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Biogas production potential from goat droppings at varying operating conditions

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Abstract

This paper investigates the biogas production potential of goat dropping under ambient and controlled temperature conditions and discusses the prospects of biogas production potential from goat dropping in Nepal. Different batches of experiments under varied total solids (TS) percentages and temperature conditions indicated that the biogas yield of goat droppings is 558 L/kgVS_{added} and 522 L/kgVS_{added} under controlled temperature conditions of 30°C at 10% and 8% TS, respectively. However, under ambient conditions in summer (average temperature 24°C), biogas yield drops to 221 L/kgVS and 143 L/kgVS at 10% and 8% TS, respectively. Inconsistent biogas production was observed at ambient conditions during winter (average temperature 10°C) with very low biogas yield of 13 and 8 L/kgVS at 8% and 10% TS, respectively. The theoretical estimation of total biogas production potential from 14 million goats in 2022 for the controlled temperature, summer and winter was estimated to be 136.82 million m^3/year, 54.34 million m^3/year and 1.86 million m^3/year, respectively. The result could pave the way forward for relevant stakeholders to prepare relevant strategies for possibilities to enhance digester temperature in winter and utilizing goat droppings together with livestock manure and other organic waste in the country.

1. Introduction

2.3 billion people worldwide still depend upon environmentally harmful and deleterious fuels for cooking [1]. As of 2022, biomass, livestock manure, and liquefied petroleum gas (LPG) contribute 83%, 4.5%, and 4.9%, respectively, to the overall residential energy mix in Nepal [2]. Excessive dependency on fuelwood and the extraction of fuelwood from forest resources cause deforestation and pose climate and environmental threats. Additionally, importing fossil fuels, such as LPG, to meet the nation's cooking energy demand has been causing an economic burden to the country [3].

Along with environmental hazards, using polluting cooking fuels associated with biomass adversely impacts health and socio-economic development. The particulates and gases from biomass combustion cause household air pollution (HAP). HAP accounts for more than 3.2 million premature deaths globally [4] and more than 18,000 premature deaths in Nepal [5]. To mitigate this reliance, various technologies such as Improved Cooking Stoves (ICS), LPG, and biogas are being implemented, while the utilization of solar and electricity technologies is infrequent [5]. Thus, developing an alternative to conventional pollutant-emitting fuel and technologies is crucial for everyone, ensuring access to clean and reliable energy sources.

Biogas produced from an anaerobic digestion (AD) process is a promising renewable energy source for Nepal and an excellent alternative to reducing heavy reliance on traditional biomass as a cooking fuel source. AD undergoes hydrolysis, fermentation, acetogenesis, and methanogenesis facilitated by a synergetic process of the consortium of microorganisms in the absence of oxygen, producing biogas mainly composed of methane

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and carbon dioxide gas [6]. AD offers multifold advantages as an environmentally friendly process of decomposing organic waste, such as energy recovery and organic fertilizer production from waste components, cost-effectively, leaving a limited environmental impact [7][8]. Additionally, it has effectively saved time and fuelwood, enhanced cooking efficiency, minimized the risk of wild animal attacks during fuelwood collection, and reduced indoor air pollution [9].

Nepal is an agricultural country, with half of the population involved in agricultural activities. Livestock is one of the most important sources of income for farm households [10]. Figure 1 shows Nepal's goat, cattle, buffalo, and pig populations from 2001/2 to 2021/22. The graph shows that the goat population has shown a noticeable increase compared to other livestock in the last ten years. Goat manure has been mostly used directly in the field, which releases large amounts of greenhouse gases (mainly methane, CH_4) into the atmosphere [11]. The Figure 1 indicates the high potential of goat manure to serve as feeding material for biogas production in Nepal.

