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Research Article

Biogas Production by Co-Digestion of Food Waste with Sewage Sludge and Poultry Litter: A Way Towards Sustainable Waste-to-Energy Conversion

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ABSTRACT

Anaerobic digestion is one of the most effective technologies for managing degradable waste, which produces renewable energy and digestate as the byproduct. In this study, sewage sludge (SS), poultry litter (PL), and food waste (FW) were co-digested at ratios (SS:PL:FW 2:1:1) with 8 % total solid content at ambient temperature (average 22 °C) and controlled temperature (35 °C) in summer. The synergistic effects of co-digesting substrates enhance the biogas production potential when digested at an optimized ratio. The maximum biogas yield was 688.7 L/kgVSa at the controlled temperature and 462.3 L/kgVSa at ambient temperature. The ambient reactor had a methane composition of 55 %, while the controlled temperature reactor had about 60 %. The results provide approaches to increase biogas production in the anaerobic digestion process through co-digestion and controlled mesophilic temperature. Biogas production from anaerobic co-digestion could significantly transform waste into energy in low-income countries to achieve the objective of clean energy production and environmental sustainability.

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1. INTRODUCTION

Solid waste generation has been on a significant rise with the growing population and unmanaged urbanization in developing countries. However, waste management has always been a challenge for the government and municipalities, leading to environmental pollution and social threats [1]. In this context, the gaining popularity of biogas production from organic waste as part of a circular economy can give a possible way out to the government and society [2]. The circular economy mainly focuses on sustainability through the transformation of the current linear economy towards a circular approach [1]. In waste management, circularity has not yet gained adequate attention, especially in low- and middle-income countries [3]. In the era of the circular economy, waste has now become a resource for clean energy production via technologies such as Anaerobic Digestion (AD). AD process utilizes locally available organic substrates to generate biogas, thus reducing the dependency on fossil-based energy sources [4]. AD further contributes to achieving clean energy and ensuring the achievement of sustainable development goal 7: access to affordable, reliable, sustainable, and modern energy for all [5].

The waste to energy generation practice in developing countries like Nepal is still in the early stages. With more than 0.2 million tonnes of manures generation per day and an estimated theoretical potential of nearly 110 million Liquefied Petroleum Gas (LPG)[2] cylinders equivalent [6], Nepal reserves enough energy source (more than 4.5 times of current cooking energy supplied by LPG) to substitute cooking energy demand of the country [6]. However, the country's energy scenario shows that these resources are yet to be unrealized. Though biogas technology has existed in Nepal for more than 55 years, AD practice is still limited to mono digestion of cattle manure which in turn is restricting the country's actual bioenergy generation potential [7].

Anaerobic Digestion (AD) systems are mostly used for simultaneous treatment of waste for the production of biogas and digestate as fertilizer. However, biogas production from mono digestion is less preferred as it causes difficulties in operation through the particular inherent properties of single substrates [8]. Due to the low C/N ratio, Sewage Sludge (SS) has less bio-methane potential, resulting in low AD efficiency [8]. Similarly, food waste has low pH and high biodegradability contributing to the rapid formation and accumulation of VFAs, resulting in digester failure [9, 10]. Furthermore, AD of poultry litter alone is unfavorable due to

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[2] 14.2 kg per LPG cylinder

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the presence of high nitrogen concentration and is ultimately reported to have low biogas production [11].

Thus, co-digestion is being used for its additional benefits including microbial synergistic effects, potential toxic dilution, improved nutrient balance, relatively higher biogas yields, and an increased digestion rate [12, 13]. Co-digestion of the substrates not only enhances methane production potential but subsequently facilitates the management of locally available wastes [14]. The selection of a co-substrate is an important factor in co-digestion and it should complement their properties which aid both stabilization of the process and improvement of the digestion process. A limited study has been conducted with SS, PL, and FW as three co-mixed substrates for biogas production under ambient as well as controlled temperature conditions. A study on co-digestion of SS with swine manure and PL at a ratio of 7:2:1 in a semi-continuous process and cow manure with FW and SS at a ratio of 7:2:1 under mesophilic conditions reported a biogas yield of 0.336 $m^3/kgVS_{added}$ and 0.6 $m^3/kgVS_{added}$, respectively [15]. Another study on co-digestion of rice straw with kitchen waste and pig manure in mesophilic (37 ± 1 °C) conditions (KW:PM:RS in 0.4:1.6:1) reported that the biogas yield of 674.4 L/kg VS_a was higher than that of the digestion of rice straw or pig manure alone by 71.67 % and 10.41 %, respectively [16]. A similar study by Callaghan et al. reported that the methane yield increased from 0.23 to 0.45 $m^3.kg^{-1}.VS_a$ by introducing the cattle slurry with fruit and vegetable wastes from 20 to 50 % in co-digestion at 35 °C [17]. All of these studies were carried out with substrates FW, SS, and PL in a controlled mesophilic environment, which reported a significant increase in biogas yield.

