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Emission reduction potential of a food waste-based biogas plant: Installation and lesson learned in Bhutan

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Abstract

Landfilling practices contribute significantly to greenhouse gas (GHG) and short-lived climate pollutant (SLCP) emissions, exacerbating climate and health risks. This study evaluates the emission reduction potential of a portable 1 ton per day (TPD) anaerobic digestion (biogas) plant in Samdrup Jongkhar, Bhutan, using food waste. An assessment was conducted using the Emission Quantification Tool (EQT) to compare baseline emissions (Business as Usual, BAU) with two scenarios: (1) biogas implementation with added fuel consumption for waste transport to the biogas plant, and (2) biogas implementation excluding transport emissions. Results indicate that BAU emits 1,274.21 kg CO_2*-eq/ton of waste, dominated by methane (43.94 kg/ton) and* CO_2 *(43.46 kg/ton). Scenario 1 reduced total GHG emissions (*CO_2*-eq) by 14.5%, while Scenario 2 achieved a 99.2% reduction, highlighting the impact of transport-related emissions. The biogas plant also demonstrated potential economic viability, offsetting 23 domestic LPG cylinders per month with net annual savings of Ngultrum (Nu.) 113,840.*

Keywords— post-harvest; Drying; performance; sustainable; temperature; efficiency

1 Introduction

Bhutan faces a growing waste management crisis, generating 172.16 metric tons (MT) of solid waste daily, 49% of which consist of organic food waste [1]. In Bhutan, the total greenhouse gas (GHG) emission from the waste sector was around 126.5 Gg CO_2-eq in 2015, and the trend for emissions is projected to increase by 41% (179 Gg CO_2-eq) by 2030 and 108% (263 Gg CO_2-eq) by 2050 [2]. The country's heavy reliance on landfills for waste disposal leads to significant methane emissions, which are 84 times more potent than carbon dioxide over a 20-year period [3]. Moreover, methane is responsible for 30% of the global increase in temperature and contributes 16% of global GHG emissions [5]. In the USA, municipal solid waste (MSW) landfills are the third-largest source of methane emissions [6], where food waste alone accounts for 21% of landfill contents [7]. Similarly, in 2016, 2.7% of India's total GHG emissions were attributed to the waste sector, of which 21.04% originated from solid waste disposal [8]. These emissions necessitate improved waste collection and disposal practices.

Despite Bhutan's strong policy commitments to sustainability, including its Carbon Neutrality Policy and the Zero Waste by 2030 initiative [9], implementation challenges persist. The country has promoted circular economy principles such as waste segregation and composting; however, it lacks sufficient infrastructure for large-scale recycling and waste-to-energy solutions. Current waste management practices remain inefficient because of inadequate waste collection and disposal systems. Although efforts have been made by the thromdes (municipal authorities) to segregate waste into organic and inorganic fractions and to establish scheduled collection for different waste streams, the segregated waste is often remixed at landfill sites, undermining these initiatives. Furthermore, recyclable materials such as PET bottles, paper, and cardboard are salvaged from landfill sites by private recycling firms; however, records of the quantities recovered remain unavailable.

One promising approach to improving waste segregation and reducing landfill disposal is the adoption of biogas technology, whereby biodegradable organic waste is used as feedstock for anaerobic digestion. Although biogas technology has been successfully deployed in rural Bhutan, these systems primarily utilize cattle manure to produce cooking gas for household use. The application of this technology for food waste treatment remains largely unexplored. Implementing food waste-based biogas systems could substantially reduce the quantity of waste disposed of in landfills, thereby improving waste management while reducing GHG emissions and odour nuisance. The methane generated can be effectively utilized for cooking and heating in boarding schools, colleges, and other institutions located near urban centres. Bhutan imported liquefied petroleum gas (LPG) worth Nu. 506 million and Nu. 487.29 million in 2023 and 2024, respectively [10; 11]. This heavy dependence on imported LPG highlights the urgent need for alternative renewable energy sources such as biogas derived from food waste.

