width, 1.5 meters in depth, and 1.8 meters in height, primarily comprises a compressor, a combustion chamber, and a turbine. In this system, air is drawn into the turbine and compressed into high-pressure gas (with a range of 379–414 kPa gauge) by the compressor. This high-pressure gas is then mixed with fuel and ignited in the combustion chamber. The resulting high-temperature gas, which reaches approximately 275°C, flows at a rate of 0.31 kg/s and exerts force to push and rotate the turbine, thereby producing shaft work. This mechanical energy is subsequently used to both sustain the operation of the compressor and generate electricity [Chang et al., 2019].

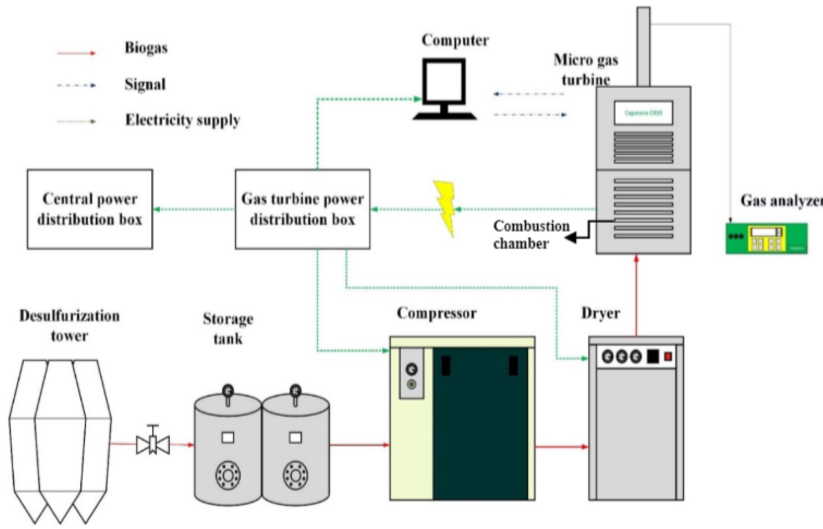

Figure 6.2: The process of biogas application in combination with a CR-30 micro gas turbine electricity generator.

6.2 Fuel Cell

A fuel cell is a device that converts the chemical energy stored in a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent. While hydrogen, often produced from steam methane reforming of natural gas, is the most common fuel used, for improved efficiency, hydrocarbons like natural gas and alcohols such as methanol can also be employed. Unlike batteries, which rely on the chemical components within them to generate electrical energy, fuel cells need a continuous supply of both fuel and oxygen or air to sustain the chemical reaction. As long as these inputs are provided, fuel cells can consistently produce electricity over an extended period [Lucia, 2014].

6.2.1 Parts of A Fuel Cell

- **Anode:** The negative terminal of the fuel cell, known as the cathode, serves as a conduit for the electrons released during the breakdown of hydrogen molecules, allowing them to flow into an external circuit. Within the fuel cell, etched channels distribute hydrogen gas evenly across the catalyst's surface.
- **Cathode:** The positive terminal of the fuel cell, referred to as the anode, facilitates the flow of electrons back from the external circuit to the catalyst. At the anode, these electrons recombine with hydrogen ions and oxygen, resulting in the formation of water. Etched channels within the fuel cell ensure the even distribution of oxygen to the catalyst's surface.
- **Electrolyte:** The proton exchange membrane, often referred to as the PEM, is a specially treated material designed to exclusively conduct positively charged ions (protons). Electrons are effectively obstructed from passing through this membrane.

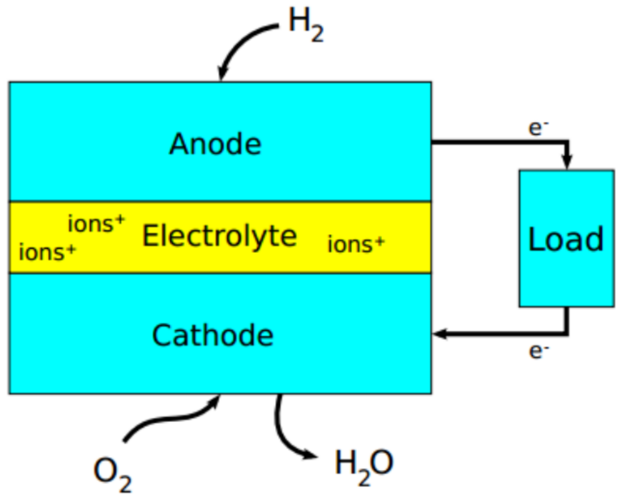

Figure 6.3: Parts of fuel cell

• **Catalyst:** This special material, which facilitates the reaction between oxygen and hydrogen, is typically platinum powder that is extremely thinly coated onto carbon paper or cloth. It possesses a rough and porous structure that maximizes the surface area exposed to hydrogen or oxygen, enhancing the efficiency of the reaction [Carrette et al., 2000].

6.2.2 Fuel Cell Operation

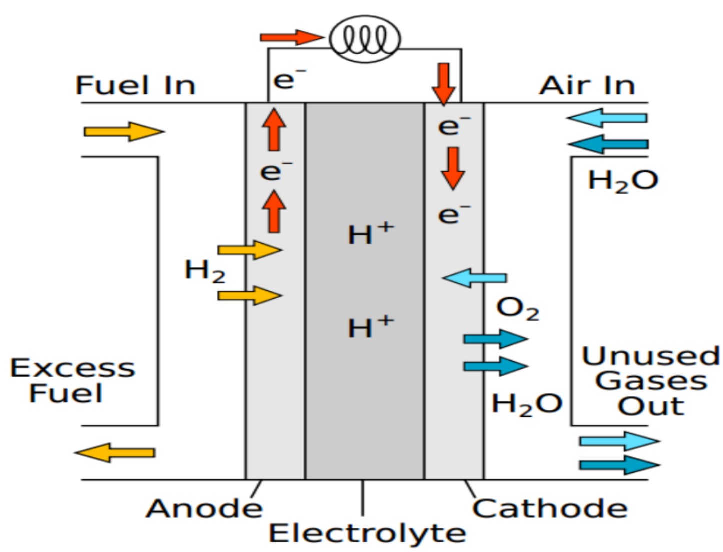

Figure 6.4: Operation of fuel cell

Pressurized hydrogen gas (H_2) enters the cell on anode side. The Gas is forced through the catalyst by pressure.

• When a hydrogen (H_2) molecule comes into contact with a platinum catalyst, it undergoes a chemical reaction in which it splits into two hydrogen ions (H^+) and two electrons (e-).

• Electrons are conducted through the anode.
• These electrons (e-) travel through the external circuit, where they perform useful work, such as powering a motor or other electrical devices. Afterward, they return to the cathode side of the fuel cell to participate in the electrochemical reaction.
• On the cathode side, oxygen gas (O_2) is forced through the catalyst.
• At the cathode side of the fuel cell, each oxygen atom, after receiving two electrons from the external circuit, forms two oxygen atoms, each carrying a strong negative charge. This negative charge attracts two hydrogen ions (H^+) through the membrane. The hydrogen ions combine with an oxygen atom and two electrons from the external circuit to create a water molecule (H_2O) through a chemical reaction [Xu et al., 2022].

6.2.3 Electricity Generation Process

1. **Biogas as Fuel:** Biogas, typically composed of methane (CH_4) and carbon dioxide (CO_2), is used as the fuel source for the fuel cell.

2. **Anode Reaction:** At the anode (the negative electrode) of the fuel cell, the methane in the biogas is oxidized (loses electrons) in the presence of a catalyst. This reaction produces electrons (e-) and hydrogen ions (protons, H^+) [Rivera, 2021]:

$$CH_4 \rightarrow 2H_2 + 2\text{e-} + 2H^+.$$

3. **Electron Flow:** The electrons produced at the anode cannot pass through the electrolyte, so they are forced to flow through an external circuit, creating an electric current.

