BIOGAS AND GREENHOUSE GAS EMISSION REDUCTION IN BANGLADESH: AN ANALYSIS OF UTILISATION PATHWAYS, EMISSION BENEFITS, AND POLICY IMPLICATIONS

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ABSTRACT

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Bangladesh is an agrarian country, and it produces massive amounts of agricultural residues and livestock manure annually. Though it is widely accepted that organic waste is a potential source of greenhouse gas emissions, its conversion to biogas through anaerobic digestion and its end-use potential for reducing greenhouse gas emissions is still in its infancy. This thesis is concerned with the end-use potential of biogas in Bangladesh, and its application in reducing greenhouse gas emissions is examined. The raw material availability and its theoretical potential for biogas production are considered background information.

Using secondary data from BBS (2023), DLS (2023-2024), peer-reviewed literature, and international databases, a quantitative estimation framework is used. The quantitative estimation framework suggests that biogas generated from animal waste and crop residues could potentially replace 8.2 Mt CO_2eq of GHG emissions associated with household cooking fuels in the form of firewood and kerosene usage on an annual basis. Similarly,

electricity generation using biogas with 30 percent conversion efficiency could potentially replace 4.76 Mt CO_2eq per annum in place of the national grid electricity supply (EEF = 0.53 tCO_2/MWh). Biofertilizer production using digestate could replace 0.95 Mt CO_2eq of GHG emissions associated with chemical fertilizers used in agriculture. Thus, full utilization potential of biogas could result in reducing Bangladesh's energy sector GHG emissions up to 13.2 Mt CO_2eq per annum by 2030, i.e., more than 13 percent of total energy sector GHG emissions.

The study concludes that household cooking substitution is the most effective end-use pathway in the near term, providing the highest reduction in GHG emissions per unit of investment in Bangladesh at the current level of biogas development. Rural electricity generation from livestock manure biogas is the most scalable end-use pathway in the medium term. The policy recommendations include scaling up the IDCOL domestic biogas programme, requiring biogas digesters in commercial livestock farms, and creating carbon finance mechanisms to monetize the quantified emission reduction benefits.

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Symbols and Abbreviations

Roman Characters

B	Biogas production (m^3)
CH_4	Methane
CO_2	Carbon dioxide
E	Energy (MJ or kWh)
EEF	Electricity emission factor (tCO_2/MWh)
GCR	Gross crop residue (kg/year)
LHV	Lower heating value (MJ/m^3)
LM	Annual manure production (t/year)
m	Mass (kg or tonne)
N	Number of animals
P	Crop production (tonne/year)
T	Temperature (°C)
W_a	Agricultural waste (tonne/year)
W_l	Livestock waste (kg/year)

Abbreviations

AC	Availability coefficient
ACoD	Anaerobic co-digestion
AD	Anaerobic digestion
AF	Availability factor
BBS	Bangladesh Bureau of Statistics
C/N	Carbon-to-nitrogen ratio
CHP	Combined heat and power
DLS	Department of Livestock Services
DM	Dry matter
EBTS	Estimated biogas per kg total solid (m^3/kg)
GHG	Greenhouse gas
GWP	Global warming potential
IDCOL	Infrastructure Development Company Limited
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change

MR	Manure rate (kg/day/animal)
Mt	Million tonne
NDC	Nationally Determined Contribution
RDF	Residue dryness factor
RRF	Residue recovery factor
RYR	Residue yield mass ratio
RVS	Ratio of volatile solid to dry matter
SAF	Surplus availability factor
TS	Total solids
TWh	Terawatt hour
VS	Volatile Solids
WtE	Waste-to-energy

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DECLARATIONS

I hereby declare that This thesis is my own work submitted in partial fulfillment for Lappeenranta–Lahti University of Technology LUT degree.

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The originality of this thesis has been reviewed with the Turnitin similarity checking service.

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The author, Abdullah-Al Mamun, takes full responsibility for the content of this thesis and has reviewed and edited the thesis.

1 Introduction

Bangladesh is one of the most densely populated countries in the world, having a population of approximately 170 million people (BBS, 2023). The backbone of the national economy is agriculture, as it utilizes around 40 percent of the total labor force and contributes around 11.5 percent to the national GDP (World Bank, 2024). Bangladesh produces huge amounts of agricultural residues, wastes from fruits and vegetables, and animal wastes every year. If these organic wastes are not disposed of in the right manner, they are burned, dumped in open places, or left to rot, releasing greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) into the atmosphere (Bishwas, 2023; Siddiki et al., 2021). At the same time, Bangladesh is suffering from an energy crisis, where the energy sector is dependent largely on fossil fuels and access to clean energy is lacking in the lives of millions of people in the country.

The biogas, which is produced by anaerobic digestion of organic wastes, is a dual-purpose solution that not only provides a solution to the organic wastes by converting them into a valuable energy source but also prevents the emission of methane into the atmosphere. The climate and development benefits of biogas are not realized at the point of production, but rather at the point of end use. The end use of the biogas, whether it is for cooking, electricity, fertilizer, or grid supply, determines the quantum of GHG reduction and the associated development benefits that are delivered to the people of Bangladesh.

This thesis therefore focuses on the end-use of biogas and its associated GHG emission reductions in Bangladesh. The availability of raw material and theoretical potential of producing biogas is contextual background information needed to establish the parameters but not an analytical contribution in itself. The analytical contribution is to establish the nature of the reduction of emissions that can be achieved by each type of end-use and in establishing the kind of policy that is needed to provide this potential.

1.1 Energy and Environmental Challenges in Bangladesh

Bangladesh’s energy outlook demonstrates significant expansion and structural weaknesses. The total primary energy consumed in Bangladesh reached around 58 million tonnes of oil equivalent in 2023. The energy consumption grew at an average of 4 percent annually from 2010 to 2023. The energy sector in Bangladesh is dominated by gas, which accounts for around 46 percent of primary energy consumption. The gas reserves are depleting at an alarming rate. The import of crude oil has increased four times between 2010 and 2023, reaching 12.5 million tonnes.

Carbon emissions from Bangladesh's power sector have risen almost eight-fold over two decades to 2024, primarily because of fossil fuel-based electricity production to meet almost all growth in demand for electricity (Ember, 2024). The grid emission factor is estimated to range from 0.53 to 0.71 ton CO2/MWh (UNFCCC, 2021; Rahman and Mallick, 2020). Although Bangladesh has set a target to reach 10 percent of its energy supply from renewable sources by 2020, currently, only 4.5 percent of installed capacity is from renewables by mid-2023 (United Nations Bangladesh, 2023).

Bangladesh is one of the most vulnerable countries to the effects of climate change. It is also one of the countries most affected by increasing sea levels, intensifying cyclones and floods, and fluctuating monsoon patterns, all of which pose a threat to agriculture and livelihoods (Smith et al., 2021). In the business-as-usual case, the country has committed to cut down on its GHG emissions by 21.8 percent by the year 2030 through its Nationally Determined Contribution (NDC) (NDC, 2021). It can be achieved by decarbonizing the energy sector and controlling the emissions of methane and nitrous oxide into the atmosphere by the agricultural sector.

The complexities are added to household energy poverty. In Bangladesh, a large percentage of rural households (35-40 percent) still use solid biomass fuels as the main cooking fuel (Firewood and Crop residue), which is mostly firewood and crop residues (Islam et al., 2021). Indoor air pollution resulting from burning solid biomass fuels for cooking results in a high disease burden and death rates, especially for women and children. Kerosene, used for lighting and cooking in areas without access to electricity, contributes to greenhouse gas emissions in the form of CO_2 and black carbon. The use of biogas for cooking is one of the most direct and impactful uses of biogas.