A study reported that urban centres in Bhutan generate approximately 0.53 kg of waste per capita per day, of which 58% is organic waste. Similarly, another study found that approximately 46% of municipal solid waste consists of organic food waste [11; 1]. These findings present a significant opportunity for investment in composting and waste-to-energy technologies such as anaerobic digestion. A comprehensive study conducted in India demonstrated that biogas generated from organic waste has the potential to replace approximately 47% of the country's gross electricity generation [13]. To support waste-to-energy development, India has installed over 5.1 million biogas plants with a combined production capacity of approximately 4.43 million m^3 of biogas per day, equivalent to about 47 GW or 3.2 billion cubic metres (BCM) annually. Additionally, large-scale urban waste-to-energy projects contribute approximately 771,008 m^3 of biogas per day, producing 264,467 kg of bio-CNG daily and generating an equivalent of 401.79 MW of electrical power through both grid-connected and off-grid systems [14].

The European Union (EU) also promotes circular economy principles by encouraging the conversion of organic and food waste into energy through biogas technology [15]. In 2023, the EU produced 4.9 BCM of biomethane and 17.1 BCM of biogas for heating and electricity generation [16]. Furthermore, the EU has the potential to generate 44 BCM and 91 BCM of biomethane annually by 2030 and 2050, respectively, through anaerobic digestion alone [17; 18]. As of July 2024, the EU had more than 1,548 biomethane production plants [16]. These large-scale government initiatives demonstrate the importance of proactive investment in waste-to-energy technologies for sustainable waste management. In Bhutan, food waste-based biogas plants remain limited. However, in 2022, with support from WWF and the National Environment Commission (NEC), a portable 1 TPD biogas plant was installed at Jigme Namgyel Engineering College (JNEC). Furthermore, in 2025, Bhutan commissioned its first utility-scale 20 TPD biogas plant with support from the SAARC Development Fund [19; 20].

This study analyses the emission reduction potential and economic viability of the portable biogas plant while also examining the practical challenges associated with its operation and maintenance. Specifically, the study compares baseline emissions with two operational scenarios—one accounting for transport-related emissions and another excluding transport emissions—using the Emission Quantification Tool (EQT) [21]. The study further evaluates the economic feasibility of biogas adoption by estimating potential savings from LPG displacement and the beneficial reuse of digestate in agriculture. By providing empirical evidence on the environmental and economic performance of food waste-based biogas systems, this research contributes to Bhutan's transition towards sustainable waste management and supports the implementation of national policies promoting circular economy and low-carbon development.

2 Materials and Methods

2.1 Study Area

Samdrup Jongkhar Dzongkhag (District) is in the Southeastern part of Bhutan bordering the Indian state of Assam in the south as shown in Fig 1. Samdrup Jongkhar is characterized by the hot and humid climate during the monsoon and cool during the winter. Samdrup Jongkhar is the one of the districts receiving highest amount of rainfall with about 3700 mm annually and temperature ranging from 9°C to 38°C. It is also one the districts in Bhutan that have a municipality (Thromde), named Samdrup Jongkhar Thromde (SJT). It has also one extended thromde known as Dewathang Thromde (DT) which is 18 km away from SJT. The thromde combined has a total population of 10,545. The portable 1 TPD biogas plant is installed in Jigme Namgyel Engineering College (JNEC) in Dewathang.