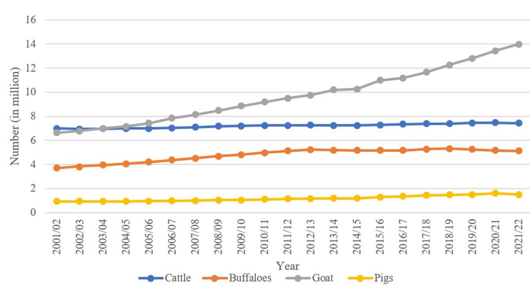

Figure 1: Livestock population in Nepal (2001/02-2021/22) [12][13]

Despite the abundant availability of goat manure at large in Nepal, awareness and knowledge regarding its potential for AD are limited in the local community. In comparison to extensive research on anaerobic digestion of food waste, cattle and poultry manure [14][15][16][17] as well as the co-digestion of food waste, poultry, sewage sludge, and goat manure [18][19][20], studies stressing the mono-digestion of goat manure have been less documented. Specifically, no documented literature has been found addressing the AD of goat manure in the Nepalese context. Therefore, goat manure is worth exploring, also due to its suitable characteristics for AD, such as low moisture content, high nitrogen content, and insensitivity to acidification, thus facilitating fermentation stability and producing less sludge with high fertilizer value [21][22][23][24].In the AD, two critical parameters influence the stability and performance of the process, i.e., temperature and hydraulic retention time (HRT). Temperature directly impacts the activity of microorganisms, and the degradation of goat manure is inherently slow [25][26]. While optimal performance is generally achieved above 30°C, the digester must at least maintain temperatures above 20°C for efficient AD process [27][28].

Given that goats constitute the largest population with massive manure availability as a biogas feedstock, yet are an underutilized resource. However, the lack of empirical data on mono-digestion of goat manure highlights a significant research gap. This study, therefore, aimed to perform the AD process of goat manure at two different total solid contents in an ambient temperature, both summer and winter of Dhulikhel, Nepal, to replicate the real operating scenario of household biogas plants. Moreover, to evaluate the effects of temperature on biogas yield, an experiment under temperature-controlled condition has also been performed.

2. Material and methods

2.1. Collection and analysis of Substrates and Inoculum

The digestate of cow manure as inoculum was collected from a functional household biogas plant from a local community at Dhulikhel, a mid-hill region in Nepal at an elevation of 1500 m with an average humidity of 62.9%which has operated since 2012. Fresh goat manure was collected from individual houses in the local community. It was manually screened for other foreign particles, such as straw and plastics, and crushed into small particles (<5mm). The substrate and inoculum were employed directly into the reactor without storage. The characteristics of digestate and goat manure are summarized in Table 1.

Substrates and inoculum were characterized before experiments. The Total solid (TS) and Volatile solid (VS) content of the substrates were determined using the standard methods defined by the American Public Health Association (APHA), 2005 [29]. The weight of the substrate was measured using a precision weighing machine. The pH was analyzed using the Exotech SOL 100 pH meter. The composition of biogas was examined with a Sewerin Multitec-545 gas analyzer. The ambient and controlled temperature was recorded every half an hour using a temperature logger to monitor temperature fluctuation. The total organic carbon was measured per standards the American Society of Agronomy and Soil Science provided. The total organic nitrogen was calculated using the APHA 4500-N_{org} Macro-Kjeldahl method [30]. The carbon-to-nitrogen (C/N) ratio of the substrate was then calculated based on these results.

Table 1: Different parameters of goat manure and digestate

Parameters	Digestate (Inoculum)	Goat Manure
pH	7.1	5.6
Total Solids (TS) (%)	10	32
Volatile Solids (VS) (%)	60	81
C/N ratio	20:1	19:1

2.2. Digestor setup and operation

AD of goat manure was performed in a single-stage, 500 ml borosilicate batch reactor with an hydraulic retention time (HRT) of 60 days. The reactor was sealed airtight using rubber corks and fitted with infusion sets, i.e., intravenous (IV) sets, as shown in Figure 2A. IV sets from the reactor were then connected to a NaOH scrubber, followed by the water displacement setup. The weight of the substrate, consisting of 50g of goat manure, was used along with 10g of digestate from the local anaerobic digester, contributing as an inoculum. The experiments were performed in different operating conditions, including two different TS levels of 8% and 10%. The first trial was conducted during the summer under ambient conditions, with a temperature range of 19-27°C.Similarly, the second experiment trial was conducted in the winter, employing the same substrate and inoculum under ambient temperature of 10°C. Finally, the third trial of experiments was conducted in a controlled condition executed using a water bath, where the temperature was maintained at 30°C throughout the experiment. The setup for the controlled trial is shown in Figure 2B. The gas volume was calculated by daily downward displacement of water, and gas composition was evaluated at the end of the experiments.