1.2 Biogas as a Renewable Energy Solution

It is done through a biological process known as anaerobic digestion, in which microorganisms break down the organic material in the absence of oxygen to produce a flammable gas, which is a mixture of methane and carbon dioxide, in which the percentage of methane ranges from 50 to 70 percent, and the percentage of carbon dioxide ranges from 25 to 50 percent (Neri et al., 2023). The percentage of methane in the mixture has the energy value, in which the lower calorific value is approximately 35.8 MJ/m^3. If the biogas is utilized in the location where it is produced, it not only generates energy but also helps in reducing the GHG emissions, which would be produced through either the natural decomposition of the waste or the burning of the fossil or biomass fuel being replaced by the biogas (Islam et al., 2021).

Bangladesh has a long history of utilizing biogas technology, dating back to the 1970s. There has been considerable institutional momentum since the 2000s through IDCOL, Grameen Shakti, and LGED (Bishwas, 2023; Chowdhury et al., 2020). Currently, IDCOL has financed over 65,800 domestic biogas plants, primarily utilizing cattle dung for cooking gas for rural households (IDCOL, 2023), as of February 2023. Nevertheless, the installed capacity of biogas technology represents a minuscule fraction of its technically feasible potential, and the entire range of biogas end-use options has yet to be exploited.

1.3 Problem Statement

The literature on biogas in Bangladesh developed so far primarily focuses on the estimation of the raw material potential and the theoretical potential of biogas production. The dimension on the application of biogas and its potential in terms of GHG emission reductions through specific application routes and cumulative potential in terms of environmental benefits is not adequately explored in the literature so far. Moreover, the grid emission factor and biomass fuels used in earlier studies are no longer accurate, and no studies have attempted to quantify GHG reductions using all application routes of biogas in Bangladesh using data up to 2022-2024.

This is an important gap in terms of policy because it is not entirely clear how to target those end-use applications that offer the best GHG reductions benefits without a good understanding of this issue. This thesis attempts to fill this gap in knowledge.

1.4 Aim and Objectives of the Study

The aim of this study is to analyze the end use of the applications of biogas in Bangladesh and to assess the reduction in the emission of greenhouse gases that is possible by each of the end-use applications.

The specific objectives of the study are as follows:

1. To identify the major end-use routes of biogas in Bangladesh for household cooking, rural power generation, biofertilizers, and biomethane enrichment, and to determine the energy yield associated with each end-use route.

2. To calculate the reduction in GHG emission that is possible through each end-use route of biogas, considering the latest emission factors and fuel emission coefficients.

3. To simulate scenarios of cumulative emission reduction from the deployment of biogas in Bangladesh under various deployment scenarios up to the year 2030 and assess the scenarios in the context of Bangladesh's NDC.

4. To evaluate the relative merits of each end-use route of biogas in Bangladesh in different parameters, including reduction in emissions, access, viability of the economic benefit, and maturity of technology.

5. To formulate policy suggestions that might help extract the maximum emission reduction potential of biogas implementation in Bangladesh.

1.5 Research Questions

These research questions inform this study:

1. How do biogas products get used, and how much energy output can be achieved using each application?
2. What level of GHG emissions reduction can be achieved from each pathway of biogas end-use applications?
3. What level of cumulative GHG emissions reduction can be achieved from different pathways of biogas end-use applications by the year 2030, and how does it relate to Bangladesh's NDC?
4. What pathway offers the maximum GHG emissions reduction benefit considering its level of development?
5. What policy interventions are necessary to achieve maximum GHG emissions reduction benefits from the end-use applications of biogas?

1.6 Scope and Limitations of the Study

This research is focused on the end-use of biogas produced from agricultural crop residues, fruit and vegetable wastes, and animal and poultry manures in Bangladesh. The analysis of the availability of biogas feedstock materials is presented in the background section of this research and is based on secondary data from sources like BBS (2023) and DLS (2023-

2024). The GHG emission reduction analysis of this research is focused on four different end-use options of biogas. The end-use options of biogas in this research include cooking, electricity generation, fertilizer production, and biomethane production. The scope of this research is at the national level. No laboratory experiment is included in this research.

This research has some limitations, like the fact that it is based on national average parameter values from literature. The economic and life cycle assessment of biogas production is not included in this research. This research does not include fishery waste, municipal solid waste, and sewage sludge as biogas production materials. Biomethane production is included in this research as a future end-use option of biogas in Bangladesh, and the emission reduction is calculated based on international standards.

1.7 Structure of the Thesis

Chapter 2 is the literature review section, in which the basic concepts of biogas technology, the end-use routes of biogas, the emission of GHGs from waste, the status of biogas in Bangladesh, and the research gap are discussed. Chapter 3 is the methodology section. Chapter 4 is the results section, in which the results are presented and discussed in the form of feedstock context, end-use energy output, reduction of GHGs by end-use routes, cumulative scenarios, and comparison of results with previous studies. Chapter 5 is the results discussion section. Chapter 6 is the conclusion, recommendations, and future research section.

2 **Literature Review**

2.1 Fundamentals of Biogas Technology

2.1.1 Anaerobic Digestion Process

Anaerobic digestion (AD) is a biological process where a community of microorganisms breaks down organic materials without the presence of oxygen, resulting in the production of biogas and a nutrient-rich digestate (Neri et al., 2023). The AD process happens through four distinct phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Cremonez et al., 2021). In the first phase, hydrolysis, polymers are converted into monomers. In the second phase, acidogenesis, volatile fatty acids, alcohols, carbon dioxide, and hydrogen are generated. In the third phase, acetogenesis, acetic acid, hydrogen, and carbon dioxide are produced. In the fourth phase, methanogenesis, methanogenic archaea convert acetic acid and hydrogen into methane (Neri et al., 2023).

The key parameters include temperature, pH, total solids (TS), hydraulic retention time (HRT), C/N ratio, and inhibitors (Khatun et al., 2023; Cremonez et al., 2021). The mesophilic temperature range of 30-40°C is most frequently used in Bangladesh. The optimal C/N ratio is 20-30, and low C/N ratio substrates such as poultry droppings may experience ammonia inhibition. Anaerobic co-digestion (ACoD), on the other hand, has a balancing effect on all parameters and results in a synergistic effect for yield improvement (Khatun et al., 2023; Siddique and Wahid, 2018). Khatun et al. (2023) showed that anaerobic co-digestion of poultry droppings and banana peel at a 50:50 ratio at 35°C resulted in maximum biogas production of 347.0 ± 53.6 ml/gVS and methane production of 200.1 ± 18.6 ml/gVS after 83 days, and cone model and Gompertz model gave the best fit for the data ($R^2 > 0.99$).

2.1.2 Types of Biogas Feedstocks

Bangladesh's biogas feedstocks include agricultural residues, livestock and poultry manure, and fruit and vegetable waste. Rice straw, the most prevalent residue, requires pretreatment to increase its biodegradability (Rahman et al., 2018). When poultry droppings are co-digested with banana peel (C/N ≈30) at a 50:50 ratio, the biogas produced is 1.68 times higher than when banana peel is digested alone (Khatun et al., 2023). Poultry droppings have a nitrogen-rich C/N ratio of 6-17. Cattle manure, which has a nearly ideal C/N of 18-25, is the most widely used standalone substrate in Bangladesh (Das et al., 2023).

2.1.3 Biogas Composition and Energy Properties

Biogas is usually made up of methane and carbon dioxide. The methane in biogas is around 50 to 75 percent and the carbon dioxide is 25 to 50 percent. This was found out by Bharathiraja and others (Bharathiraja et al., 2018; Neri et al., 2023). In Bangladesh the biogas that comes from livestock has around 50 to 65 percent methane (Sabbir et al., 2021). The biogas that has 60 percent methane does not give out a lot of heat. It gives out around 23 megajoules of energy per meter. The energy that biogas gives out is important because it determines what we can get from it. We can use biogas for cooking and for generating electricity. The energy properties of biogas determine how well it can do these things.