4. **Proton Transport:** The hydrogen ions (protons) generated at the anode move through a proton-conductive electrolyte material to reach the cathode (the positive electrode). This movement of protons creates a flow of positive charge, which is essential for the functioning of the fuel cell.

5. **Cathode Reaction:** At the cathode, oxygen from the air combines with the electrons that have traveled through the external circuit and the protons that have moved through the electrolyte to produce water (H2O):

$$2H_2 + O_2 \rightarrow 2H_2O.$$

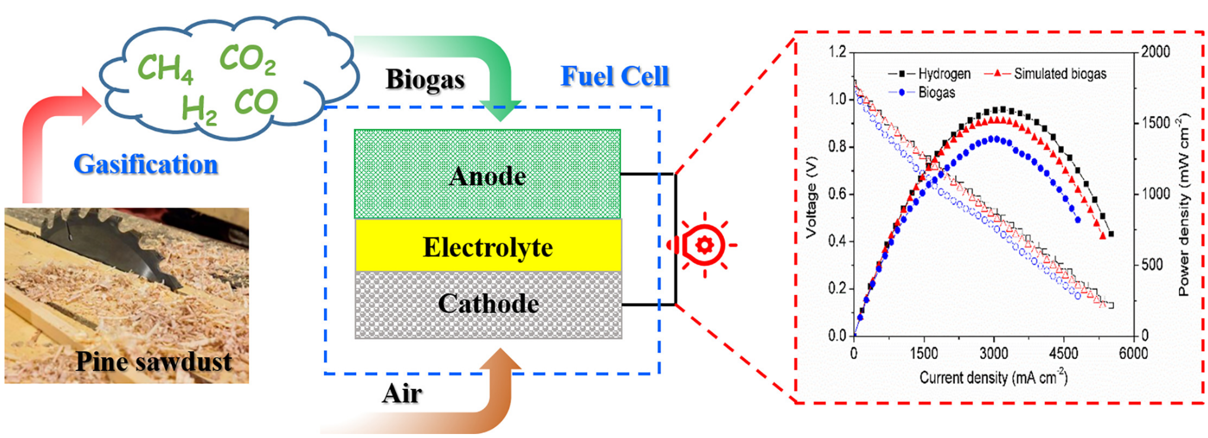

Figure 6.5: Electricity generation

6. **Electricity Generation:** This electrochemical process at the cathode generates electrical energy in the form of a flow of electrons through the external circuit, creating an electric current. This electric current can be harnessed and used as electricity [Kenter and Kenter, 2018].
7. **Waste Products:** The only waste products produced during this process are water vapor (H_2O) and a small amount of heat, making fuel cells highly efficient and environmentally friendly.

6.3 Internal Combustion Engine

An Internal Combustion Engine (ICE or IC engine) is an engine in which the process of fuel combustion occurs within the engine cylinder itself. It is versatile in its ability to utilize various fuels such as gasoline, diesel fuel, hydrogen, methane, and propane gas as its working fluid. The fundamental operation of an internal combustion engine involves compressing a mixture of air and fuel within the engine cylinder. The choice of fuel typically includes gasoline or diesel. Once inside the cylinder, this compressed air-fuel mixture is ignited, which can be achieved either through a spark plug (in the case of gasoline engines) or through compression (common in diesel engines). This ignition process results in a carefully controlled explosion. When the combustion occurs within the engine's combustion chamber, it generates a high-pressure and high-temperature force that acts on the engine piston. This force, in turn, produces useful mechanical work. As the piston is pushed by the force, it moves back and forth within the cylinder, effectively converting the chemical energy stored in the fuel into mechanical energy or power. This mechanical energy is harnessed to propel a vehicle or perform other useful tasks [Kenter and Kenter, 2018].

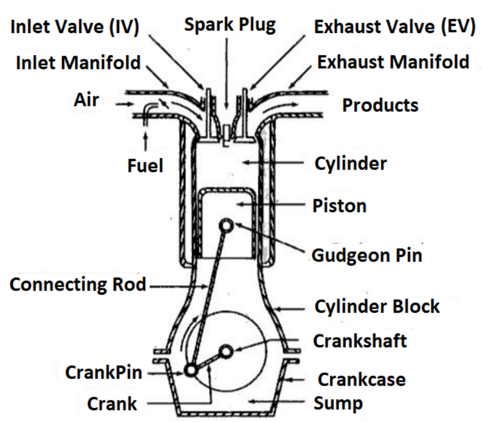

Figure 6.6: Internal Combustion Engine

6.3.1 Working Principle of an IC Engine

An Internal Combustion (IC) engine operates by combusting fuel within the engine itself, during which the engine transforms the thermal energy from the fuel into rotational motion. Key components of an IC engine include a crankshaft, camshaft, reciprocating piston, and a stationary cylinder. The IC engine functions as follows [Gupta, 2016]:

Suction Stroke: To begin, the engine draws in air from the surroundings into the compression cylinder.

Compression Stroke: Following the inhalation phase, the reciprocating piston located within the compression cylinder increases the pressure and temperature of the air. The piston compresses the air to such an extent that when the fuel pump injects fuel and mixes it with the compressed air, the air-fuel blend self-ignites, creating power.

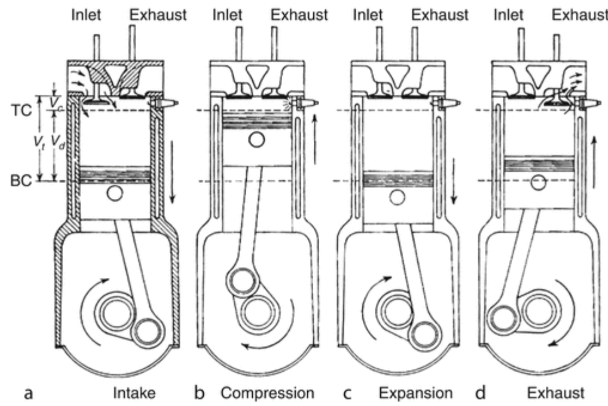

Figure 6.7: Working Principle of IC Engine

Expansion Stroke: The expansion phase commences after the combustion process. During this phase, the combusted air-fuel mixture passes through an expansion valve, causing it to expand. As the air-fuel mixture expands, it propels the piston to move up and down. This piston movement drives the crankshaft, subsequently propelling the vehicle's wheels.

Exhaust Stroke: In this phase, the engine cylinder expels the exhaust gases. After the exhaust gases are discharged, fresh air is introduced, and the entire cycle repeats itself.

6.3.2 Electricity Generation Process

Electricity generation from biogas in an internal combustion engine (ICE) involves the use of biogas as a fuel source to power the engine, which in turn drives an electrical generator. Here's how the process works [Bezerra, 2020]:

1. **Biogas Production:** Biogas is first produced through the anaerobic digestion of organic materials such as agricultural waste, food scraps, or sewage sludge. This biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2), along with trace gases.

2. **Biogas Storage:** Biogas is typically collected and stored in tanks or containers until it is needed for electricity generation.

3. **Fuel Injection:** Biogas is fed into the internal combustion engine's fuel system, which typically includes a carburetor or fuel injector.

4. **Compression:** The engine's piston compresses the biogas-air mixture inside the combustion chamber. This compression raises the temperature and pressure of the mixture, making it more suitable for combustion.

5. **Ignition:** A spark plug or other ignition source is used to ignite the compressed biogas-air mixture within the combustion chamber. The ignition causes a controlled explosion that pushes the piston down, generating mechanical energy.