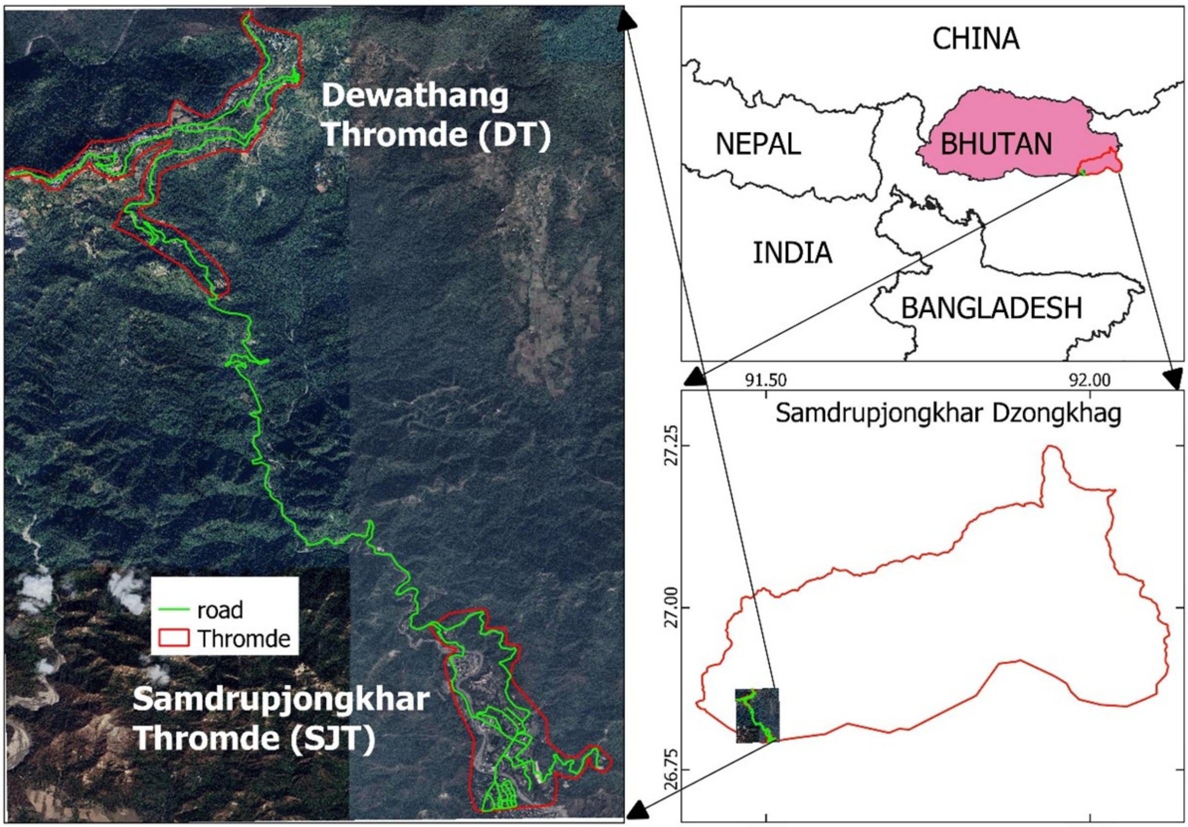

Figure 1: Study Area

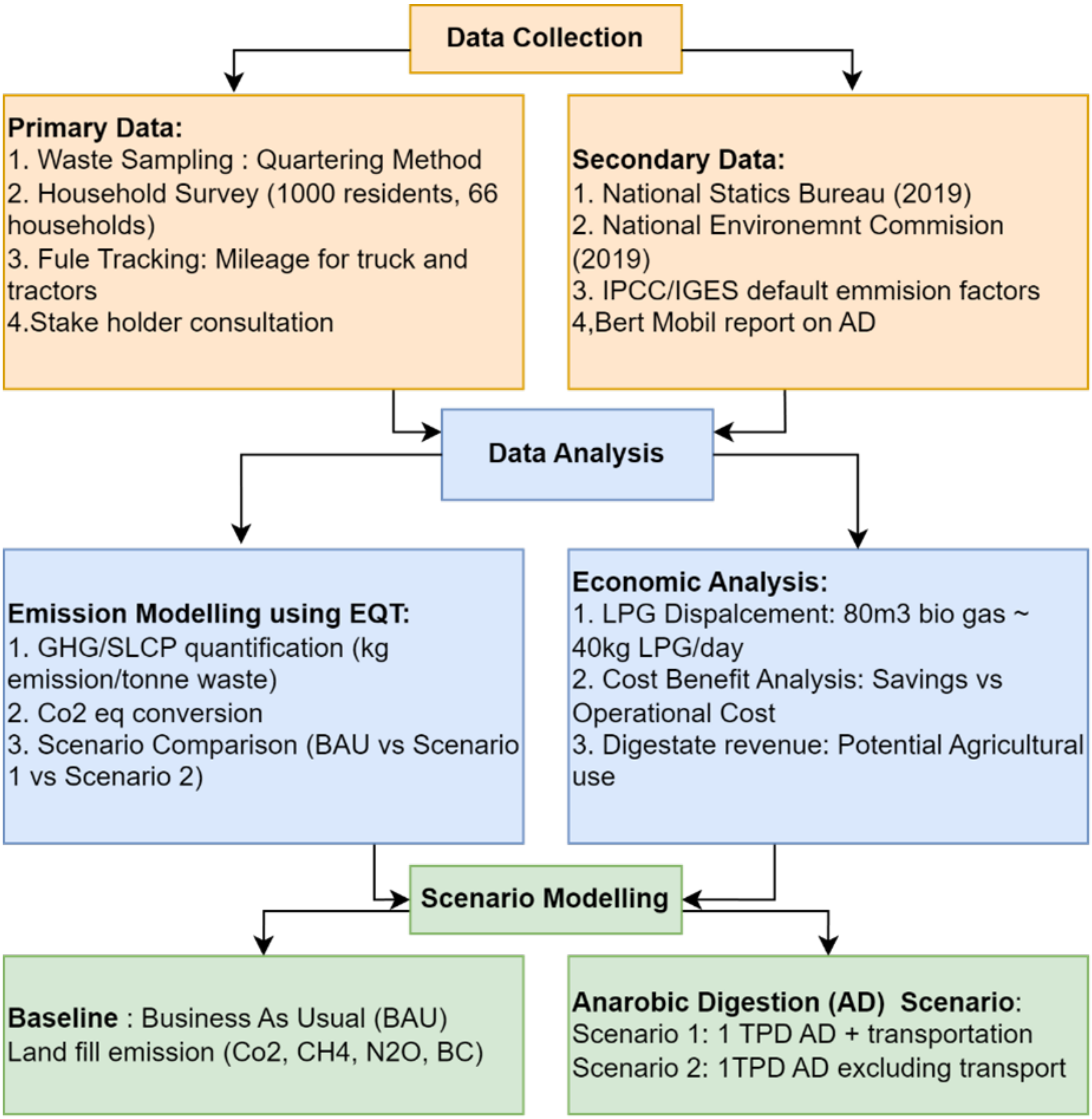

Figure 2: Methodology

The study follows the overall approach as shown in Fig 2. The approach begins with data collection, which is primarily divided into primary and secondary data. Primary data sources include waste sampling at landfill, a household survey covering 1000 residents across 66 households, fuel tracking for trucks and tractors and stakeholder consultations. Waste sampling was carried out using a quartering method in which the waste from the dump trucks was divided into 4 equal parts. In this study waste sampling was basically carried out from one single part only. Waste sampling was carried out continuously for two weeks (May to June 2022) at the landfill site when the dump truck disposed of the waste at landfill.

Fig 3 shows the waste collection schedule for both the towns in Samdrup Jongkhar. The fuel consumed by the dump trucks and tractors were also tracked using the vehicle mileage. In this study the total average fuel consumed by combining all the waste carrying vehicles was 36.79 litters/day. This is inclusive of operational fuel consumption. This means total fuel consumption in a week was 257.58 liters.