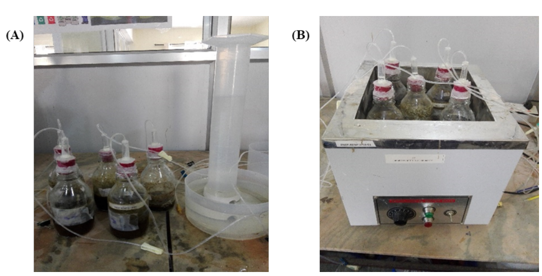

Figure 2: Digester Setup: (A) Batch experiment setup, (B) Batch setup in controlled condition

2.3. Theoretical Biogas production

Biogas production highly depends on different factors such as the feedstock's total solid content (TS%), volatile solid content (VS%), temperature, pH, etc. Hence, the theoretical biogas production potential of livestock manure can be evaluated by considering several factors using Equation 1 [27].

$$\begin{aligned} &\text{Theoretical biogas} \\ &\text{potential } (\mathrm{m^3/year}) = \text{Total manure (kg/year)} \\ &\qquad \times \text{TS content of manure (\%)} \\ &\qquad \times \text{VS content of manure (\%)} \\ &\qquad \times \text{Biogas yield}_{\mathrm{VS}}\ (\mathrm{m^3/kg}) \end{aligned} \tag{1}$$

To compare theoretical biogas production equivalent to an LPG cylinder (14.2 Kg), it is assumed that the energy content in a cylinder of LPG is equivalent to the energy content in 29m^3 of biogas [3].

3. Results

3.1. Summer start-up

The daily production of biogas from goat manure in a batch reactor was measured under different TS levels (8% and 10%) at ambient room temperature during the summer in Dhulikhel, Nepal (Figures 3A and 3B). The total biogas production from batch reactors at 8% and 10% TS was 2279 mL and 3038 mL, respectively (Figure 3C). The biogas yield was calculated to be 143 and 221 L/KgVS at 8% and 10% TS, as shown in Figure 3D. A higher biogas yield was obtained at 10% TS compared to 8% TS. The recorded temperature range during the experiment was between 20°C and 27 °C, which assisted in adequate biogas production.

3.2. Winter start-up

The experimental temperature range was maintained between 10-15°C during winter. The daily production of biogas was measured under different TS levels, as shown in Figures 4A and 4B. The total biogas productions from batch reactors at 8% and 10% TS was 275 mL and 205 mL, respectively (Figure 4C), with corresponding biogas yield of 12.98 and 7.56 L/KgVS (Figure 4D), which is notably low when compared to the gas produced during summer start-up. The frequent discontinuation in biogas production was observed in both batches. However, the discontinuation lasted longer in the 8% TS batch than in the 10% TS batch. Also, a greater volume of gas was produced in 10% TS condition than 8% TS at the same temperature and HRT.

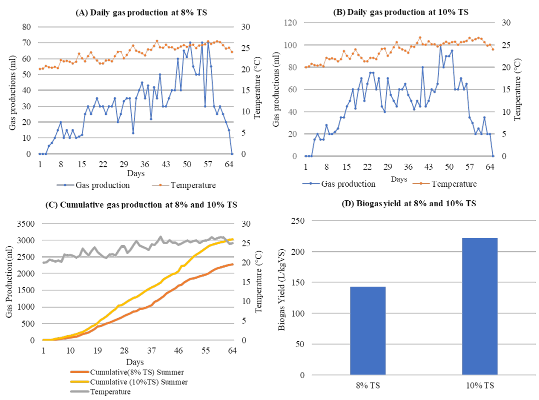

Figure 3: Biogas produced for the summer start-up: (A) Daily gas production at 8% TS, (B) Daily gas production at 10% TS, (C) Cumulative gas production at 8% and 10% TS, (D) Biogas yield at 8% and 10% TS

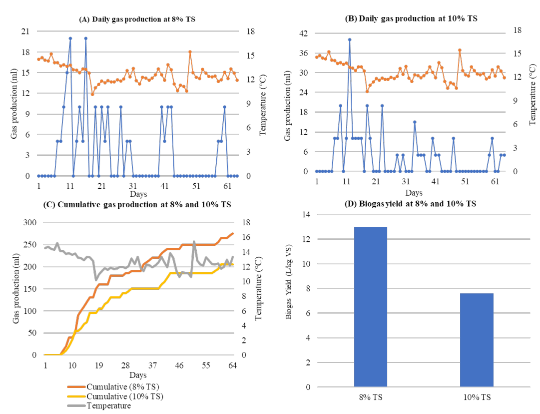

Figure 4: Biogas produced for the winter start-up: (A) Daily gas production at 8% TS, (B) Daily gas production at 10% TS, (C) Cumulative gas production at 8% and 10% TS, (D) Biogas yield at 8% and 10% TS