6. **Mechanical Energy:** As the piston moves downward due to the force generated by the combustion, it turns the engine's crankshaft. This rotational motion is the source of mechanical energy.

7. **Electric Generator:** The mechanical energy from the crankshaft is transferred to an electrical generator. The generator contains coils of wire within a magnetic field. As it rotates, it induces a flow of electrons, creating an electric current.

8. **Electricity Generation:** The electric current produced by the generator is the electricity generated from biogas. It can be used to power electrical devices, charge batteries, or feed into the electrical grid.

9. **Exhaust:** After the combustion process, the exhaust gases, which include water vapor, CO_2, and other byproducts, are expelled from the engine through an exhaust system.

10. **Waste Heat Recovery:** In some applications, the waste heat from the engine can be captured and used for heating or other purposes, improving overall energy efficiency.

    Internal combustion engines can be used for electricity generation from biogas in various settings, from small-scale backup generators for homes and businesses to larger-scale systems for agricultural or industrial applications. They offer flexibility and can efficiently convert biogas into electrical power, making them a viable option for sustainable energy production [Kabeyi and Olanrewaju, 2022].

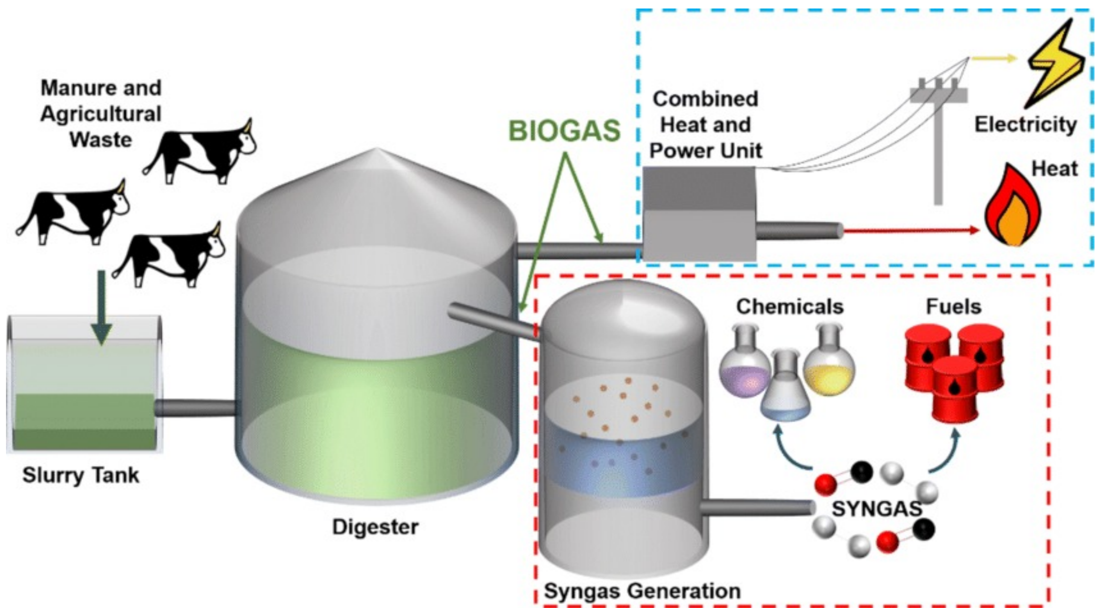

Figure 6.8: Electricity Generation from Biogas: A Brief Overview.

CHAPTER 7
EXPLORING CURRENT BIO GAS TECHNOLOGIES IN BANGLADESH

In 1972, Biogas was first introduced in Bangladesh by Dr. M. A. Karim. Although there have been other plants constructed, the dissemination of biogas has been relatively slow. More than 90 percent of Bangladesh rural households are still using traditional biomass for cooking, which accounts for 50 percent of Bangladesh's total energy supply. The focus of Bangladesh rural household energy policy on improved stoves and cleaner fuels stems largely from a desire to accelerate advancement along an energy ladder and provide households with the benefits of cleaner, more efficient energy, which extends beyond reduction of Indoor Air Pollution (IAP) [BSERT, 2018].

Organization	No. of Biogas plants
Infrastructure Development Company Ltd (IDCOL)	65,224
Local Government Engineering Department (LGED)	46900
Department of Environment	260
Bangladesh Rural Advancement Committee (BRAC)	2850
German Technical Cooperation (GTZ)	2270
Ministry of Youth and Sports	8100
Bangladesh Small & Cottage Industries Corporation	30
Bangladesh Agricultural Development Corporation	20
Danish International Development Agency (DANIDA)	4
Bangladesh Agricultural University	2
Housing & Building Research Institute	2
Bangladesh Academy for Rural Development (BARD)	1
Bangladesh Commission for Christian Development	1
Bangladesh Rice Research Institute	1
Department of Livestock	70

Table 7.1: Biogas plants installed in Bangladesh (till 2022

7.1 Biogas Technology Providers in Bangladesh

Bangladesh, identified as a nation with low energy consumption on a global scale, confronts significant challenges in accessing energy. At present, only 35 percent of the population is connected to the national electricity grid, and a mere 3 percent have access to piped gas services. This lack of access is particularly acute in rural areas, where roughly 97 percent of the population resides, exacerbating the trend of rural-to-urban migration. In rural regions characterized by scattered settlements, centralized grid or piped gas infrastructure is not a feasible solution. As a result, decentralized energy supply systems such as solar, biogas, and wind have emerged as indispensable alternatives to address these energy deficiencies. Table 7.1 contains a list of providers and number of plants developed by them till 2016. No recent data is available from reliable sources.

7.1.1 Local Government Engineering Department (LGED)

LGED is a government-backed village development organization dedicated to improving the lives of rural communities through infrastructure development initiatives. With a strong commitment to national service, the Local Government Engineering Department (LGED) has been actively promoting biogas technology since 1985. As a result of LGED's efforts, successful demonstrations of biogas technology have been carried out at over a thousand sites across diverse regions of Bangladesh [Gofran, 2007]. The organization has taken numerous steps to promote the use of biogas technology in rural areas, including the development of biogas plants and the provision of technical support to farmers. LGED's efforts have also included the establishment of biogas training centers and the distribution of biogas appliances to rural households. The promotion of biogas technology in rural areas has numerous benefits, including improved access to energy, reduced dependence on non-renewable energy sources, and the creation of job opportunities. Additionally, the use of biogas technology can help to mitigate the negative impacts of climate change by reducing greenhouse gas emissions and promoting sustainable agriculture practices. Despite the success of LGED's biogas promotion efforts, challenges remain in scaling up the technology and ensuring its widespread adoption. These challenges include limited funding for biogas projects, a lack of awareness among rural communities about the benefits of biogas technology, and the need for greater technical expertise to support the development of biogas infrastructure.

7.1.2 The Infrastructure Development Company Limited (IDCOL)

IDCOL, a well-known infrastructure financier in the country, holds a notable position as the leading Infrastructure Development Company Limited. The company focuses on providing inclusive financing through various renewable energy and energy-efficient initiatives. Since its inception in 2003 with the Solar Home System program, IDCOL has played a pioneering role in promoting off-grid renewable energy across Bangladesh. The company has now expanded its reach to encompass nationwide projects in solar home systems, domestic biogas, solar irrigation, solar mini-grids, and biomass and biogas-based electricity generation plants.