2.2 Biogas End-Use Pathways in Bangladesh

2.2.1 Household Cooking and Heating

Direct combustion of biogas in household cookstoves is the most dominant end-use application in Bangladesh. This is the most technologically advanced and commonly used application. A rural household requires 1.5 to 2.0 m^3 of biogas for cooking purposes, which can be generated from a 4 to 6 m^3 fixed dome type of biogas plant using cattle dung as the input material (IDCOL, 2023; Chowdhury et al., 2020). Biogas cookstoves can attain thermal efficiency ranging from 55 to 60 percent, while conventional biomass cookstoves attain only 10 to 20 percent. This is higher than the thermal efficiency of biomass cookstoves, indicating greater useful output from biogas compared to biomass fuels. Using biogas in place of firewood or dry dung cakes eliminates the emissions of CO_2, black carbon, and particulate matter. These emissions are responsible for indoor air pollution, which affects women and children in rural Bangladesh (Islam et al., 2021). Using biogas in place of kerosene for lamps and traditional cookstoves also eliminates the emissions of CO_2 and black carbon, which are responsible for climate change.

2.2.2 Rural Electricity Generation

Electricity production from biogas can be carried out through combustion processes using gas engines, micro-turbines, or generator sets. Small and medium-sized gas engines have overall electrical efficiency of 25-35 percent (Bishwas, 2023; Siddiki et al., 2021). The overall energy efficiency of 70-85 percent can be attained through a combination of heat and power recovery, also known as Combined Heat and Power (CHP) (Neri et al., 2023). In Bangladesh, 3 percent of the rural population relies on the absence of access to grid electricity, and the proposed mini-grid power plants can be a cost-effective solution for the rural community (United Nations Bangladesh, 2023). The greenhouse gas emission reduction of biogas power plants can be realized by comparing it with the carbon intensity of the grid, which is 0.53 tCO_2/MWh as adopted by this study (UNFCCC, 2021; Rahman & Mallick, 2020).

2.2.3 Biofertilizer Application

The digestate obtained in AD is a nutrient-rich liquid medium containing mineralized N, P, and K, which is directly used as a biofertilizer in soil (Dahiya and Vasudevan, 1986; Yu et al., 2010). Biofertilizer acts as an alternative to chemical fertilizers used in agriculture, whose production requires considerable amounts of energy and results in significant CO_2 emissions into the atmosphere. Synthetic nitrogen fertilizers production GHG emission factor is between 3.8 and 8.0 kg CO 2eq/kg N depending on the production process (IPCC, 2019). In Bangladesh where the use of nitrogenous fertilizers in the form of urea is on the rise in the soil and imports, biofertilizer made from biogas digestate take up a significant economic and environmental importance. A study conducted in Bangladesh showed that the use of digestate can immensely enhance the fertility of the soil and its yield (Yu et al., 2010; Bishwas, 2023).

2.2.4 Biomethane Upgrading

It is also possible to upgrade biogas to biomethane (>95 percent CH4), which is compatible with natural gas infrastructure and can be used as a vehicle fuel (CNG equivalent) or injected into gas grids. Though biomethane upgrading is not currently implemented in Bangladesh, global experience has confirmed its technical viability and cost competitiveness, especially as natural gas prices increase (Neri et al., 2023). With the natural gas resources in Bangladesh running out, biomethane is a domestically producible substitute, which does not produce GHG emissions when burned.

2.3 GHG Emissions from Unmanaged Organic Waste in Bangladesh

Organic waste that are not routed into the biogas system is contributing to atmospheric GHG emissions from open burning, anaerobic decomposition in landfills and open fields, and enteric fermentation. Open burning of agricultural crop residues is a common practice in Bangladesh after the harvest of the Boro rice crop. This open burning of agricultural crop residues results in the emission of CO2, CO, methane, black carbon, particulate matter, and volatile organic compounds (Bhuvaneshwari et al., 2019; Mehta and Badegonkar, 2023). Livestock waste that are left to decompose anaerobically in open storage are contributing to the emission of methane into the atmosphere, which has a global warming potential 28 times that of CO2 over a 100-year time frame (IPCC AR5; Yasmin et al., 2022). From 1994 to 2012, enteric fermentation and manure management contributed to 47-55 percent of Bangladesh's agricultural sector GHG emissions (Islam et al., 2021).

This waste gas flow is directed to biogas digesters where methane that would have been released in an uncontrolled manner is instead utilized in an environmentally friendly manner after combustion to CO_2, resulting in a 28-fold reduction in climate forcing potential. This methane capture benefit is in addition to the fuel substitution benefit.

2.4 Current Status of Biogas Development in Bangladesh

Domestically, Bangladesh has made significant achievements in the development of biogas plants. IDCOL had financed over 65,800 biogas plants across the country by February 2023, Grameen Shakti had installed over 35,000, and LGED had completed approximately 6,000 (IDCOL, 2023; Bishwas, 2023). These are small, fixed dome plants used for household purposes, replacing firewood and kerosene. Although this is a significant achievement, this is only a very small percentage of the technically feasible potential. A study undertaken across the country by Siddiki et al. (2021) estimated the biogas potential from animal waste alone as 27,923 million m^3/year, which can produce approximately 50 TWh of electricity. The overall share of renewable energy remains lower than 5 percent of the installed power capacity (United Nations Bangladesh, 2023; Ember, 2024).

2.5 **Environmental and Economic Benefits of Biogas End-Use**

The environmental advantages of utilizing biogas end-use can be viewed from a multidimensional perspective. At a household level, utilizing biogas for cooking avoids indoor air pollution, black carbon deposition on vegetation and ice surfaces, and deforestation related to firewood collection (Islam et al., 2021; Chowdhury et al., 2020). At a system level, utilizing biogas to produce electricity for end-use avoids CO_2 emissions at a rate equivalent to the national grid's emission factor. On a soil level, the use of digestate as a bio-fertilizer saves the production process of synthetic fertilizers that is energy-intensive (Yu et al., 2010).

Economic impacts are lower household spending on firewood, kerosene, and LPG; biofertilizer sales; employment in the rural areas to build and maintain digester; and possible revenue on carbon credits gained through documented emission reductions (Economic Feasibility Bangladesh Biogas, 2020; Parvez et al., 2023). An investigation of 140 biogas adopters in Bangladesh affirmed that it is economically feasible in the range of 2 to 120 m 3 of the plant size (Economic Feasibility Bangladesh Biogas, 2020).

2.6 Research Gap

The existing literature on biogas in Bangladesh primarily focuses on estimating the quantity of feedstocks and theoretical volume of production (Rahman et al., 2018; Siddiki et al., 2021; Bishwas, 2023). The dimension of using the results for quantifying GHG reduction by using different pathways, modeling cumulative emission reduction scenarios, and evaluating the performance of different pathways from different dimensions has not been addressed for Bangladesh using data from 2022-2024. In addition, the values of the grid emission factor, which range from 0.67 tCO2/MWh (Rahman & Mallick, 2020) to 0.53 tCO2/MWh (UNFCCC, 2021), have not been considered, nor have the values of the cooking fuel emission coefficients. The results on the co-digestion pathway by Khatun et al. (2023) have not been considered from the perspective of GHG reduction. This research addresses all four issues.

3 Methodology

3.1 Research Design and Approach

The research design adopted for the research is quantitative, estimation-based, and secondary data-driven. The conceptual framework is divided into two stages. In the first stage, the availability of the feedstock for the biogas is established, providing context, using existing calculation techniques (Rahman et al., 2018; Bishwas, 2023; Das et al., 2023). In the second stage, the key contribution of the thesis is quantified, i.e., the reduction potential of GHG emissions through different routes of using the biogas. This is achieved by using updated values for emissions, fuel emission coefficients, etc. This is direct compliance with the supervisor's instruction to focus on the utilization and emission side of the biogas, rather than the production potential.

3.2 Study Area

The study area covers the entire area of Bangladesh, located in South Asia between latitudes 20°44'N and 26°38'N, with a total land area of about 147,570 km². The subtropical monsoon climate of Bangladesh is suitable for intensive agricultural activities and large populations of cattle. There are eight divisions in Bangladesh.

