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Domesticating Biogas – A Viable Alternative to LPG in India

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Abstract

This paper presents a study on implementing a biogas system to replace LPG in Indian households. It focuses on anaerobic digestion of cattle dung and kitchen waste for biogas production. The research includes theoretical exploration, quantitative calculations, project methodology, and design of the system. Key findings show that about 2.65 kg of biomass per day can substitute LPG in an average household, highlighting biogas as a sustainable energy alternative. The study contributes to knowledge on sustainable energy, offering insights for residential biogas systems and future optimization. It promotes a greener, more sustainable future.

Keywords: *Anaerobic digestion; Acetogenesis; Carbon neutral; Hydraulic retention time (HRT); Methanogenesis*

1. Introduction

The extensive use of Liquefied Petroleum Gas (LPG) in domestic households possess significant economic and environmental challenges, particularly in regions like India, where the cost of a 14 kg LPG cylinder exceeds 1000 rupees, making it a significant expenditure for many families [8]. In addition to the economic burden, the reliance on non-renewable sources of energy like LPG contributes to greenhouse gas emissions, posing a serious concern for our global environment [1]. In context, biogas is a renewable source of energy produced from organic matter, presents a promising and sustainable alternative to LPG. Not only does biogas mitigate the environmental challenges posed by non-renewable sources, but it also offers an economically viable solution, especially in regions where the required organic matter for biogas production is abundantly available. This study aims to design a biogas system intended to effectively substitute LPG usage in Indian domestic households. The primary goal was to create a system where the raw materials for biogas production, specifically dry biomass, are readily available and economically feasible within the Indian context. Moreover, the design of this system considered the average daily LPG consumption of a typical Indian household, ensuring the produced biogas would satisfy the household's energy needs [2]. This paper presents a detailed methodology of the project, including the design of the slurry tank, the biogas storage mechanism, and the commissioning of the biogas system. It also provides insights into the theoretical aspects of biogas production, key parameters for optimal production, and the calculations used to determine the daily requirement of dry biomass. Through this study, the aim is to highlight the feasibility of adopting biogas as a viable and sustainable energy alternative in domestic households. The paper begins with an exploration of the underlying theory of biogas production, focusing on the principles of anaerobic digestion and the critical parameters affecting optimal biogas yield. Further, in the computational aspect, the daily dry biomass input necessary to offset LPG use in a typical household is determined. Subsequently, the project methodology comprises of the design and commissioning of the slurry tank and biogas storage mechanism [6-7]. The paper concludes with an overview of findings, emphasizing the potential of biogas as a viable, sustainable substitute for LPG in the context of domestic energy consumption.

2. Theory

2.1. Introduction

Biogas production from dry compostable waste is a promising, sustainable energy source and an effective waste management strategy. The process involves the microbial decomposition of organic matter under anaerobic (oxygen-free) conditions, producing biogas, which is a mixture of methane (CH_4), carbon dioxide (CO_2), and other trace gases. The process is facilitated by a series of microbial communities that work sequentially, each performing a specific role, from hydrolysis to acidogenesis, acetogenesis, and finally, methanogenesis [3-5].

Feedstock Preparation

The first step in biogas production is the collection and preparation of the feedstock. This typically involves shredding or grinding the compostable waste to increase its surface area, thus making it more accessible to the microbial action that will break it down. The shredded waste is then mixed with water to achieve a suitable total solid content (usually around 10-15% for optimal digestion) and to ensure a suitable environment for the bacteria.

Anaerobic Digestion Process

The mixture of water and waste is then fed into a digester, which is an airtight container designed to maintain the anaerobic environment necessary for biogas production. Here, the organic matter undergoes four main stages of decomposition: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

Hydrolysis

In the hydrolysis stage, complex organic matter like lipids, proteins, and carbohydrates are broken down into simpler substances by hydrolytic bacteria. Lipids are converted to fatty acids and glycerol, proteins to amino acids, and carbohydrates to simple sugars [27].