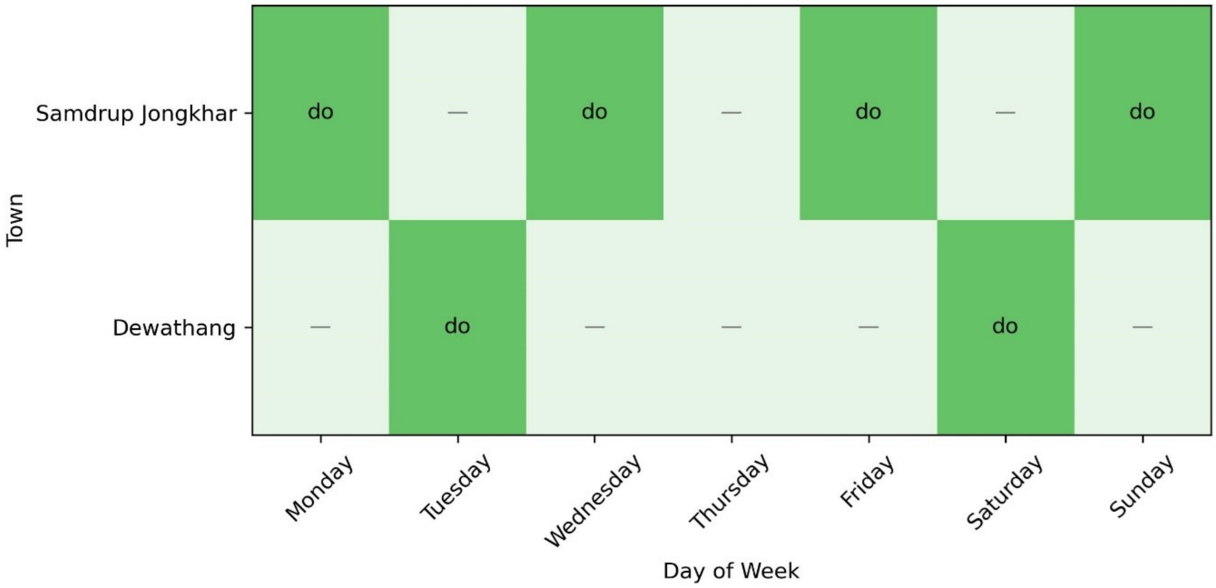

Figure 3: Waste Collection Schedule as of July 2022

Secondary data sources include reports from the [1], the National Environment Commission, default emission factors from IPCC/IGES [22], and the Bert Mobil report on anaerobic digestion [23]. Following the data collection, the study proceeds to data analysis, which involves two key components: emission modelling and economic analysis. The study assessed the biogas emission reduction potential using the EQT developed by the Institute for Global Environmental Strategies (IGES). This tool enables rapid evaluation of GHG and SLCP emissions across the entire waste management system. This tool converts emissions from waste into CO equivalent values and compares different scenarios (Business As Usual (BAU) versus alternative scenarios). Two scenarios were modelled:

- **Business As Usual (BAU):** Existing waste collection, transport, and landfill practices.
- **Scenario 1:** Integration of a 1 TPD anaerobic digestion (biogas) plant with added fuel consumption for food waste transportation to biogas plant by one tractor every day.
- **Scenario 2:** biogas implementation excluding fuel consumption for transportation of food waste to biogas with the assumption that biogas plant is located near by the landfill area.

Furthermore, the study also assessed the economic viability of adopting biogas by analysing the displacement of LPG cylinders used as a case study in JNEC. It evaluates cost benefit in terms of savings versus operational costs and considers the potential agricultural use of digestate from anaerobic digestion.

3 Results

3.1 Waste Collection and Dumping

The total waste dumped from Samdrup Jongkhar town was 2.057 tons/day while the total waste dumped from Dewathang town was 0.666 tons/day making a gross total of 2.723 tons/day dumped at the landfill. It was found out that the plastics and papers were the maximum proportion of waste being dumped at the landfill with 18.65% and 18.07% respectively. On the other hand, food waste dumped at the landfill constitutes only 15.86% equivalent to 0.432 tons/day. The proportion of the other waste dumped at the landfill is shown in Fig 4.

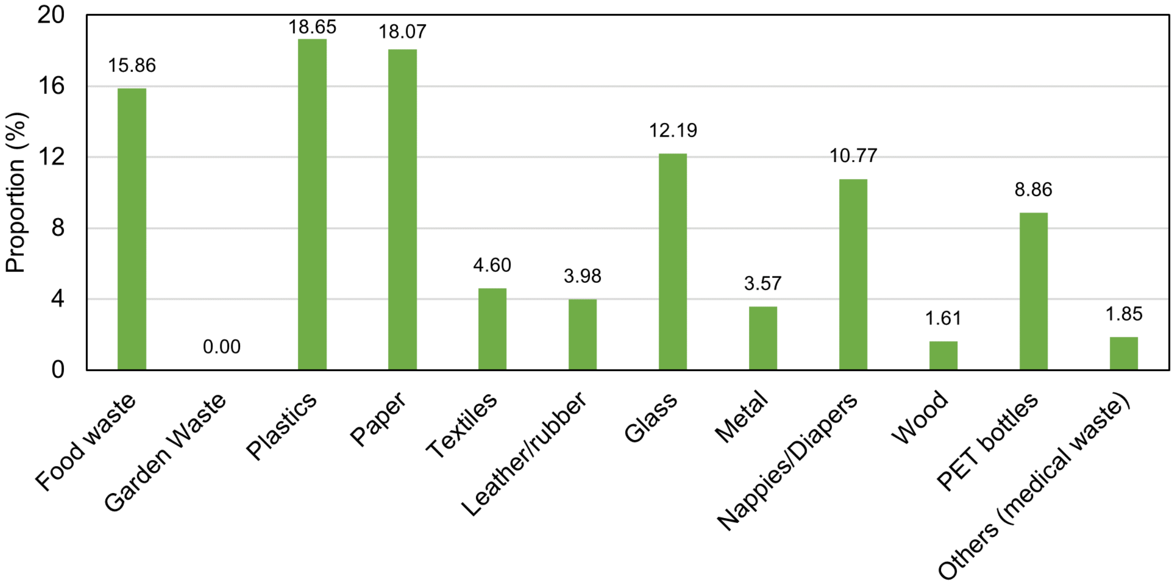

Figure 4: Combined waste composition from both the towns dumped at the landfill. The data reflected above are observations made for two weeks' duration.