3.3 Data Sources and Collection

The data for crop production is collected from the BBS Yearbook of Agricultural Statistics 2023. The data for livestock and poultry populations is collected from DLS Livestock Economy briefly 2023-2024. The residue characteristic factors are collected from Rahman et al. (2018). The coefficients for biogas yield are collected from different sources, namely Bishwas (2023), Khatun et al. (2023), and Das et al. (2023). The grid emission factor is used at 0.53 tCO2/MWh, collected from UNFCCC (2021). The GHG emission factors for cooking fuels are collected from the IPCC Emission Factor Database. In addition, the results from different Bangladeshi household energy surveys conducted in Bangladesh are used (Islam et al., 2021; Chowdhury et al., 2020). The GWP for methane is collected at 28 CO2 equivalent for a time horizon of 100 years.

3.4 Estimation of Agricultural Waste Generation

Gross crop residue (GCR) and theoretical net residue (CRth) are calculated using the following equations (Rahman et al., 2018):

$$GCR = Y \times RYR \qquad \text{(Equation 1)}$$

$$CRth = GCR \times RRF \times SAF \qquad \text{(Equation 2)}$$

where Y is annual crop yield (tonne/year), RYR is the residue-to-yield mass ratio, RRF is the residue recovery factor, and SAF is the surplus availability factor. Annual livestock manure production is:

$$LM = N \times M \times 365 \qquad \text{(Equation 3)}$$

where N is animal population and M is daily manure generation rate (kg/day). Theoretical biogas production from manure is:

$$TPB = LM \times AC \times TS \times EBTS \quad \text{(Equation 4)}$$

where AC is availability coefficient, TS is total solids fraction, and EBTS is biogas yield per kg total solids (m³/kgTS). These calculations establish the upper bound of biogas available for end-use applications.

3.5 Estimation of Biogas End-Use Energy Output

The energy output of each end-use pathway is computed as below. To cook in the home the thermal energy provided by biogas is:

$$Q_t^{herM_n G} = TPB\_cooking \times LHV^{bA} \times \eta_t^{eokrM_n G} \qquad \text{(Equation 5)}$$

LHV5 is the lower heating value of biogas (23 MJ/m3 at 60% CH4) and 5 is the biogas cookstove efficiency (0.57, halfway between 55 and 60 percentage range). For electricity generation:

$$QE = LCVM \times CH_4 \times TPB\_elec \times \eta^{elec} \qquad \text{(Equation 6)}$$

where LCVM is the lower calorific value of methane (10 kWh/m³), CH_4 is the fraction of methane in the biogas (0.60 for large ruminants and poultry, 0.45 for small ruminants), and η^{elec} is the electricity conversion efficiency (0.30). The volume of biofertilizer produced per unit of feedstock is calculated using published digestate yield ratios (Das et al., 2023; Bishwas, 2023).

3.6 GHG Emission Reduction by End-Use Pathway

GHG emission reductions are calculated separately for each end-use pathway. For cooking fuel substitution, the emission reduction is:

$$GHG^{ceokrM_n G} = \Sigma\,(F_i \times EF_i) - GHG^{le_a k_a Ge} \qquad \text{(Equation 7)}$$

where F_i is the quantity of fuel i (firewood, kerosene, LPG) replaced by biogas (tonne or litre/year) and EF_i is the GHG emission factor for fuel i ($kgCO_2eq$ per unit). The GHG from methane leakage in the biogas system is:

$$GHG^{le}{}_{a}{}^{k}{}_{a}{}^{Ge} = 0.05 \times CH_4 \times \rho^{dH}{}_{4} \times GWP^{dH}{}_{4} \qquad \text{(Equation 8)}$$

where $\rho^{dH}{}_{4} = 0.717$ kg/m³ and $GWP^{dH}{}_{4} = 28$. For electricity substitution:

$$GHG^{elec} = QE \times EEF - GHG^{le}{}_{a}{}^{k}{}_{a}{}^{Ge} \qquad \text{(Equation 9)}$$

where EEF = 0.53 tCO_2/MWh. For biofertiliser application, the GHG offset is:

$$GHG^{\text{bæo}} = D_v{}^{ol} \times N^{co}{}_{n}{}^{ce}{}_{n}{}^{t} \times EF^{\text{ıre}}{}_{a} \quad \text{(Equation 10)}$$

where $D_v{}^{ol}$ is the volume of digestate applied (t/year), $N^{co}{}_{n}{}^{ce}{}_{n}{}^{t}$ is the nitrogen content of digestate (kgN/t), and $EF^{\text{ıre}}{}_{a}$ is the GHG emission factor for synthetic urea production (approximately 5.0 $kgCO_2eq$ per kgN, following IPCC, 2019).

3.7 Assumptions and Limitations

Assumptions: The main assumptions are: (i) 50 percent of the available rice straw is utilized for biogas production; (ii) thermal efficiency of biogas cook stove is 57 percent; (iii) electricity generation efficiency is 30 percent; (iv) methane leakage from biogas digesters is 5 percent of total biomethane generated; (v) nitrogen content in digestate of cattle manure digesters is 3.5 kg N/tonne; and (vi) grid emission factor is 0.53 tCO_2/MWh. Limitations: The limitations are the same as mentioned in Section 1.6, except that the biomethane upgrading scenario relies on international benchmarks and will be considered indicative of future estimates pending availability of data from pilot projects in Bangladesh.

4 Results and Analysis

4.1 Biogas Feedstock Availability

In this section, the context for the amounts of organic waste available in Bangladesh is provided, which determines the upper limit of available biogas for end-use applications. For further details on methodology, please refer to Chapter 3; here, only the results are presented.

Table 1. Major crop residue characteristic factors (Rahman et al., 2018)

Crop Residue	RYR	RRF	SAF
Rice straw	1.76	0.60	0.80
Sugarcane tops	0.30	0.70	1.00
Wheat straw	1.75	0.35	0.20
Jute stalks	3.00	0.35	0.50
Maize stalks	2.00	0.60	1.00
Pulses straw	1.90	0.35	0.20

Using BBS (2023) crop production data, crop residues, and the parameters presented in Table 1, it is estimated that the total amount of crop residues is about 53.9 Mt annually. Rice crop residues account for about 46.1 Mt, followed by maize crop residues, which amount to about 5.2 Mt. On the other hand, fruit and vegetable waste is about 0.43 Mt annually, considering the loss during harvesting, according to Hasan (2010).

Table 2. Livestock and poultry population in Bangladesh

Livestock/Poultry	Population (millions)	Source
Cattle (cow + ox)	24.85	DLS 2023–2024
Buffalo	0.90	DLS 2023–2024
Goat	16.5	DLS 2023–2024
Sheep	1.9	DLS 2023–2024
Chicken (layers + broilers)	330	DLS 2023–2024

Applying Equation 3, where rates of manure generation for large ruminant livestock, small ruminant livestock, and poultry are 22.5 kg/day, 1.6 kg/day, and 0.045 kg/day, respectively (Das et al., 2023), the total estimated amount of manure generated is approximately 227.3 Mt/y, primarily composed of cattle manure, which is approximately 203.8 Mt/y. Applying Equation 4, the theoretical amount of biogas generated from livestock and poultry manure is approximately 13.02 billion m^3/y, and from crop residues and fruit and vegetable waste through AD, the energy potential is approximately 31.9 TWh/y. This provides the upper bound of the amount of biogas that can be used for end-use purposes, as shown in Table 3.

Table 3. Biogas feedstock availability summary

Waste Category	Annual Quantity (Mt/year)	Biogas/Energy Potential
Agricultural crop residues	53.9	31.9 TWh/year (AD)
Fruit and vegetable waste	0.43	Included in above
Cattle manure	203.8	11.22 billion m³/year
Buffalo manure	7.4	0.41 billion m³/year
Goat and sheep manure	10.7	0.145 billion m³/year
Chicken manure	5.4	1.24 billion m³/year
Total livestock manure	227.3	13.02 billion m³/year
Total combined	281.2	55.16 TWh electricity equivalent

4.2 Biogas End-Use Applications and Energy Output

Having outlined the context of the feedstock, the discussion now turns to the end-use applications. Figure 1 shows the distribution of existing and projected end-use applications for biogas in Bangladesh, in terms of the distribution of biogas amounts along the end-use pathways.