IDCOL's ability to provide subsidy and concessionary loans has played a vital role in supporting the sustainability of these renewable energy programs and projects. The company also extends assistance in feasibility analysis, training, capacity building, and awareness campaigns to ensure the success of these initiatives. Despite being government-owned, IDCOL operates as a public-private partnership, aiming to foster private sector involvement in infrastructure, renewable energy, and energy-efficient ventures through sustainable public-private initiatives. Notably, IDCOL's involvement in biogas initiatives began in May 2006, with a specific focus on small domestic biogas systems for rural farm households. The company has been instrumental in the development of the National Domestic Biogas and Manure Program (NDBMP), which was officially recognized in May 2010. This program has resulted in approximately 100,000 small household biogas plants, covering 0.4 percent of rural households in the country. IDCOL's efforts have been critical in ensuring that rural households have access to reliable and sustainable sources of energy. The success of these initiatives highlights the importance of public-private partnerships in promoting sustainable development in the country [BSERT, 2018].

IDCOL's Director, S M Formanul Islam, highlights the potential of biogas plants as an effective solution for rural households seeking clean energy for cooking, thereby mitigating indoor pollution. He notes that while the current cost of a biogas plant stands at Taka 35,000, it can be recouped within a three-year timeframe, emphasizing both its environmental benefits and long-term economic viability [Gofran, 2007].

7.1.3 IDCOL's Financial Performance

IDCOL, the Infrastructure Development Company Limited, demonstrated positive financial performance in 2021 and 2022 from their 2022 Annual Report.

Shareholder's Equity. The company's shareholder's equity increased from BDT 10,095 million in 2021 to BDT 10,945 million in 2022. This substantial growth indicates a stronger financial position and underscores IDCOL's ability to accumulate net assets, potentially through retained earnings and capital injections.

Net Profit After Tax. IDCOL's net profit after tax witnessed significant growth, rising from BDT 1,097 million in 2021 to BDT 1,350 million in 2022. This increase suggests improved profitability and effective financial management during this period.

Total Operating Income Profit Before Provision and Tax. The total operating income before provision and tax showed remarkable growth, increasing from BDT 3,977 million in 2021 to BDT 6,988

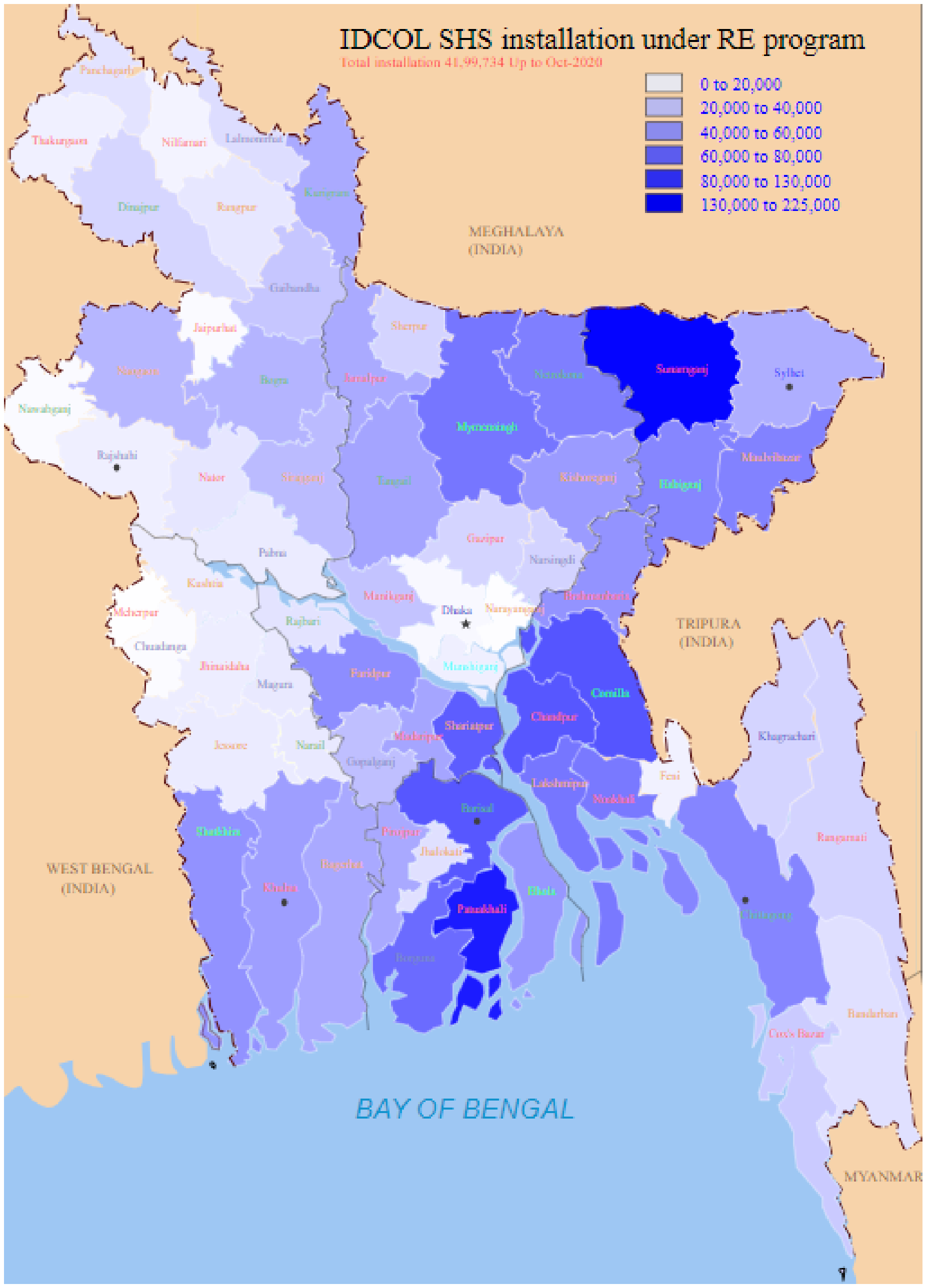

Figure 7.1: Green Energy Setup Map of Bangladesh by IDCOL [IDCOL, 2020].

million in 2022. This surge in operating income points to the successful execution of revenue-generating activities, possibly through project implementations and other income sources.

Total Revenue. Total revenue also experienced substantial growth, rising from BDT 5,291 million in 2021 to BDT 8,877 million in 2022. This indicates that IDCOL's overall earnings increased significantly, potentially due to the expansion of its operations and successful project implementations.

Earnings Per Share (EPS). The Earnings Per Share (EPS) for 2022 increased to 17.13, up from 13.92 in 2021. This rise in EPS is a positive signal for shareholders, as it implies increased earnings attributable to each share, which may lead to higher dividends or a stronger market position.

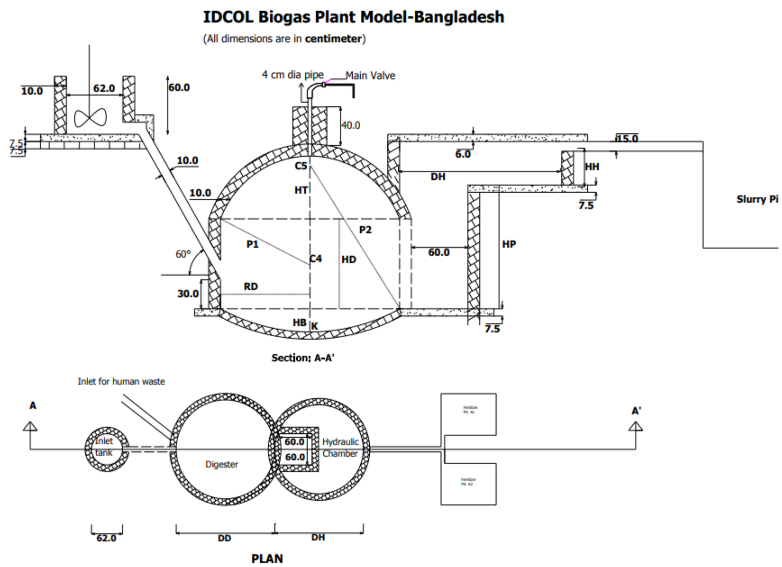

Figure 7.2: IDCOL's Biogas Plant Design.