3.3. Temperature controlled conditions

During the temperature-controlled condition experiment, the temperature was maintained at 30°C. The daily biogas produced for 8% TS and 10% TS is shown in Figure 5A and Figure 5B, respectively. It can be observed from the figures that biogas was produced continuously for 75 days. The total biogas production recorded was 6780 ml and 7500 ml at 8% and 10% TS, respectively (Figure 5C), with corresponding biogas yields of 522.4 and 558.2 L/KgVS (Figure 5D).

3.4. Biogas production potential from goat manure in Nepal

The theoretical biogas production potential from goat manures at an ambient temperature of Kathmandu and a controlled temperature at 10% TS is shown in Table 2. The TS and VS content of manure varies depending

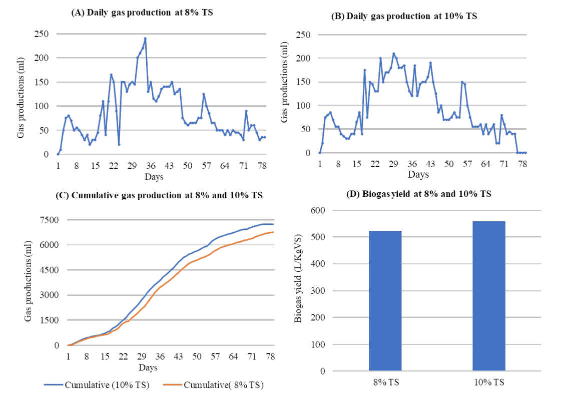

Figure 5: Biogas produced for the temperature-controlled condition: (A) Daily gas production at 8% TS, (B) Daily gas production at 10% TS, (C) Cumulative gas production at 8% and 10% TS, (D) Biogas yield at 8% and 10% TS

on the source and location. The biogas production potential estimation, average percentage of TS, VS, and biogas yield have been taken from the results of this experiment. The total number of goats is nearly 14 million (Figure 1), producing 3.06 million tons of manure annually, potentially producing 136.82, 54.34 and 1.86 million m^3/year of biogas under temperature-controlled, summer and winter conditions, respectively (Table 2). The biogas produced using goat manure could produce 4.72 million LPG cylinder equivalent when operated at controlled temperature conditions.

Firewood has been the dominant cooking energy source in Nepalese households, comprising 51.02% of the total energy used in 2021, followed by LPG at 44.29% [31]. Firewood combustion is associated with carbon monoxide (CO) emissions of 5.1 g/MJ and particulate matter (PM 2.5) emissions of 408 mg/MJ. However, LPG combustion is associated with CO and PM 2.5 emissions of 0.4 g/MJ and 9.5 mg/MJ, respectively. In contrast, transitioning to a biogas cooking stove, CO emissions of 1.1 g/MJ and PM 2.5 emissions of 7.4 mg/MJ can be achieved [32]. Substituting conventional open-burning firewood and LPG with sustainable and clean fuel like biogas can significantly improve indoor air quality, mitigate associated health concerns, and compensate for the high price of imported fuel [3].

4. Discussion

The anaerobic batch test revealed that batch sets with 10% TS demonstrated higher biogas yield than sets with 8% TS, indicating that goat manure at 10% TS could be suitable for optimum biogas production. Controlling only the temperature resulted in the maximum biogas

Table 2: Theoretical Biogas Potential and LPG Equivalent

Operating conditions	**Biogas yield (10% TS) L/kg VS**	**Theoretical biogas potential (million m^3/year)**	**LPG equivalent (million LPG cylinders)**
Summer start-up	221.7	54.34	1.87
Winter start-up	7.6	1.86	0.06
Temperature-controlled conditions (30°C)	558.2	136.82	4.72

yield of 558 L/Kg VS at 10% TS, indicating the biogas production potential to be 136.82 million m^3/year. The methane content measured on temperature-controlled conditions was over 62%. Similarly, an average operating temperature during summer start-up of 23.7 resulted in a biogas yield of 221.7 L/KgVS, corresponding to 54.34 million m^3 biogas production per year. Surprisingly, an increment of almost 250% in the biogas production was achieved while maintaining the temperature at 30 when compared to the ambient summer temperature and a staggering 7350% compared to the ambient winter temperature.