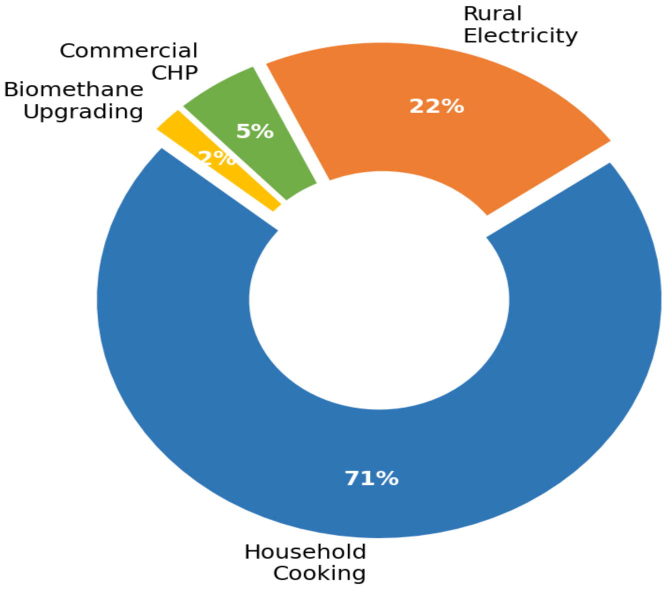

Figure 1. Distribution of biogas end-use applications in Bangladesh (%)

Household cooking (71%): This is the prevailing utilisation channel in Bangladesh and is aligned with the IDCOL domestic biogas programme which is running over 65,800 fixed-dome digesters that are primarily used to cook (IDCOL, 2023). Chowdhury et al. (2020) affirm that end-use in rural Bangladesh is mostly direct combustion used to cook food. Rural electricity generation (22%): It is an indication of the increasing commercial scale of electricity generation segment, in line with Siddiki et al. (2021) who estimate large electricity generation potential, on animal waste, and with the increasing commercial scale of biogas plants at livestock farms.

Commercial CHP (5%): Reflects the new segment of combined heat and power at agro-industrial plants. Neri et al. (2023) highlight CHP as an important future direction with 70-85% total energy efficiency.

Biomethane upgrading (2%): The nascent and predominantly future use of biogas upgrading to biomethane (>95% CH 4) to inject into a pipeline or feed into vehicles. This is a pathway that is currently not deployed on a large scale in Bangladesh (Neri et al., 2023).

Table 4. Household cooking fuel use and biogas substitution potential in Bangladesh

Fuel Type	Current Use (Mt or billion L/year)	Biogas Substitution (%)	Energy Substituted (PJ/year)	GHG Factor ($kgCO_2eq$/unit)
Firewood	27.4 Mt	30	163	1,540 per tonne
Dried dung cakes	8.6 Mt	25	31.5	1,200 per tonne
Kerosene	0.85 billion L	20	27.9	2,530 per 1,000 L
LPG	0.43 Mt	10	7.8	3,030 per tonne

Table 5. GHG emission factors for conventional cooking fuels in Bangladesh

Fuel	GHG Emission Factor	Source
Firewood (non-renewable)	1.54 tCO_2eq/tonne	IPCC EF Database; Islam et al. (2021)
Dried dung cakes	1.20 tCO_2eq/tonne	Islam et al. (2021)
Kerosene	2.53 tCO_2eq/1,000 litres	IPCC EF Database
LPG	3.03 tCO_2eq/tonne	Chowdhury et al. (2020)
Biogas (methane leakage only)	0.12 $tCO_2eq/1,000\ m^3$	Calculated, this study

Table 6. GHG avoided by cooking fuel substitution with biogas

Fuel Replaced	GHG Avoided (Mt CO_2eq/year)	Notes
Firewood	3.8	Based on 30% substitution of rural firewood use
Dried dung cakes	0.7	25% substitution of dung cake use
Kerosene	1.05	20% of household kerosene replaced
LPG	0.75	10% of LPG replaced in peri-urban areas
Less: biogas leakage	−0.10	5% methane leakage from cooking-scale digesters
Net GHG avoided (cooking)	6.2	Mt CO_2eq/year

The results in Table 6 show that the potential for household cooking substitution to reduce emissions is around 6.20 Mt CO_2eq annually in Bangladesh. This is the highest potential for any single pathway, compared to electricity substitution. This is possible through existing technology. For electricity generation in rural areas, the main biogas source is livestock manure, as it is most concentrated in commercial and semi-commercial farms. The parameters for electricity generation from biogas are presented in Table 7.

Table 7. Rural electricity generation parameters from biogas

Parameter	Value	Unit	Source
Methane content (cattle, poultry)	60	%	Bishwas (2023)
Methane content (small ruminants)	45	%	Bishwas (2023)
LCV of methane	10	kWh/m³	Siddiki et al. (2021)
Electricity conversion efficiency	30	%	Bishwas (2023); Siddiki et al. (2021)
Methane leakage rate	5	%	Afotey and Sarpong (2023)
Grid emission factor (EEF)	0.53	tCO_2/MWh	UNFCCC (2021)

Table 8. Biogas electricity generation potential by livestock source

Animal	Biogas (billion m³/year)	Electricity (TWh/year)	Share of Total (%)
Cattle	11.22	20.2	87
Buffalo	0.41	0.74	3
Goat	0.13	0.07	0.3
Sheep	0.015	0.008	0.03
Chicken	1.24	2.23	10
Total	13.02	23.25	100

Total electricity generation from livestock biogas is estimated at approximately 23.25 TWh per year, with cattle manure contributing 87 percent of this total. Figure 5 presents this by feedstock source and end-use type.

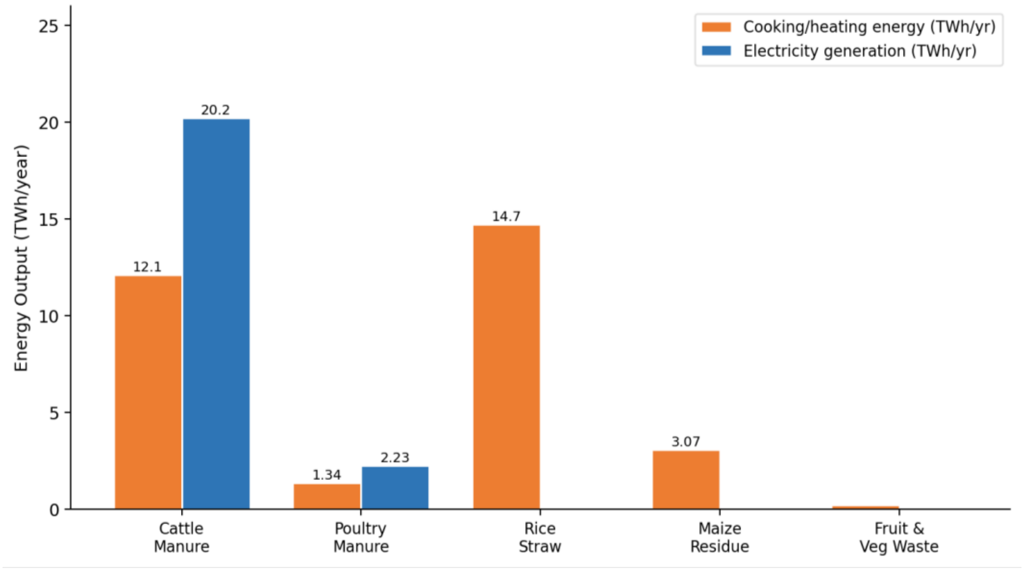

Figure 2. Biogas energy output by feedstock source and end-use application (TWh/year)

4.3 GHG Emission Reduction by End-Use Pathway

In this section, the key analytical results of the thesis are presented, i.e., the GHG emission reduction potential associated with each biogas end-use pathway. Figure 2 shows a comparison of GHG emission profiles for the four end-use scenarios, from no biogas use to cooking substitution, electricity substitution, and finally, to full deployment.