7.1.4 IDCOL's Development Performance

Infrastructure Development Segment. IDCOL's focus on infrastructure development has significantly contributed to social and economic growth within Bangladesh. Through their initiatives, they have successfully improved the quality of life for citizens, showcasing their commitment to inclusive development. The financial aspect of their performance is equally impressive, with a total loan book of US 1.11 billion in 2022, indicating substantial financial support for crucial infrastructure projects. Additionally, IDCOL's involvement in financing 39 projects and maintaining a Tk. 44.51 billion asset portfolio demonstrates their dedication to developing critical infrastructure. Furthermore, their low Non-Performing Loan (NPL) ratio of 0.23% suggests effective loan management, contributing to the sustainability of these projects.

Infrastructure & PPP Segment. IDCOL's performance in the Infrastructure & PPP segment reflects their commitment to climate action and fostering green, resilient growth through public-private partnerships (PPPs). The remarkable 299% growth in their portfolio from 2017 to 2022 highlights their dedication to these goals. They have also focused on energy efficiency, with a Total Energy Efficiency Portfolio of BDT 1,567 crore and financing for 18 projects involving energy-efficient equipment worth BDT 920 crore. These endeavors align perfectly with global climate objectives and promote sustainable industrialization.

Energy Efficiency Segment. In the Energy Efficiency segment, IDCOL's investments in renewable energy underscore their commitment to climate action and providing affordable, green energy solutions to the public. Their Tk. 1.59 billion Solar Rooftop Program (SRP) portfolio, featuring 40 MW of installed capacity, signifies a substantial contribution to clean energy generation. Additionally, IDCOL's financing of 65,224 biogas plants exemplifies their efforts to improve the quality of life for citizens by providing access to sustainable energy sources. These initiatives contribute significantly to both environmental and societal well-being.

Climate Change Mitigation and Resilience Segment. IDCOL's accreditation as one of the two national Direct Access Entities of the Green Climate Fund highlights their commitment to mitigating and adapting to climate change. Their active role in ensuring climate-resilience and facilitating low-carbon transitions is evident. The prospect of receiving a concessional loan of US 250 million for channelization in

Bangladesh further underscores IDCOL's dedication to advancing climate-resilient, low-carbon solutions that benefit both the environment and the economy.

7.2 Biogas Technology in Bangladesh

There are various technologies available to address the issue of excessive biomass utilization for household energy consumption in rural areas of developing countries, such as solar, wind, hydro power, and tidal power. Each technology's suitability often depends on the availability of natural resources in specific areas. However, many of these technologies face common challenges, including high initial capital costs and a reliance on foreign financing and expertise.

In Bangladesh, a solution that has demonstrated significant usefulness in numerous areas is the use of biogas. Biogas is generated via the anaerobic digestion of organic materials, including kitchen waste, human excreta, cattle manure, wastewater, and agricultural residues. Among the most prevalent biogas plant designs employed in developing countries are small household-based fixed dome models. These plants are cost-effective to construct and can be assembled using locally available materials. Common feedstock for household biogas plants in Bangladesh includes kitchen waste, toilet waste (human excreta), and cattle manure.

Typically, there are three primary types of biogas plant designs utilized in Bangladesh:

- Floating cover digester
- Fixed cover digester
- Plastic-tubular cover digester

These designs cater to different construction and operational requirements, offering flexibility in biogas production for rural households.

7.2.1 Floating cover digester

It operates based on the principle of maintaining constant pressure while varying volume. The digester, typically constructed from brick and cement in a cylindrical shape, is encased with a floating steel cylinder that possesses an open bottom. This steel cylinder maintains a consistent weight, causing it to ascend when gas production exceeds consumption and descend when the opposite scenario occurs.

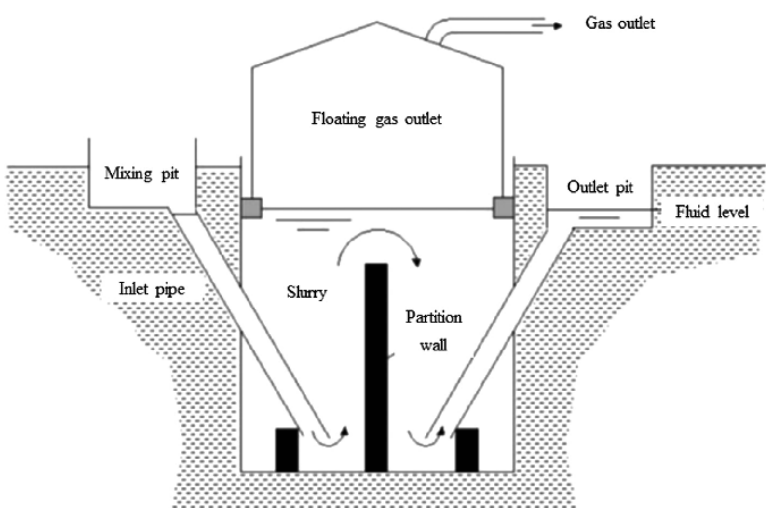

Figure 7.3: Floating cover digester diagram [K C et al., 2014].

Figure 7.4: Floating cover digester in work.

7.2.2 Fixed cover digester

The fixed cover digester, on the other hand, functions according to the principle of maintaining constant volume while altering pressure. When the rate of gas production surpasses gas consumption, the pressure within the digester increases and forces some of the digester contents into the outlet compartment. Conversely, when consumption outpaces production, the pressure inside the digester decreases, allowing the expelled materials in the outlet compartment to return to the digester.

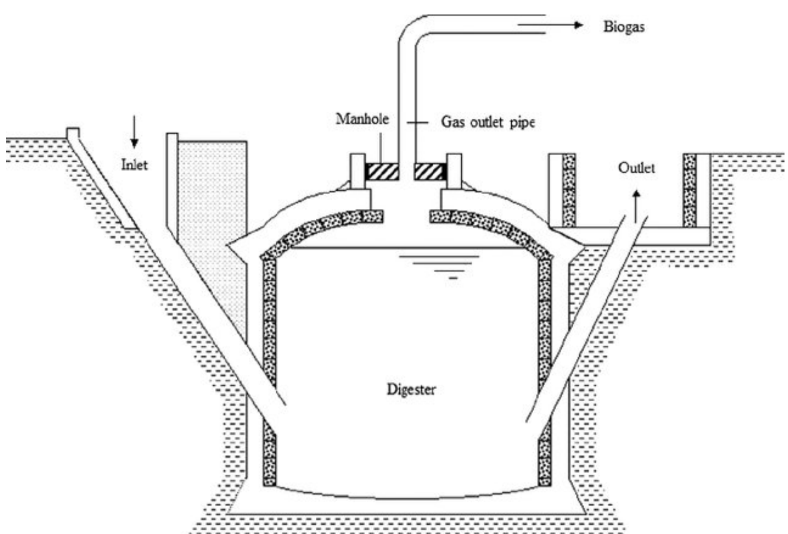

Figure 7.5: Fixed cover digester diagram [K C et al., 2014].

Figure 7.6: Fixed cover digester in work.

7.2.3 Plastic-tubular cover digester

A lengthy cylindrical bag made of polythene or PVC is partially buried lengthwise in the ground. Fresh cow-dung slurry is introduced at one end and exits at the opposite end. As gas accumulates within the bag, it inflates similar to a balloon. To transport the gas to its destination, external pressure is applied to the inflated balloon, directing the gas through a pipe. This method is employed infrequently.