3.2 Baseline Emissions (Business as Usual, BAU)

Under current waste management practices in SJT and DT, the GHG and SLCP emissions per ton of waste are quantified and are shown in Table 1:

Table 1: BAU emission (current waste management practices)

GHG/SLCP	**Emission per ton waste**
Methane (CH_4)	43.938 kg/ton
Black Carbon (BC)	0.018 kg/ton
Carbon Dioxide (CO_2)	43.464 kg/ton
Nitrous Oxide (N_2O)	0.002 kg/ton
Total GHG emissions (CO_2 eq)	**1,274.21 kg/ton**

The two towns (SJT and DT) combined emit a total annual CO_2 eq emission of 200.83 ton approximately from food waste and 1266.6 ton from total waste, as shown in Table 2.

Table 2: CO_2 emission from food waste and total waste

Waste	**Combined waste (ton/day)**	**Combined waste (ton/year)**	**CO_2 eq/year**
Food Waste	0.432	157.6	$157.6 \times 1.27421 = 200.82$ ton
Total Waste	2.723	994	$994 \times 1.27421 = 1266.6$ ton

3.3 Scenario 1: biogas plant installation with transportation emissions

In this scenario, a 1 TPD biogas plant is installed, where an additional fuel consumption of 8.4 liters/day is considered for transportation (50 km to and fro) of food waste to the biogas plant from the collection point. This scenario results in an overall reduction of total GHG emissions (CO_2 eq) by 14.5% with respect to BAU, as shown in Table 3.

Table 3: Scenario 1 emission

GHG/SLCP	Emission per ton waste	% Reduction w.r.t BAU
Methane (CH_4)	37.795 kg/ton	13.98%
Black Carbon (BC)	0.011 kg/ton	38.89%
Carbon Dioxide (CO_2)	23.660 kg/ton	45.56%
Nitrous Oxide (N_2O)	0.001 kg/ton	50%
Total GHG emissions (CO_2 eq)	**1,089.45 kg/ton**	**14.5%**

3.4 Scenario 2: biogas plant installation excluding transportation emissions

In this scenario, 1TPD biogas plant is installed excluding the fuel consumption for food waste transportation. It is assumed that it is not required to transport food waste. The emission for this scenario is shown in Table 4.

Table 4: Scenario 2 emission

GHG/SLCP	Emission per ton waste	% Reduction w.r.t BAU
Methane (CH_4)	0.144 kg/ton	99.67%
Black Carbon (BC)	0.005 kg/ton	72.22%
Carbon Dioxide (CO_2)	5.692 kg/ton	86.90%
Nitrous Oxide (N_2O)	0.001 kg/ton	50%
Total GHG emissions (CO_2 eq)	**10.11 kg/ton**	**99.2%**

3.5 Economic Viability

Although the total capacity of the biogas plant is 1 ton, only 0.432 ton is fed into the plant daily. A 1 TPD biogas plant produces approximately 80 m^3/day of biogas, which means that with the current input of 0.432 tons/day, approximately only 34.56 m^3/day of biogas will be produced. Considering 70% operational efficiency of the biogas plant, only 24.2 m^3/day of biogas is available for use. Moreover, 60% of the biogas constitutes methane and 40% carbon dioxide [23]. Therefore, the total available fuel for burning is only 14.52 m^3/day.

As per the specification of the biogas plant, the calorific value of biogas is 21 MJ/m^3, while the calorific value of Liquefied Petroleum Gas (LPG) is 46 MJ/kg. The detailed comparison between biogas and LPG is shown in Table 5.