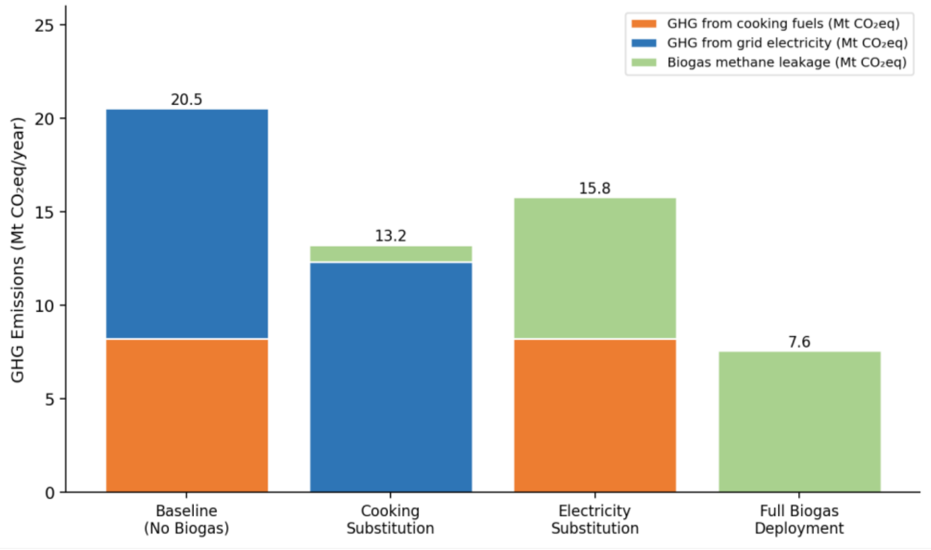

Figure 3. GHG emission profiles under different biogas end-use scenarios

Table 9. GHG reduction from biogas electricity substituting grid electricity

Parameter	Value	Unit
Total electricity from livestock biogas	23.25	TWh/year
Grid emission factor (EEF)	0.53	tCO_2/MWh
GHG avoided (grid substitution)	12.32	Mt CO_2eq/year
Methane leakage (5% of CH_4)	0.27	Mt CH_4/year
CO_2eq from leakage (GWP=28)	7.56	Mt CO_2eq/year
Net GHG reduction (electricity)	4.76	Mt CO_2eq/year

Biofertilizer produced from digestate provides an additional GHG offset through substitution of synthetic fertilizers. Table 10 presents the calculation.

Table 10. Digestate biofertilizer production and GHG offset

Parameter	Value	Unit
Digestate yield (from cattle manure AD)	approx. 185	Mt/year
Nitrogen content of digestate	3.5	kgN/tonne digestate
Total nitrogen in digestate	647,500	tN/year
GHG factor for urea production	5	$kgCO_2eq/kgN$
Gross GHG offset (fertilizer replacement)	3.24	Mt CO_2eq/year
Adjustment (not all digestate applied to fields)	0.3	Fraction applied
Net GHG offset (biofertilizer)	0.95	Mt CO_2eq/year

The horizontal bar chart in Figure 3 summarizes the net GHG emission reduction achievable through each end-use pathway in Bangladesh.

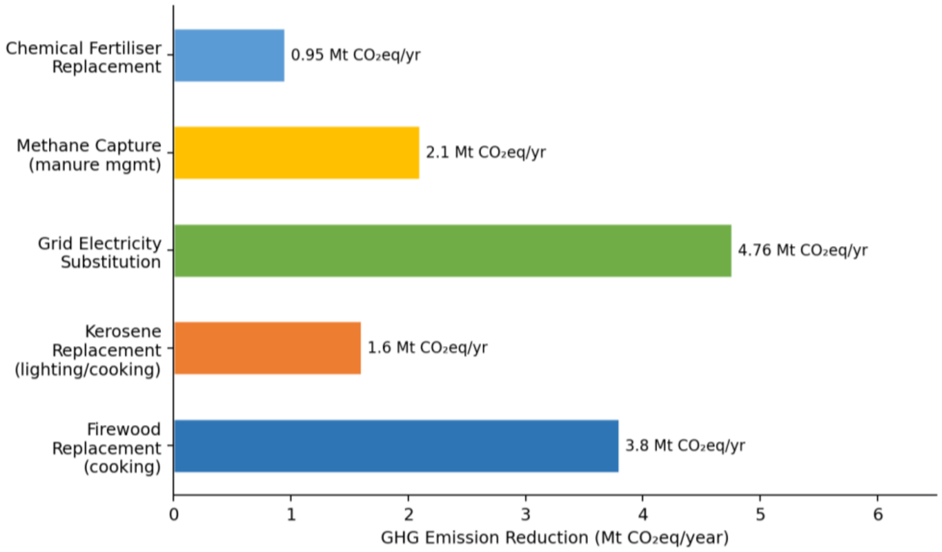

Figure 4. GHG emission reduction by biogas end-use pathway (Mt CO_2eq/year)

The highest individual reduction is achieved by the substitution of cooking fuel, which amounts to approximately 6.2 Mt CO2eq per year, followed by grid electricity substitution at approximately 4.76 Mt CO2eq, methane capture from manure management at approximately 2.1 Mt CO2eq, firewood substitution at approximately 3.8 Mt CO2eq (which is partly overlapping with the cooking substitution), and lastly, the application of biofertilizers at approximately 0.95 Mt CO2eq. Table 11 shows the results in detail.

Table 11. GHG emission reduction by end-use pathway summary

End-Use Pathway	GHG Reduction (Mt CO_2eq/year)	Key Mechanism
Household cooking substitution	6.2	Replace firewood, dung cakes, kerosene, LPG
Grid electricity substitution	4.76	Displaces fossil-based grid electricity (0.53 tCO_2/MWh)
Methane capture (manure management)	2.1	Prevents uncontrolled methane release from manure
Biofertiliser application	0.95	Substitutes synthetic urea production emissions
Biomethane upgrading (future)	0.4	Replaces natural gas; provisional estimate
Less: methane leakage (all pathways)	−1.21	5% leakage across all digesters
Net total (all pathways)	13.2	Mt CO_2eq/year at full deployment

4.4 Cumulative GHG Reduction Scenarios

Three scenarios for deployment have been modeled for the 2025-2030 period based on varying levels of scale-up of biogas production in Bangladesh. Scenario A: “Electricity substitution only” represents a very conservative case, representing a slow growth rate of commercial-scale biogas production in livestock farms. Scenario B: “Cooking and electricity substitution” represents a medium-scale deployment case, representing growth of both IDCOL’s domestic program and commercial-scale growth. Scenario C: “Full deployment of all pathways” represents a high-scale deployment case, representing a situation where strong policy support is needed for deployment.