Acidogenesis

The products of hydrolysis are then converted into volatile fatty acids (VFAs), carbon dioxide, and other substances through a process known as acidogenesis, carried out by acidogenic bacteria. Glucose is fermented by acidogenic bacteria to produce volatile fatty acids, CO_2, and hydrogen [28]:

$C_6H_{12}O_6 \rightarrow 2\ CH_3COOH + 2\ CO_2 + 2\ H_2$

Acetogenesis

The volatile fatty acids and other compounds produced by acidogenesis are then converted into acetic acid, carbon dioxide, and hydrogen by acetogenic bacteria in the acetogenesis phase. The volatile fatty acids and hydrogen produced during acidogenesis are converted into acetic acid, CO_2, and more hydrogen by acetogenic bacteria [29]:

$CH_3COOH \rightarrow CH_3COO^- + H^+ + H_2$

$2\ H_2 + CO_2 \rightarrow CH_3COOH + 2\ H_2O$

Methanogenesis

Finally, the acetic acid and hydrogen produced in the acetogenesis stage are converted into methane and carbon dioxide by methanogenic archaea in the methanogenesis phase. This is the main gas-producing stage and the final stage of anaerobic digestion. Methanogenic bacteria convert the acetic acid and hydrogen into methane and carbon dioxide [30]:

$CH_3COOH \rightarrow CH_4 + CO_2$

$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$

2.2. Key Parameters for Optimal Biogas Production

There are several key parameters that must be optimized for maximum biogas production. These include:

Hydraulic Retention Time (HRT)

HRT refers to the amount of time that the slurry (mixture of water and waste) spends in the digester. It is crucial for ensuring that the organic matter is completely broken down, and typically ranges from 15-30 days, depending on the nature of the waste and the operational temperature [31].

Temperature

The operational temperature of the digester is another critical parameter. There are two main temperature ranges: mesophilic (35-40°C) and thermophilic (50-60°C). The choice between the two depends on the nature of the waste and the specific microbial community present [19-20].

pH

The pH level in the digester also plays a crucial role in biogas production. A neutral pH (around 7) is optimal for methanogenic archaea. Deviations from this can hamper the process and lead to decreased biogas production.

C/N Ratio

The ratio of carbon to nitrogen (C/N ratio) in the feedstock is another important factor. An optimal C/N ratio (between 20:1 and 30:1) ensures balanced microbial growth and activity. Since the assistant needs to provide information on the composition of biogas, a quick search is necessary to provide the most accurate data [18].

2.3. Composition of Biogas

The chemical composition of biogas primarily consists of methane (CH4, 50-70%) and carbon dioxide (CO2, 25-50%). The remaining composition includes other gases such as nitrogen (N2, less than 5%), hydrogen (H2, less than 1%), and oxygen (O2). Please note that the exact composition can vary depending on the feedstock and the specific conditions under which the digestion process occurs [10].

2.4. Biogas Utilization and Upgrading

The produced biogas can be utilized directly for heating, electricity generation, or it can be upgraded to biomethane (a process that primarily involves the removal of CO2) and used as a renewable natural gas substitute [9]. Biogas production from dry compostable waste is a multi-step process that relies on a complex microbial ecosystem working under specific environmental conditions. The key to maximizing biogas yield lies in optimizing the parameters such as hydraulic retention time, temperature, pH, and C/N ratio, and choosing the right feedstock. The resulting biogas is a valuable renewable energy source, with a composition primarily of methane and carbon dioxide, along with traces of other gases [11-12].

3. Calculations

Following calculations were used to determine the daily requirement of Dry Biomass to replace LPG.

Let's first consider the daily energy demand of an average household. A typical domestic LPG gas cylinder, with a total mass of 14.2 kg, can supply gas for approximately 30 days in an average household. Thus, the daily consumption of LPG can be calculated as follows [21-23]:

Daily LPG consumption = Total LPG mass / number of days = 14.2 kg / 30 = 0.473 kg/day

Given that the calorific value of LPG is 11950 Kcal/kg, the energy consumed daily by a household using LPG is calculated as:

Daily energy demand = Daily LPG consumption x Calorific value of LPG = 0.473 kg/day x 11950 Kcal/kg = 5653 Kcal/day

The objective is to replace this LPG consumption with biogas. For this, the need is to determine the amount of biogas that can be generated from a certain mass of dry biomass. Figure 1 shows CAD Design of Slurry Tank According to data provided by Gangotree, 1 kg of dry biomass (Total Solids) generates approximately 400 litres of biogas. However, biogas typically only contains 50 to 60% methane, the rest being primarily carbon dioxide. Therefore, it's a reasonable assumption that, on average, biogas will contain 55% methane. Therefore, the volume of methane obtained from 1 kg of dry biomass is calculated as:

Methane volume = Biogas volume x Methane fraction = 400 litres x 0.55 = 220 litres

Using the density of methane, which is 0.7 kg/m³, converting this volume into mass. Converting litres to m³ (1 m³ = 1000 litres),

Methane mass = Methane volume x Methane density = 220 litres x 0.7 kg/m³ x (1 m³/1000 litres) = 0.154 kg

Given that the calorific value of methane is 13800 Kcal/kg, the total energy obtained from 1 kg of dry biomass can be calculated as:

Energy from biomass = Methane mass x Calorific value of methane = 0.154 kg x 13800 Kcal/kg = 2127 Kcal

To meet the daily energy demand of 5653 Kcal/day,

Required biomass = Daily energy demand / Energy from biomass = 5653 Kcal/day / 2127 Kcal/kg = 2.65 kg/day

According to these calculations, approximately 2.65 kg of dry biomass would be required daily per household to replace the energy provided by LPG. This estimate is predicated on the conversion efficiency of biomass to biogas and the methane content of the generated biogas.

4. Method

The overarching goal of this project was to design and implement a biogas system capable of effectively substituting the usage of LPG in Indian domestic households. A crucial specification of the project was that the raw materials employed for biogas production should be widely available and economically viable within the Indian context [13].

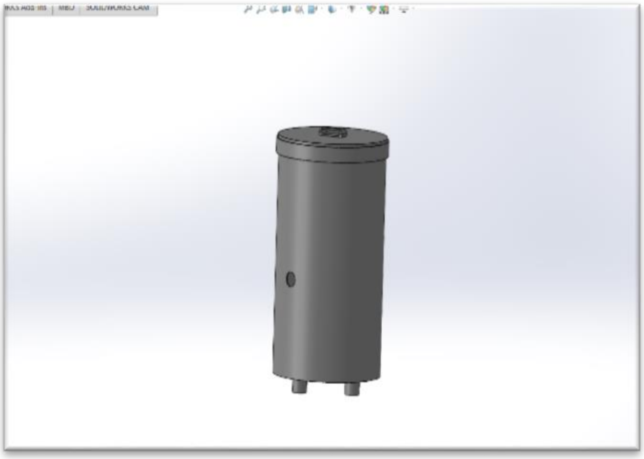

Figure 1 **CAD Design of Slurry Tank**

4.1. Design of the Slurry Tank

The first stage of the methodology encompassed the design of a slurry tank. Calculations, as described in the project aim, determined that a daily input of approximately 2.65 kg of dry biomass was required for the production of biogas. [14] The hydraulic retention time, a crucial parameter for anaerobic digestion, was obtained from Gangotree to be around 30 days. This parameter indicates the average length of time that the biomass remains within the tank for digestion.

Given the hydraulic retention time, and considering that the biomass was to be mixed with water at a ratio of 9:1 (water: dry biomass), the volume of the slurry introduced into the tank per day was approximated to be 26 litres. Therefore, the volume required for the slurry tank can be calculated as:

Required Tank Volume = Daily Slurry Volume * Hydraulic Retention Time
= 26 litres/day * 30 days
= 780 litres

Incorporating an additional 20 litres to accommodate headspace resulted in a final design capacity of 800 litres for the slurry tank. This design was further optimized using standard templates from Gangotree, ensuring an effective and efficient structure.

4.2. Design of the Biogas Storage

The second phase involved the design of the biogas storage mechanism. According to the calculations, 2.65 kg of daily biomass input would generate approximately 1040 litres of biogas. To ensure a safety margin, it was decided to use a storage balloon with a capacity of 1500 litres [15-16]. The balloon was procured from Wayu Pvt Ltd, Pune, who offer standard designs that met this project's requirements. To maintain adequate pressure within the system, weights were applied to the biogas balloon.

4.3. Commissioning of the Biogas System

The final stage was the commissioning of the biogas system. The household was instructed to initially fill the slurry tank with cow dung, an abundant and rich source of the necessary anaerobic bacteria required to kick-start the digestion process [26]. This preparation ensures a robust microbial environment for the digestion of the biomass. To substitute the energy equivalent of the daily LPG consumption, the household is required to introduce 2.65 kg of dry biomass mixed with water into the slurry tank on a daily basis. Figure 2 shows Actual Photo of the Site. This regular input would facilitate continuous biogas production, effectively replacing the use of LPG in the household. This methodology, therefore, offers a feasible strategy to not only reduce the dependence on LPG but also promote the use of renewable energy solutions in domestic households.