Table 5: Energy equivalent from Biogas

Gas	Quantity	Calorific value	Energy	Remarks
LPG	14.2 kg	46 MJ/kg	$14.2 \times 46 = 653.2$ MJ	1 LPG
Biogas	24.2 m^3/day	21 MJ/m^3	$24.2 \times 21 = 508$ MJ/day	0.78 LPG cylinders/day

It is observed that 24.2 m^3/day of biogas is equivalent to 0.78 LPG cylinders/day.

LPG cylinders saved per month = 0.78 LPG cylinders/day × 30 days = 23 LPG cylinders/month.

To analyse the cost saving, LPG consumption of a student hostel at Jigme Namgyel Engineering College (JNEC), Dewathang located in Samdrup Jongkhar is taken as the case study. On average, 18 LPG cylinders are consumed every month in JNEC. Since each LPG cylinder costs around Nu. 990, the total cost of LPG is Nu. 17,280/month. Therefore, the annual cost for LPG consumption in JNEC is Nu. 213,840.

Based on the above analysis, the use of biogas can completely offset the LPG consumption in JNEC. Therefore, JNEC can save Nu. 213,840 annually, which otherwise would have been spent on LPG consumption. However, considering the annual operation and maintenance cost of Nu. 100,000, JNEC can have a net saving of Nu. 113,840 annually.

Moreover, the community in JNEC can also benefit from the digestate slurry produced as a byproduct from the biogas, which can be used as a potential organic manure, further offsetting the use of chemical fertilizers and promoting organic agriculture.

4 Discussion

The study analysed only the waste that was disposed of in the landfill located in Samdrup Jongkhar. It was not feasible to collect household waste because residents located away from town disposed of food waste directly into kitchen gardens. A few households were also observed burning solid waste generated in their backyards. Therefore, these observations necessitated sampling directly at the landfill site to quantify the overall waste generation from DT and SJT. Based on sampling over two weeks, it was observed that 15.85% of the total waste constitutes food waste that is disposed of in the landfill, while the national average food waste generation is 49.6% [**?**]. This implies that around 34% (49.6 – 15.85) is either disposed of in kitchen gardens or openly dumped.

The adoption of a portable 1 TPD biogas plant offers potential benefits in the management of food waste, drastic reduction of GHG emissions, and cost savings from the use of generated biogas. When the biogas plant was installed at JNEC, all food waste from the towns was diverted to the biogas plant, significantly reducing the dumping of food waste in the landfill. It was also observed that the landfill became relatively odor-free. Furthermore, based on EQT modelling of the biogas plant under Scenario 1, total GHG emissions (CO_2 eq) were reduced by 14.5%. It was also interesting to note a sharp decline in total GHG emissions by 99.2% for Scenario 2. These variations in emissions between the two scenarios emphasize the role of transportation in waste management. In this study, the biogas plant was located 20 km away from SJT, meaning the waste-carrying vehicle must travel 40 km in total considering both ways. The results suggest that to minimize emissions, the location of biogas plants should not be too far from waste collection points. Moreover, the cost-benefit analysis from the expected generation of biogas indicates that its use can completely offset current LPG consumption in JNEC and is anticipated to generate a net annual saving of Nu. 113,840.

4.1 Installation of portable 1 TPD biogas in JNEC and Lesson Learned

The 1 TPD biogas plant was installed in JNEC with the support from WWF, Thimphu, Bhutan. JNEC was essentially chosen because of daily generation of food waste from the student kitchen. Despite the enormous benefit from adoption of biogas plant, the installation and operation of the plant was faced with enormous challenges. Firstly, it was difficult to get the consistent amount of food waste. The daily required food waste was one ton; however, the plant received only 0.4 tons every day. This resulted in the under operation of the plant by inhibiting the formation of bacterial growth in the plant days causing low methane yield. Secondly, the food collected from the towns often contained inorganic substances such as metal spoon, forks, plastic wrappers, paper, glasses and clothes which affected the overall operation of the biogas plant. Finally, there is no dedicated manpower or technical expertise for daily operation and maintenance of the plant. For instance, during the winter season, excessive amounts of orange peels were found in the food waste which was directly fed into the plant causing pH imbalance due to its acidic nature. This had a negative impact on the plant thereby reducing the growth of bacteria. To counteract this effect a certain amount of limestone (calcium carbonate) was added to neutralize the acid formation, however there were no signs of improvements. All these factors led to low production of biogas and at times had to be completely shut down for maintenance.