Table 12. Cumulative GHG reduction scenarios 2025-2030 (Mt CO_2eq)

Year	Scenario A (Electricity only)	Scenario B (Cooking + Electricity)	Scenario C (Full Deployment)	NDC Cumulative Target
2025	0.3	0.5	0.6	2.4
2026	0.8	1.2	1.6	4.8
2027	1.5	2.2	3	7.2
2028	2.4	3.5	5	9.6
2029	3.5	5.1	8.5	12
2030	4.76	7.2	13.2	20.7

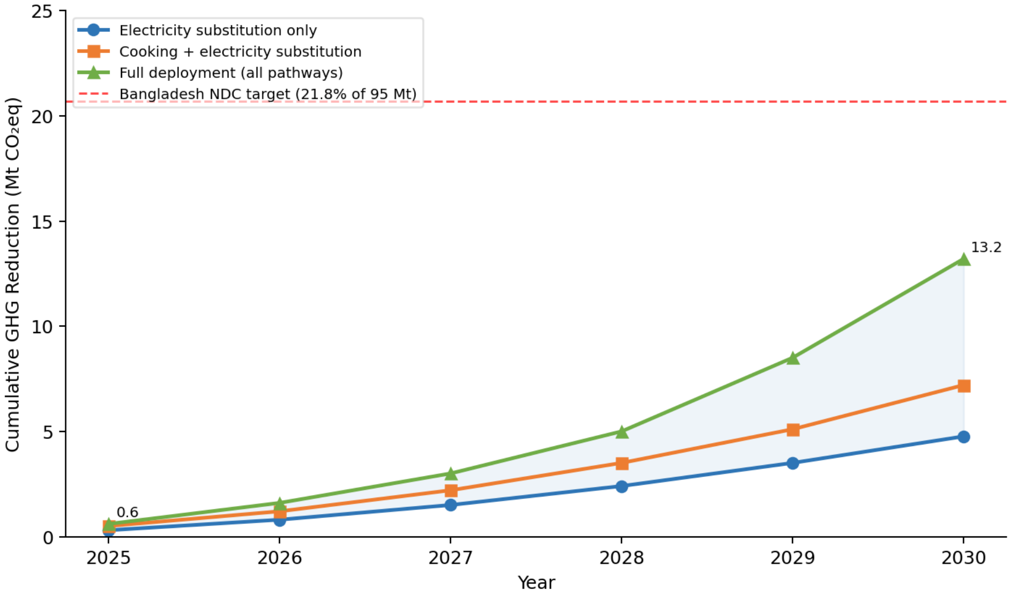

Figure 5. Projected cumulative GHG reduction under biogas end-use deployment scenarios (2025-2030)

Under the full deployment scenario (C), the cumulative GHG reductions achieved in the end-use of biogas add up to around 13.2 MtCO2-eq by 2030, which is around 64 percent of the illustrative NDC target of 20.7 MtCO2-eq/year of reductions in the energy sector. Not even the moderate Scenario B manages to achieve 35 percent of this target. These findings again reinforce the fact that biogas end-use deployment is a significant and viable contributor to Bangladesh's 2030 climate pledges.

4.5 Comparison with Prior Studies

The results of this study are broadly consistent with prior assessments where comparisons can be made, with differences attributable to the end-use-centred framing, updated data, and revised emission factors.

Table 13. Comparison with previous national-level studies on biogas in Bangladesh

Study	Focus	Biogas/Energy Estimate	GHG Reduction Estimate	Grid EEF Used
Bishwas (2023)	Production potential	22 TWh/yr (livestock)	7 Mt CO_2eq/yr	0.67 tCO_2/MWh
Siddiki et al. (2021)	Production potential	50 TWh/yr (livestock)	31.6 Mt CO_2eq/yr	Not stated
Khatun et al. (2024)	GIS suitability	Farm-level only	Not quantified	N/A
Das et al. (2023)	Farm-level survey	1.2 million m^3/yr (farm)	Not quantified	N/A
This study (2026)	End-use and emissions	55.16 TWh/yr (combined)	13.2 Mt CO_2eq/yr (all pathways)	0.53 tCO_2/MWh

The GHG reduction estimate of 13.2 Mt CO_2eq annually in this study is higher than the 7 Mt CO_2eq in Bishwas (2023), as all end-use pathways, i.e., cooking substitution and biofertiliser, are included in the study, while electricity substitution alone is included in Bishwas (2023). However, the updated EEF of 0.53 tCO_2/MWh, compared to 0.67 in the original, offsets the higher GHG reduction estimate to some extent, as electricity substitution is reduced. The 31.6 Mt CO_2eq in Siddiki et al. (2021) is higher than the GHG reduction estimate in this study, as the EBTS is higher and the scope of feedstocks is broader; however, the figure is not directly comparable as the system boundary is different. Figure 6 is a radar chart comparing end-use pathway performance in terms of six evaluation dimensions.

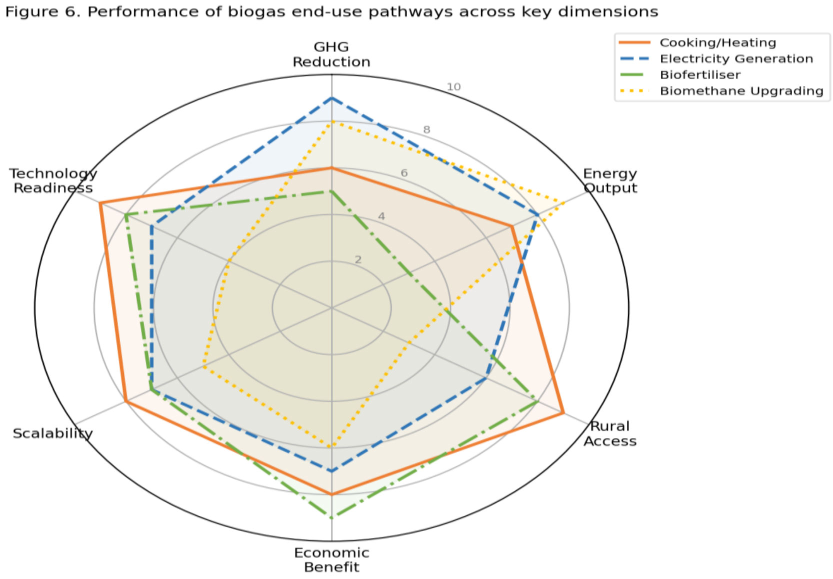

Figure 6. Performance of biogas end-used and biofertilizer pathways across key dimensions

Table 14. Summary of biogas end-use outcomes and GHG benefits

End-Use Pathway	Energy Output	GHG Reduction	Rural Access	Current Deployment Scale
Household cooking	163 PJ/yr thermal	6.20 Mt CO_2eq/yr	Very High	65,800+ plants
Rural electricity	23.25 TWh/yr	4.76 Mt CO_2eq/yr	Medium	Limited commercial
Biofertiliser	185 Mt digestate/yr	0.95 Mt CO_2eq/yr	High	Informal/limited
Biomethane upgrading	Future pathway	≈0.40 Mt CO_2eq/yr	Low	Not deployed
Total (full deployment)	-	13.20 Mt CO_2eq/yr	-	-

5 Discussion

5.1 Interpretation of Results

Moreover, the results of this thesis have established that the end-use of biogas in Bangladesh provides substantial and quantifiable greenhouse gas emission reductions benefits across various end-uses of biogas. The most important finding of this thesis is that the end-use of biogas in cooking substitution provides the single largest greenhouse gas emission reductions benefits at 6.20 $MtCO_2eq/y$. This finding is consistent with the global literature on the end-use of biogas in developing countries, which suggests that the end-use of biogas in cooking substitution is one of the most impactful greenhouse gas emission reductions interventions in developing countries, including in Bangladesh (Islam et al., 2021; Chowdhury et al., 2020).

The dominance of the cooking substitution end-use of biogas in this thesis stems from two reasons. Firstly, the amount of solid biomass consumed in cooking in rural Bangladesh is enormous, and the combustion of this biomass produces substantial greenhouse gas emissions. Secondly, the thermal efficiency advantage of biogas stoves in cooking substitution is substantial, with a biogas stove operating at 57 percent efficiency providing more than three times the useful energy output of a traditional biomass stove operating at 15 percent efficiency.

The end-use of biogas in electricity generation in rural areas of Bangladesh provides a greenhouse gas emission reductions benefit, although lower in magnitude than the end-use of biogas in cooking substitution at 4.76 $MtCO_2eq/y$ net of leakage. This end-use of biogas provides some developmental benefits in the sense that it provides electricity to areas of the country that are not connected to the national grid and also provides a greenhouse gas emission reductions benefit that is quantifiably measured against the national grid's greenhouse gas emission factor. The greenhouse gas emission reductions benefit of biogas electricity will decrease in the future as the national grid becomes increasingly decarbonized with the introduction of solar PV and other renewable energy sources.