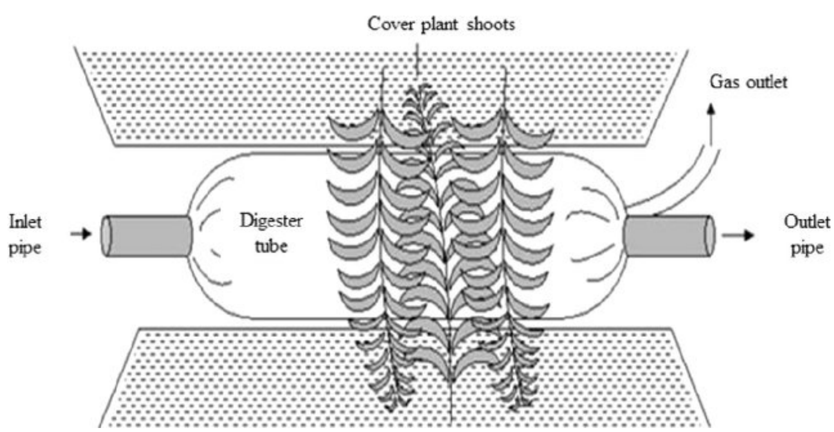

Figure 7.7: Plastic-tubular cover digester diagram [K C et al., 2014].

7.3 Cost of Biogas Plants in Bangladesh

In Bangladesh, hardly any user buys a piece of land to set up a biogas plant; rather, it is assumed that biogas users already have a piece of land for biogas plant construction. Assuming this, the cost of a biogas plant varies with changes in the following cost components:

- Model or type of the biogas plant

Figure 7.8: Plastic-tubular cover digester in work.

- Size and dimension of the biogas unit
- Amount and prices of materials
- Labor input and wages

At present, there are two major types of biogas plants constructed in Bangladesh. One is based on cow dung, and the other on poultry droppings [Chy, 2017].

In a comparative analysis of biogas plant costs presented in Table 7.2, it's evident that the size of the plant plays a significant role. As the plant size increases, both the maximum and minimum costs in BDT rise, indicating a direct correlation between size and initial investment. This trend extends to the average cost as well, with larger plants generally requiring a higher upfront expenditure. Notably, there is substantial cost variability across different plant sizes, with the largest plant (300 cft gas production per day) having the highest average cost of 32,500 BDT, while the smallest plant (100 cft gas production per day) boasts the lowest average cost at 13,575 BDT. Therefore, selecting the appropriate plant size should consider the trade-off between cost and gas production capacity.

Size of Plant (cft gas production per day)	Maximum Cost in BDT	Minimum Cost in BDT	Average Cost in BDT
100	15500	11800	13575
125	17600	12450	15750
150	23000	15200	18500
200	24000	15800	20100
250	28000	17000	23850
300	34500	30500	32500

Table 7.2: Cost of Installation of Biogas Plant (2017)

7.4 Motivation of Biogas Plants in Bangladesh

In his MS thesis [Chy, 2017], Chy surveyed respondents to ascertain the key factors motivating the installation of biogas plants. According to the respondents' data presented in Table 7.3, the predominant motivating factors encompassed economic advantages such as time and cost savings, environmental benefits, the presence of subsidies, and health benefits, notably the reduction in smoke-related illnesses. The ensuing table displays the respondents' feedback regarding the incentives behind their decision to install biogas plants.

Motivating factors	Percentage of user (%)
Economic benefits (saves time and energy)	47
Subsidy	23
Health benefits	82
Non-availability of other fuel sources	5
Environmental benefits (saving of forest, clean surrounding etc.)	41
Motivation from other plant owners	35
Proper use of cattle dung	17
Pressure from neighbors (in the case of poultry)	11
Use digester as septic tank	5
Fish feed	35
Adopt the new technology and make the village ideal living place	23
Motivation from service provider	29

*Some respondents gave more than one reasons

Table 7.3: Motivating factors to install biogas plant (2017) [Chy, 2017]

7.5 Saving of Conventional Fuel Sources

7.5.1 Financial gain

As per Table 7.4, the average annual financial savings attributed to the biogas plant were calculated to amount to BDT 52,235 per household, a notably substantial sum. This increase was primarily due to households switching from firewood as their fuel source before the biogas plant installation to biogas while the plant was operational, and subsequently, to LPG after the biogas plant experienced a malfunction. The transition to LPG was prompted by the housewives' reluctance to return to using firewood after experiencing the convenience of cooking in a smoke-free environment when utilizing biogas.

Traditional fuel	Quantity use and saving (unit/year/family)			Average cost in BDT/unit	Total saving in BDT/family/year
	Before	After	Saving		
Firewood (kg)	3525	1138	2387	15	35805
Agricultural residues (kg)	1742	747	995	6	5970
Dried dung (kg)	1376	648	728	7.5	5460
Lpg (cylinder)	6.5	2.5	4	1250	5000
Natural gas (BDT)	0	0	0	900	0
				Total	52235

Table 7.4: Financial gain from saving of traditional fuel (2017) [Chy, 2017]

7.5.2 Financial Savings

The table 7.5 presents a comprehensive overview of financial savings in biogas households, categorized by the amount saved in BDT per month and the corresponding percentage of families falling into each category. Notably, the majority of households fall within the categories of BDT 101 to 500 (17%) and g BDT 501 to 1000 (23%), indicating a significant proportion of families are able to accumulate moderate to substantial savings each month. Conversely, 11% of households report "Zero saving," suggesting that a notable portion faces financial challenges even with biogas utilization. Moreover, the table underscores the positive impact of biogas on household finances, with 17% of families saving in the range of BDT

1001 to 3000 and another 11% managing to save more than 3000 BDT, affirming its role in fostering economic stability and reducing energy-related expenses within these households.

Amount saved (in BDT/month)	Percentage of family (%)
More amount needed	5
Zero saving	11
Saving less than BDT 100	11
Saving BDT 101 to 500	17
Saving BDT 501 to 1000	23
Saving BDT 1001 to 3000	17
Saving more than 3000	11

Table 7.5: Financial saving in Biogas households (2017) [Chy, 2017]

7.6 Energy Output Analysis

As per [Energypedia, 2016], the average calorific value of biogas falls within the range of 21 to 23.5 megajoules per cubic meter (MJ/m^3). This indicates that 1 cubic meter of biogas is roughly equivalent to 0.5 to 0.6 liters of diesel fuel or possesses an energy content of approximately 6 kilowatt-hours (kWh). Nevertheless, owing to conversion losses, the effective electrical energy that can be derived from 1 cubic meter of biogas amounts to approximately 1.7 kilowatt-hours (kWh). Figure 7.9 shows output per feedstock type (toe = tonne of oil equivalent. 1 toe = 11.63 MWh = 41.9 gigajoules).

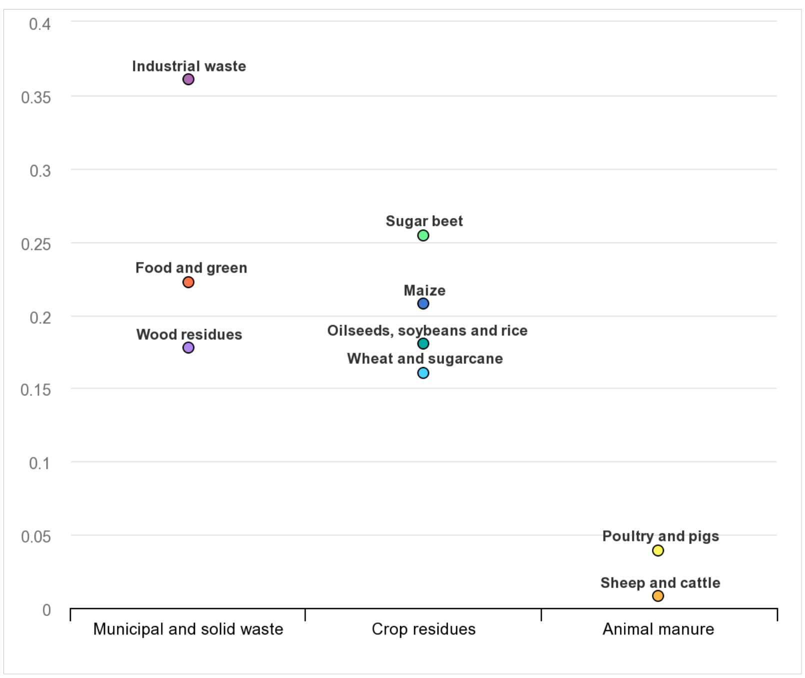

Figure 7.9: Average biogas production yield by tonne of feedstock type [IEA, 2022].