Moreover, the biogas plant was located near the student kitchen and dining hall and hence the student felt the pungent odor from the digestate slurry thus inhibiting the operation of the plant. A comprehensive study [24–26] revealed that the use of additives such as organic, inorganic and microbial agents has significant potential in increasing the methane yield and improving the overall efficiency of the plant. Organic additives include biochar[27], activated carbon and graphene which provides high surface area that facilitates enhanced microbial adhesion and accelerated microbial growth while inorganic additives include essential micronutrients such as iron, cobalt nickel which serve as cofactors for key enzymes in the generation of methane. Pretreatment of food waste before feeding the bigas has also shown promising results [25].

4.2 Key Recommendations

The study suggests the following recommendations for the efficient operation of the biogas plant:

- Choose the capacity of the biogas plant based on the availability of food waste. 1 TPD plant is highly viable for the urban centers like Thimphu, Gelephu and Phuntsholing because of apparent higher generation of food waste owing to population size.
- Prioritize the waste segregation strictly in the urban centers. Biodegradable waste (food waste) should be collected separately and should not contain any inorganic materials such as metal, plastic, paper, glasses and fabrics. This eases the pretreatment of food waste and improves the efficacy of the biogas plant.
- Install the plant at a strategic place and the route should be optimized to minimize the transportation logistics to the plant. Moreover, it should be away from the urban center and at the same time the odor from the digestate should not affect the residents.
- Dedicated and trained professionals must be kept in charge of daily operation and maintenance of the biogas plant.
- The digestate slurry produced as a byproduct form the biogas should be efficiently used as alternative manure. Prolonged storage of digestate results in pungent odors affecting the nearby environment.
- Adequate additives must be added to facilitate higher methane generation.

5 Conclusion

Municipal solid waste has been a major challenge for developing countries like Bhutan, which has been grappling with issues of collection, disposal, and reuse. Much of the waste collected from urban areas is typically dumped in landfill sites. Several thromdes (municipal towns) in Bhutan have initiated separate collection of biodegradable waste. However, once collected, these wastes are ultimately dumped in landfills, making the entire collection process largely ineffective. Waste is also one of the major contributors to environmental pollution, including the emission of greenhouse gases such as carbon dioxide and methane.

To reduce greenhouse gas emissions, this study aims to assess the life cycle of a portable 1 TPD biogas plant installed at JNEC, Dewathang, Samdrup Jongkhar. It also attempts to understand the emission reduction potential of the plant. The study began with data sampling at the landfill site using the quartering method. The data included waste from both towns, Dewathang and Samdrup Jongkhar. A consultation workshop was also held with the environmental officer to validate the overall weight of the sampled data against the waste collected by waste-carrying vehicles. Fuel consumption by waste-carrying vehicles was also validated by the environmental officer of the thromde.

Based on the sampled waste data from both towns, food waste constituted 15.86%, while plastic and paper constituted 18.65% and 18.07%, respectively.

The study further assessed the emission reduction potential of the plant under different scenarios. Scenario 1 and Scenario 2 reduced total GHG (CO_2 eq) emissions by 14.2% and 99.2%, respectively, with respect to current waste management practices. Furthermore, if the plant operates at 70% efficiency, it is expected to produce biogas of 24.2 m^3/day, which is equivalent to 23 LPG cylinders/month. As a result, JNEC can save Nu. 113,840 annually by offsetting LPG consumption. JNEC can also benefit from the sale of digestate slurry as organic manure. This demonstrates significant benefits of biogas in enhancing waste management efficiency, reducing GHG emissions, and improving economic outcomes. However, several challenges need to be addressed before realizing these benefits. Waste must be adequately segregated at source, and dedicated trained personnel must be appointed for daily operation of the plant. Furthermore, the plant must be strategically located to optimize collection and disposal routes and to minimize odor exposure from digestate slurry. By addressing these challenges, JNEC can support the national goal of advancing the Zero Waste 2030 policy while minimizing GHG emissions.

The adoption and installation of the biogas plant at JNEC directly supports Bhutan's National Waste Management Flagship Program to achieve Zero Waste Bhutan by 2030 [9]. The initiative also aligns with the following acts [28;29].

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