As of now, about 430,000 household biogas plants are installed in Nepal, solely operating at ambient temperature, without any digester heating provisions or feedstock pretreatments [6]. A field study conducted at the Kavre district of Nepal reported that more than 80 % of household biogas plant users (300 households surveyed) were not satisfied with the plant performance [18]. The insufficient biogas production especially during the winter was the primary concern of most users. Thus, understanding the co-digestion performance in ambient and controlled temperature conditions helps designers, bio-gas companies, and policymakers adequately assess the performance of existing biogas plants in the local context and plan for optimized performance of the plants. However, there is a dearth of literature on the performance of biogas plants practicing co-digestion of various wastes in ambient temperature conditions and their performance compared with those being operated in controlled temperature conditions or mesophilic temperature conditions. Hence, this study aims to: i) compare the biogas yield obtained from co-digestion of locally available substrates under both ambient and controlled temperature conditions and ii) explore the possibility of the use of locally available co-substrates in the household anaerobic digestion process. Moreover, this study also helps provide solutions to achieve more efficient and sustainable energy generation techniques for similar digesters operating at similar ambient temperatures in other low- and middle-income countries.

2. METHODOLOGY

In this lab-scale semi-continuous process, experiments were conducted under ambient and controlled temperature conditions. Co-digestion of SS, PL, and FW at a mixing ratio of 2:1:1 was taken as the optimal feed co-digestion ratio since it gave the highest biogas yield during the previous experiment [19]. The overall laboratory experiment was conducted from April to July in the temperature range of 13 °C to 29 °C, which is a different temperature range from the previous experiment.

2.1. Feeding material

Sewage sludge was collected from a community wastewater treatment plant operating at ambient temperature in Dhulikhel, Nepal. Food waste was collected from the university canteen comprised of mainly cooked rice, vegetables/peels, and lentils presented in Table 1. Before feeding, FW was blended to get a finer particle size less than 10 mm in diameter and/or length as suggested by Hollinger et al. [20]. Fresh cow dung was obtained from the cattle farms of residents. A mixture of sewage sludge and cow manure at a ratio of 2:1 (wt/wt) was used as inoculum for the experiment. Poultry litter was collected from a Deep litter poultry farm in Dhulikhel. All the samples to be fed to the reactor were collected and stored at 4 °C for the entire experiment.

Table 1. Composition of food waste

Feed compositions	Percentage
Rice	60 %
Potato peels	10 %
Cucumber peels	5 %
Carrot peels	5 %
Potato cooked	3 %
Daal	10 %
Peas (Cooked vegetables)	7 %

2.2. Digester setup and operation

The experiment was carried out under ambient and controlled temperature conditions in a semi-continuous process from April to July at an average ambient temperature of 22 °C, with a maximum of 28.8 °C and a minimum of 13.5 °C recorded in the temperature logger. For the ambient temperature condition, two 5 L bottles were taken, as shown in Figure 1, with a fitted infusion set to measure the amount of gas produced during the experiment. A PVC pipe attached to plastic funnels was used to feed the substrates. Proper sealing was done to ensure an airtight setup as required for the AD process. The gas production was measured with the help of a measuring cylinder through the water displacement method.

For the experiment in ambient temperature conditions, three reactors in triplicate were set up and a co-digestion mixture of SS, PL, and FW at a mixing ratio of 2:1:1 was fed into those reactors. The mixing ratio of 2:1:1 was chosen from the previous work [19] from the Renewable and Sustainable Energy Laboratory (RSEL), Kathmandu University, which gave the highest biogas yield and maintained a stable AD process. The difference from the previous study lies in the ambient temperature range of the experiment. Moreover, this study carries out a new set of controlled temperature (35 °C) experiments so that the result can be compared with ambient temperature result, a task that was not conducted in the previous study. The organic loading rate of 1.2 g VS/L.d, HRT of 45 days, and 8 % of TS were maintained in the tests.