7.7 Assessing Electricity Generation

From Figure 7.10, we can notice a upward trend in biogas plant constrction, biogas generation and electricity generation from biogas. We used least square method to predict current estimates. In 2023, the predict amount is 8.312 Gwh.

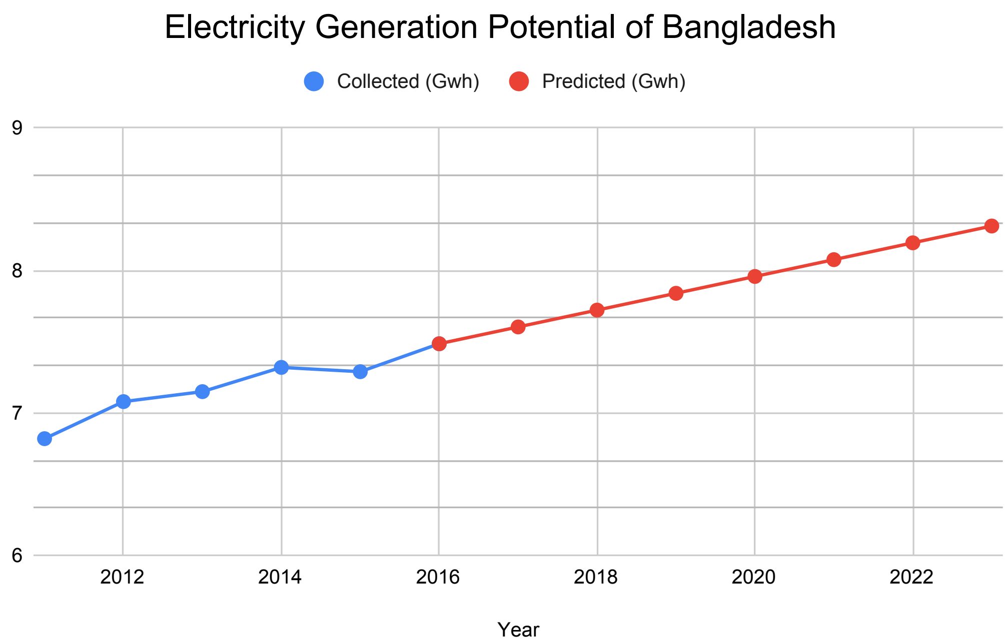

Figure 7.10: Electricity Generation Potential of Bangladesh (Data till 2015).

7.7.1 Measurng Potential Electricity Generation from Biogas

Table 8.1 illustrates the projected biogas production and electricity potential derived from animal and poultry waste in Bangladesh during the fiscal year 2014-2015. The data indicates the capacity to generate a substantial 2023 MW of electricity through the utilization of these animal manures, potentially resolving the country's energy demand challenges and alleviating the issue of load shedding. The daily waste production per animal or poultry was estimated based on generation ratios observed in neighboring countries, resulting in values of 10 kg of manure per day for cattle and buffalo, 1.55 kg per day for goats, 1.44 kg per day for sheep, and 0.1 kg per day for poultry. In 2014-2015, amount of electricity generation from biogas is 1.4 $\left(\mathrm{kWh/m^3}\right)$ of biogas, but total electricity potential from biogas was 7.30 GWh [Islam et al., 2017], as per Table 7.6.

Sources	Total amount (in millions)	Manure generation (kg/day)	Biogas (m^3/kg)	Total biogas production (Mm^3/ year)	Amount of electricity generation (kWh/m^3 of biogas)
Cattle	23.63	10	0.037	3191.232	
Buffalo	1.46	10	0.037	197.173	
Goat	25.6	1.55	0.06	868.992	
Sheep	3.27	1.44	0.06	103.1227	1.4
Poultry	312.29	0.1	0.074	843.49	
			Total	5204.01	

Table 7.6: Potential for biogas generation from animal waste in 2014-2015 [Islam et al., 2017].

CHAPTER 8
ASSESSING SUSTAINABILITY AND SCALABILITY

Electricity generation through biogas is acknowledged as a sustainable energy source. Derived from biomass, biogas finds versatile applications across multiple sectors, including transportation, electricity generation, heat production, combined heat and power (CHP) systems, and fuel cells. Furthermore, upgraded biogas can serve as a transportation fuel, powering internal combustion engines (ICE) for vehicles and electricity stations for electric vehicles [Abanades et al., 2022a].

In the grand scheme of things, while biogas currently stands as a more sustainable alternative compared to traditional natural gas, it should be viewed as a vital transitional fuel as we strive to completely decarbonize our energy supply [Juliani and Pearson, 2020]. Biogas has the potential to contribute to sustainable and scalable electricity generation. Various mathematical models have been proposed to optimize anaerobic fermentation processes for biogas production [Akpojaro et al., 2019]. The sustainability of agricultural anaerobic digestion (AD) plants, which produce biogas, can be assessed using eco-efficiency models and the triple bottom line approach. Biogas, derived from biomass waste fermentation, offers a renewable energy source for power generation, leading to economic development and waste management. Biogas-based off-grid power plants can be economically feasible, especially when different raw materials are mixed in the right ratio [Omer, 2017].

Electricity generation from biogas is considered to be a scalable energy source. Biogas has the potential for electricity generation in power plants by internal combustion engines (ICEs) or gas turbines (GTs) as the two most commonly used power generation methods. Micro gas turbines are also an attractive method due to lower NOx emissions and flexibility to meet various load requirements [Abanades et al., 2022b]. In 2020, bioenergy electricity generation increased 53 TWh (+8%) from 2019, exceeding the 7% annual rate needed through 2030 in the Net Zero Emissions by 2050 Scenario. However, to raise bioenergy electricity generation from 718 TWh in 2020 to more than 1,400 TWh in 2030 as modeled in the scenario, it will be necessary to add an average of 15 GW of new capacity annually – a considerable increase from the 9 GW deployed in 2020. Policies to support bioenergy power development are improving around the world, but stronger efforts will be needed to ensure that policy goals are reached and the pace of generation growth is maintained [Juliani and Pearson, 2020].

Comparing Sustainability and Scalability.
The sustainability score presented in Table 8.1 reflects the environmental impact of biomass production and use, such as greenhouse gas emissions, land use change, water consumption, and biodiversity loss. The scalability score reflects the potential for expanding biomass supply and demand, considering factors such as availability, cost, infrastructure, and policy support [Bojek and Moorhouse, 2021].

Biomass source	Sustainability score	Scalability score
Agricultural residues	High	High
Forestry residues	High	Medium
Energy crops	Medium	Low
Municipal solid waste	Low	High
Biogas (Direct from another sources)	Medium	High

Table 8.1: Sustainability and Scalability score of different bio-mass plants.

8.1 Acheiving Sustainable Development Goals

The Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace, and justice.