The temperature fluctuation in summer led to a fluctuation in daily gas production. The acidogenic and methanogenic phases experience a decline in performance due to the adverse impact of low temperature, which inhibits microbial activity [33]. Consequently, biogas production was reduced during the start-up. Considering biogas generation at an ambient temperature in the summer, the total biogas production potential is estimated at 54.34 million m^3/year, equivalent to 1.87 million LPG cylinders. Nepal's total LPG consumption in 2022 was 100.2 million, while the residential sector consumed 28.73 million LPG cylinders [34]. Consequently, the biogas generated from goat manure has the potential to substitute 2% of Nepal's overall demand for LPG cylinders and 7% of the total residential demand.

The hydrolysis stage, the first step in AD, which converts particulate matter into a soluble compound, is significantly affected by temperature. Furthermore, HRT is considered as the rate-limiting step at low-temperature conditions [35]. Due to a decrease in the degradation of organic matter at low temperatures in winter, organic matter accumulates at the bottom and limits the growth of methanogenic microorganisms, resulting in irregularity with lower biogas production [36]. Consequently, biogas production was significantly low during the winter season start-up, which could be improved by implementing summer start-up measures such as insulation and a greenhouse for stable temperature . For temperature-controlled conditions, the economic trade-off of HRT could be about 60 days, as there appears to be a decrease in biogas production beyond this point. The shortest HRT is effective in terms of economic efficiency. However, the longer HRT of goat manure could be attributed to its complex degradable substrate.

The present study found that to generate biogas from goat manure, several process constraints must be carefully managed. In mono-digestion , unbalanced nutrient levels, rapid acidogenesis, poor buffering capacity, elevated ammonia concentrations, nitrogen and other lignocellulosic materials and inhibition of long-chain fatty acids may inhibit methanogenesis and disrupt the biogas production process [37][38]. By contrast, co-digestion of various organic wastes, such as food, poultry, cattle manure and sewage sludge, consistently improves stability and methane yield relative to monodigestion [18][19]. Similarly, in co-digestion, the ammonia and enzymes of goat manure can aid biodegradability of acidic food waste, therefore contributing to improved biogas production [14][20]. The substantial amount of goat manure (60%), with food waste (40%) have shown to maintain the pH of the digester by manipulating high volatile fatty acid concentration [26]. Additionally, as goat manure has a low C/N ratio, blending it with carbon-rich organic waste such as cow dung and agriculture residues enhances the nutrient balance, allowing C/N ratio within the recommended range for stable AD [20][23].

From the present study, we observed the challenges in collecting sufficient amount of goat manure at the household level, which directly impacts digester operation and biogas production. The total goat population in Nepal is 14 million, which could theoretically provide sufficient feedstock for biogas production from a digester. However, manure collection at a common point for monodigestion is a major challenge due to sporadic goat-rearing pattern. Therefore, co-digestion of goat manure with food waste, poultry manure, cow dung, and agriculture residue is highly recommended for adequate biogas production.

5. Conclusion

Biogas production using goat manure at different TS% under seasonal temperature variations and controlled temperature experimental conditions was studied. Under the controlled experimental condition, manure with 10% TS showed the highest biogas yield with 558.2 L/Kg VS. Under the ambient condition, higher biogas yield was observed during summer start-up, at 221.7 L/Kg VS, than that of winter start-up at 7.5 L/Kg VS. Discontinuity in the biogas production was observed in most of the days during winter, depicting the operation and efficiency scenario of household biogas plants of developing nations, operating under ambient condition. Considering the high availability of goats in Nepal, the potential of biogas production from goat manure could increase significantly if co-digestion with food waste, poultry litter, cattle manure, and sewage sludge, along with heat-insulating techniques to the digester, is applied. This study suggests studying the co-digestion of other organic waste with goat manure to optimize and maximize the biogas yield in Nepal's diverse climatic conditions.

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