The methane capture from livestock manure management, valued at approximately 2.1 Mt CO2 eq/yr, provides a GHG reduction benefit that is separate and independent from the energy end-use benefit. This benefit is derived solely from the prevention of uncontrolled methane emission from unmanaged manure. It would be obtained even if the captured methane is simply flared rather than being used productively. In reality, the economic incentive for productive use rather than flaring provides a self-reinforcing feature for this option.

The biofertilizer option, valued at approximately 0.95 Mt CO2 eq/yr, is the smallest of the three GHG reduction benefits. It is, however, worthy of note for the contribution it provides to the circular economy. In Bangladesh, fertilizers consume approximately USD 1.2 billion in subsidies every year. The country's independence from synthetic fertilizers would result in a co-benefit for the economy along with the GHG benefits. (Bishwas, 2023). The experimental results on the quality of digestate produced from AD of poultry dropping with a balanced NPK content and low pathogen levels provided in Khatun et al. (2023) support the value of this co-product.

5.2 Policy and Practical Implications

The results of this thesis have several significant implications for policy and practice in Bangladesh. The first is that the importance of the cooking substitution pathway for overall GHG reductions means that scaling up the IDCOL household biogas program currently serving 65,800 households should be a top priority. This is especially true since Bangladesh has 3 million households that have access to sufficient cattle manure for a household digester (Economic Feasibility Bangladesh Biogas, 2020). This means that even a 10 percent scaling of this program, which is well within IDCOL's reach, would more than double the existing program.

The second is that the amount of GHG reduction from biogas electricity generation, 4.76 MtCO2 eq/y, is a material contribution to Bangladesh's NDC commitment. In order for this potential to be realized, IDCOL and relevant government agencies need to extend their existing financial support and subsidies from household digesters to medium- and large-scale commercial biogas plants for livestock farms, slaughterhouses, and agro-industrial plants. Poultry farms, for instance, have nearly 100 percent manure availability coefficients and high EBTS values, making them prime targets for medium- and large-scale biogas plants.

Finally, the overall climate mitigation benefits of biogas end-use, now systematically quantified for the first time by this thesis, can serve as a credible foundation for carbon finance under Article 6 of the Paris Agreement. Bangladesh, as a least developed country, can proactively work on programmatic approaches for carbon finance for biogas-related

GHG reductions, using carbon revenues for subsidizing plant construction and operation costs.

Fourth, the experimental results from the research by Khatun et al. (2023) on the co-digestion of poultry droppings and banana peel offer an evidence-based solution to tackle two common waste types at once. This is an opportunity for extension services to disseminate information on different co-digestion techniques, especially for large-scale poultry farms where banana peel waste from market channels can be used for co-digestion with poultry droppings to maximize the energy output from biogas digesters, compared to the mono-digestion scenario.

Fifth, the results from the radar chart analysis presented in Figure 6 show that no single outcome is best across different dimensions. While cooking substitution is best for GHG reduction and rural access, electricity generation is best for energy output and scalability, and biofertilizer application is best for economic benefit to the farmer. Therefore, an optimum solution would involve the simultaneous pursuit of all outcome options, depending on the specific conditions of different regions in Bangladesh.

6 Conclusion and Recommendations

6.1 Summary of Findings

This thesis has examined the biogas end-use applications in Bangladesh and measured the GHG emission reduction that can be achieved by each utilization pathway, based on the latest available data published by BBS (2023) and DLS (2023-2024). The main conclusions are the following ones:

1. Biogas feedstock background: Bangladesh generates approximately 53.9 Mt of agricultural crop residues and 227.3 Mt of livestock and poultry manure annually hence the theoretical maximum potential of generating approximately 13.02 billion m 3 of biogas using livestock manure and 31.9 TWh of energy using crop residues through the mechanism of AD.
2. Household cooking substitution: If biogas is substituted for firewood, dried dung cakes, and kerosene, it could avoid around 6.20 Mt CO_2eq every year. This is the highest reduction potential from any single pathway and is possible by using already proven and widely available technology.
3. Rural electricity generation: If the electricity is produced from the biogas obtained from livestock manure and is utilized in the rural sector, it could avoid around 4.76 Mt CO_2eq every year net of methane leakage if it is substituted for the national grid (EEF = 0.53 tCO_2/MWh).
4. Methane capture benefit: If the methane is not released into the atmosphere in an uncontrolled manner from the livestock and poultry manure, it could avoid around 2.1 Mt CO_2eq every year, irrespective of the energy end-use avoidance.
5. Biofertilizer application: Biofertilizers obtained from the process of AD could avoid around 0.95 Mt CO_2eq every year by substituting synthetic urea fertilizer.
6. Cumulative GHG reduction: If all the above end-uses of biogas are fully utilized, it could provide the basis for achieving around 13.2 Mt CO_2eq every year by the year 2030, which is around 64 percent of the indicative NDC electricity sector contribution benchmark.

6.2 Conclusions

This thesis proves that the end-use of biogas in Bangladesh provides a large, quantified, and actionable opportunity for greenhouse gas emission reduction. The cooking substitution opportunity provides the greatest near-term mitigation opportunity, providing more greenhouse gas emission reduction for each unit of investment than any other opportunity for Bangladesh's level of biogas development. The electricity generation opportunity from livestock manure biogas provides the greatest medium-term opportunity and provides the greatest opportunity for direct engagement with Bangladesh's energy policy through grid emission factor benchmarking.

The aggregate greenhouse gas emission reduction opportunity of approximately 13.2 $MtCO_2eq/y$ from full biogas end-use development is significant compared to Bangladesh's NDC targets and can be realized through technologies that are technically ready for deployment in Bangladesh. The only barrier is not technological readiness but rather the policy and investment frameworks that can support deployment at the required scale.

6.3 Recommendations

Based on the findings of this study, the following recommendations are made for policymakers, practitioners, and researchers in Bangladesh:

1. Expansion of IDCOL's domestic biogas programme: The government should set a goal to achieve 500,000 domestic biogas systems by 2030, targeting cattle-keeping rural households for biogas use in cooking energy substitution. Increased subsidies for poorer families should be prioritized.
2. Mandate biogas systems in commercial livestock farms: The Ministry of Fisheries and Livestock should make it mandatory for commercial poultry and dairy farms above a certain scale to install biogas systems, using biogas for electricity generation and digestate for biofertilizer production.
3. Establishment of a national carbon finance programme for biogas: Bangladesh's climate finance institutions should develop a programmatic Article 6 mechanism for domestic biogas, to generate carbon revenues for cross subsidizing the cost of biogas plant installation.
4. Co-digestion in commercial biogas systems: Extension activities should be conducted to demonstrate the co-digestion of poultry droppings and banana peels,

following the validated results of Khatun et al. (2023), in pilot commercial biogas systems.

5. Biogas end-use targets in the updated Nationally Determined Contribution: The updated Nationally Determined Contribution should include specific targets for biogas cooking penetration and biogas electricity generation, along with associated MRV systems.
6. Digestate quality standards: The Bangladesh Agricultural Research Council should develop quality standards for biofertilizer from biogas digestate, to allow its safe and controlled use as a substitute for chemical fertilizers and to support the development of a commercial biofertilizer industry.

6.4 Suggestions for Future Research

Several avenues for further research become apparent considering this thesis. Firstly, a spatial analysis using GIS techniques on biogas end-use demand mapping cooking fuel usage patterns, electricity access deficits, and fertilizer demand in relation to livestock manure supplies would facilitate more effective planning strategies in biogas plant placement. Secondly, a life cycle analysis on all biogas end-use options in Bangladesh in terms of net GHG impact would give a more complete picture on this issue. Thirdly, techno-economic studies on medium-scale and large-scale commercial biogas plants in Bangladesh using prevailing cost data on equipment and financing options would be useful in facilitating investment decisions on this option. Fourthly, social science studies on factors influencing biogas adoption in cooking and electricity generation in Bangladesh, including gender and cultural considerations and willingness to pay, would also enhance this thesis's utility in behavior change communication strategies. Fifthly, studies on biomethane production using biogas from commercial livestock farms would give local data on this potential future biogas end-use option in Bangladesh.

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