Biogas is one of the promising renewable energy sources that has been successfully implemented at domestic and industrial scales. Biogas has been found to have direct impacts and contributions to 12 out of the 17 SDGs. These SDG goals are zero hunger, good health and wellbeing, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry-innovation and infrastructure, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land. The main contributions of biogas come from its ability to increase renewable energy, reduce climate change, enhance the waste management process, and create jobs.

Biogas, as a clean and renewable energy source, it aligns with SDG 7 by providing affordable and environmentally friendly energy. Biogas projects create jobs and economic opportunities, thereby supporting SDG 1 by reducing poverty. By converting organic waste into energy and nutrient-rich fertilizers, biogas promotes responsible consumption and production (SDG 12) and enhances agricultural productivity, supporting SDG 2. Moreover, its role in reducing indoor air pollution improves public health (SDG 3), while wastewater treatment in biogas systems positively impacts clean water and sanitation (SDG 6). Biogas mitigates climate change (SDG 13) by reducing methane emissions and contributes to sustainable urban development (SDG 11) by offering decentralized energy solutions. Additionally, responsible waste management through biogas aligns with goals related to life below water (SDG 14) and life on land (SDG 15). Biogas exemplifies the interconnectedness of the SDGs and underscores its pivotal role in advancing a sustainable and equitable world [Obaideen et al., 2022].

8.2 Impact on Circular Economy

Anaerobic digestion is a key component in the circular economy model as it allows for the valorization of biogas and the recycling of nutrients through the land application of digestates. Biogas can be upgraded to have a methane content similar to natural gas, making it compatible with various industrial applications. However, the high installation and operating costs of upgrading plants hinder the widespread application of this technology in many countries. Wastewater treatment plants and waste treatment centers play an important role in the circular economy by offering the possibility of obtaining valuable materials and energy. Anaerobic digestion is widely used for treating organic waste and producing biogas, which can be used as fuel for heat and electricity production. The aim of making biogas a major component of the energy mix market is still far from being a reality due to high costs and low revenues, as well as social rejection associated with the transport of waste and concerns about negative impacts on health and the environment [Ellacuriaga et al., 2021].

CHAPTER 9
FUTURE PROSPECTS AND POSSIBILITIES

The use of biogas plants presents a promising future for electricity generation, both in Bangladesh and globally. The escalating demand for energy and the pressing need for sustainable solutions have heightened the importance of biogas as a viable alternative. In Bangladesh, where energy shortages persist as a challenge, the utilization of agricultural and livestock waste for biogas production can provide a solution to the nation's power deficits, particularly in off-grid regions. Additionally, the environmental advantages of biogas, such as curbing greenhouse gas emissions, highlight its significance in the global battle against climate change. With government support, technological advancements, and a focus on rural electrification, biogas is poised to play a pivotal role in the transition to cleaner and more accessible energy sources.

1. **Meeting Soaring Energy Demands**: The escalating global energy demand, driven by urbanization and industrialization, underscores the pressing need for sustainable energy sources. Biogas plants offer a promising solution by harnessing organic waste, such as agricultural residues and livestock manure, to generate electricity. In Bangladesh, a country grappling with energy shortages, biogas presents a viable means to meet its growing electricity needs, especially in rural areas where grid connectivity is limited.

2. **Abundance of Agricultural and Livestock Waste**: Bangladesh's predominantly agrarian economy is accompanied by a substantial agricultural and livestock sector. This abundance of organic waste serves as a valuable resource for biogas production. By efficiently converting agricultural residues and animal manure into electricity, biogas plants not only contribute to the country's energy grid but also address environmental concerns associated with unmanaged organic waste disposal.

3. **Environmental Benefits and Emission Reduction**: On a global scale, biogas plays a pivotal role in mitigating climate change. The capture and utilization of methane, a potent greenhouse gas emitted by decomposing organic matter, significantly reduces emissions. Biogas plants, when integrated into waste management systems, facilitate a dual-purpose solution by curbing environmental pollution and generating clean energy, thereby aligning with international efforts to combat climate change.

4. **Rural Electrification and Economic Growth**: In Bangladesh and similar developing nations, biogas-based electricity generation holds the promise of rural electrification. By providing access to reliable and sustainable energy sources, biogas plants can transform the lives of rural communities. Access to electricity not only enhances the quality of life but also opens doors to economic opportunities, stimulating growth in agriculture and small-scale industries [Islam et al., 2017].

5. **Government Support and Technological Innovation**: The growth of biogas as a renewable energy source is reinforced by supportive policies and incentives from governments worldwide. These measures promote investment in biogas infrastructure and research. Moreover, ongoing technological innovations, such as improved digester designs and gas purification methods, enhance the efficiency and reliability of biogas plants, making them increasingly attractive for both domestic and industrial applications.

9.1 Aspect of Bangladesh

Energy constitutes a pivotal element in contemporary society, exerting a substantial influence on socioeconomic progress. In developing nations, especially in rural locales, the continued use of traditional biomass for cooking purposes poses a range of environmental, societal, economic, and public health challenges. To attain sustainable development in these areas, it is imperative to grant access to clean and cost-effective energy sources. One potential remedy lies in the enhancement of biomass resources into cleaner and more efficient energy forms, such as generating biogas through anaerobic digestion. This approach can provide clean and dependable energy while simultaneously safeguarding the environment [K C et al., 2014].

Bangladesh holds significant promise for generating electricity through biomass gasification. Various biomass resources, including agricultural waste, rice husks, bagasse, wheat straw, jute stalks, maize residues, lentil straw, coconut shells, forest residue, and municipal solid waste, can be harnessed to produce power.

Crops	Production in 2011 (million tons)	Fractions	Amount of fractions	Crop residue (million tons)
Rice	50.63	Straw	50.00	25.31
		Husk	20.00	10.13
Maize	1.02	Stalks	200.00	2.04
		Cobs	30.00	0.31
Wheat	0.97	Straw	65.00	0.63
Jute	1.52	Stalk	58.84	0.90
		Leaves	13.91	0.21
Sugarcane (trimmed)	4.67	Bagasse	36.00	1.68
Mustard	0.23	Straw	75.00	0.17
Coconut	0.08	Husk	31.00	0.024
		Shell	24.40	0.019
Lentil	0.081	Straw	72.46	0.058
	Total residue production in 2011 (million tons)			41.66

Table 9.1: Total residue production with percentage of fractions of some selected agricultural crops in Bangladesh. (2011) [Das and Hoque, 2014].

Biomass gasification is a promising technology for meeting rural electricity needs and can produce fuel gas from biomass conversion. Gasification is an efficient way to utilize waste biomass and the produced gas can be used for electricity generation and chemical industry. Bangladesh has strong potential for power generation from agricultural residues, particularly rice husk and straw, with a potential of around 1010 MWe. The country's sugar mills can also be a great energy resource, with bagasse having the potential to produce around 50 MWe. Other biomass resources like wheat straw, jute stalks, maize residues, lentil straw, and coconut shell can also contribute to power generation.

Overall, Bangladesh has a great potential and future in electricity generation from biogas or biomass, for provding electricity in in rural areas.

CHAPTER 10
CONCLUSION

The utilization of organic waste for the production of biogas has garnered significant interest across several regions of the world. Compared to other forms of bio-energy, the biogas production system offers a diverse range of benefits, including the provision of various energy types and the reduction of significant environmental impact. Bangladesh, being an agricultural nation, possesses a large amount of biomass that can be utilized as a source of biogas production. The future of electricity generation from biogas plants appears promising, with a focus on sustainability and the resolution of energy challenges. Biogas emerges as a vital element in the global energy transition towards cleaner and more sustainable sources of electricity, as it allows for the utilization of organic waste resources, reduces emissions and promotes rural development. As governments and industries invest further in biogas technology and infrastructure, its role in meeting future energy demands becomes increasingly significant.

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