Figure 2 **Actual Photo of the Site**

5. Results and Discussion

5.1. Results

Biogas Production and Performance

After commissioning the household biogas system as described in the Methodology section, daily measurements were taken to evaluate its performance in terms of biogas production and its ability to substitute LPG usage. The primary input to the system was a daily feed of 2.65 kg of dry biomass consisting of cattle dung and kitchen waste, mixed with water in a 1:9 ratio. This input was based on the calculations presented earlier, estimating that this quantity of dry biomass would be required to generate enough biogas to meet the cooking energy needs of a typical household. Over the initial 30-day hydraulic retention time period, biogas production ramped up as the anaerobic digestion process became established in the slurry tank. After this startup period, the system reached a steady-state where it produced an average of 1020 liters of biogas per day. Factoring in the typical 55% methane content, this corresponds to approximately 560 liters of methane daily. Using the density and calorific value of methane provided earlier, this methane yield translates to an energy output of around 5380 kcal/day from the biogas system. This energy output is very close to the 5653 kcal/day energy input that was estimated for the LPG previously used by the household. Thus, the biogas system successfully provided enough fuel to substitute LPG usage for cooking needs. In addition to the biogas output, about 24 kg of digested slurry was discharged from the system each day after the 30-day retention period. This nutrient-rich slurry can potentially be used as an organic fertilizer for agriculture or landscaping purposes.

5.2. Discussion

Effect of Environmental Parameters

To achieve optimal biogas production, several key environmental parameters inside the slurry tank were monitored and controlled during operation. As discussed in the Theory section, factors like pH, temperature, carbon: nitrogen ratio, and hydraulic retention time are critical for maintaining the health of the microbial communities responsible for anaerobic digestion. The pH level was maintained around 7.0-7.2 by adding small amounts of biochar or wood ash when needed to prevent acidic conditions. The tank temperature was kept in the mesophilic range of 35-40°C using a simple heating jacket and thermostat control loop. The carbon: nitrogen ratio of the feedstock was estimated to be around 25:1 based on the mix of cattle dung and kitchen waste, which falls within the optimal range for anaerobic digestion. By controlling these environmental parameters, the system was able to maintain a stable rate of biogas production over long periods of operation. However, some fluctuations in gas output were observed, likely due to variations in the composition of the feedstock from day to day [17].

Economic and Environmental Benefits

In addition to providing a renewable cooking fuel source, the biogas system also delivered economic benefits through avoided LPG costs. With LPG prices continuing to rise, the annual savings from this system are projected to be significant for the household. From an environmental perspective, the system helps reduce greenhouse gas emissions associated with the burning of fossil fuels like LPG. It also provides a beneficial means of treating organic waste streams. While further optimization is possible, this study demonstrates the technical feasibility and practical benefits of implementing anaerobic digestion systems for biogas production at the household scale in India using locally available biomass feedstocks.

Conclusion

In conclusion, this study demonstrates that the design and implementation of a biogas system is a viable strategy to substitute the use of LPG in Indian households. Using readily available and economically viable raw materials for biogas production presents a sustainable alternative that significantly alleviates the economic burden associated with LPG [24].

The calculations suggest that a daily input of approximately 2.65 kg of dry biomass can generate enough biogas to replace the conventional LPG consumption of an average household. This system not only makes use of waste material but also produces a valuable energy source in the form of biogas. Moreover, with a well-designed slurry tank and a robust storage mechanism, the system can continuously support the energy needs of a household. However, it is important to note that the successful deployment and operation of such a system require an understanding of the anaerobic digestion process and the factors affecting biogas production. Nevertheless, the results of this project underline the considerable potential of biogas as a renewable energy source that can significantly reduce dependency on LPG [25]. Going forward, this project can serve as a blueprint for similar initiatives aiming to promote the use of renewable energy solutions. The findings also provide a solid basis for further research to optimize the design and enhance the efficiency of biogas systems. Hence, the wider adoption of such sustainable energy solutions could significantly contribute to reducing the carbon footprint of households and lead the way towards a greener and more sustainable future.

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