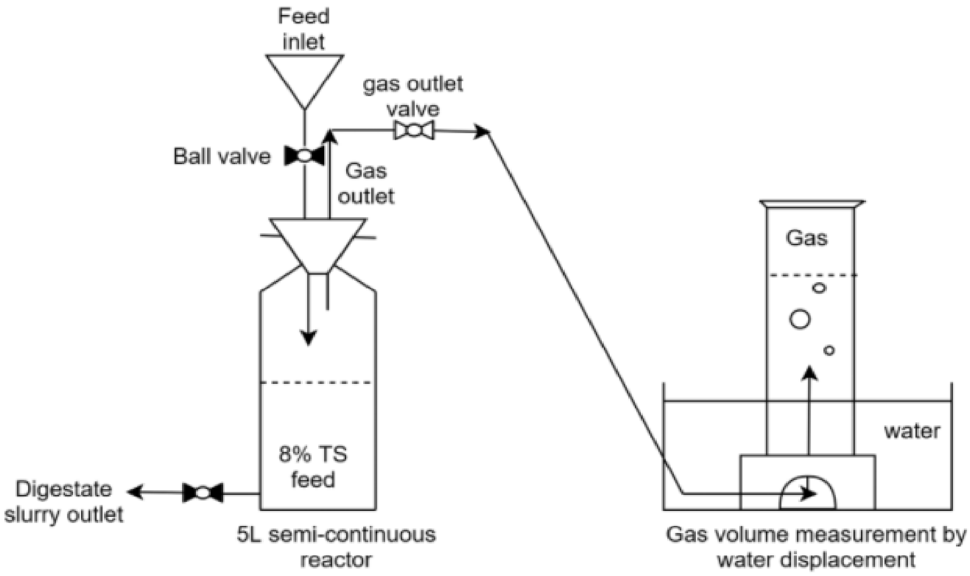

Figure 1. Schematic diagram of reactor setup for the ambient condition

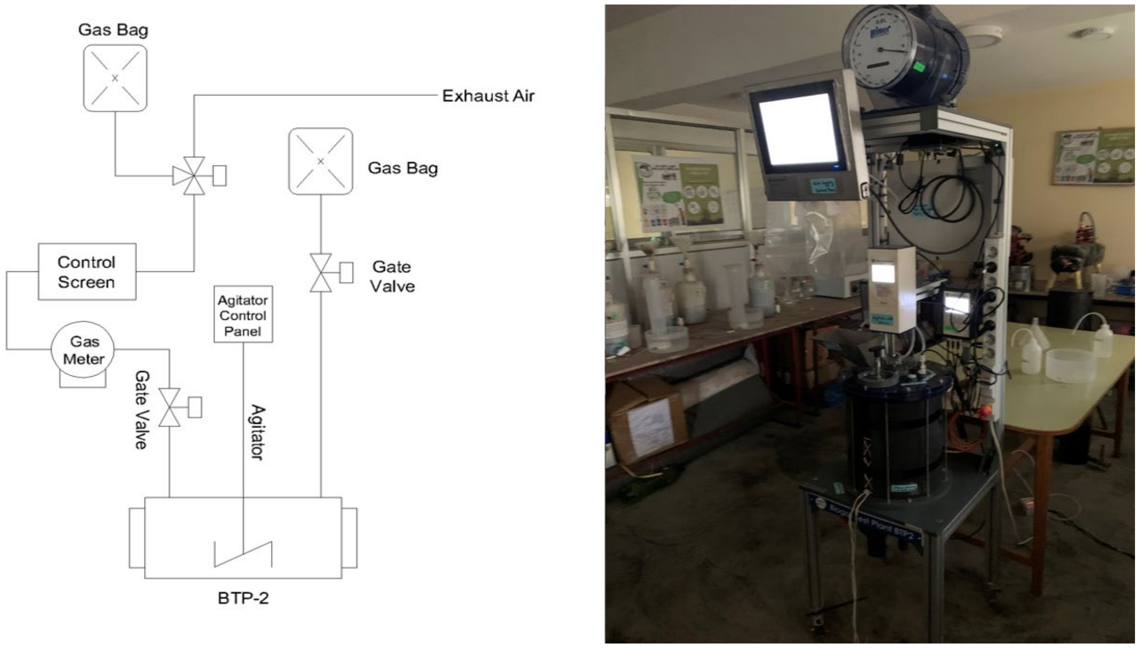

Figure 2. Schematic diagram of biogas test plant-2 (Left); biogas test plant-2 (Right)

For the controlled temperature condition, a lab-scale Biogas Test Plant (BTP 2, Umwelt-und Ingenieurtechnik GmbH Dresden) with a working volume of 15 L (Figure 2) was used. A total working volume of 8 liters was used, while 7 liters was left as the headspace. The reactor is fitted with the silicon heater band including an adjustable temperature sensor. The universal automation system SENSOcontrol is used for data acquisition applications and control of the units (pumps, agitator) in the test facility measuring pH-Value, temperature, and gas volume. An intuitive touch screen is integrated for real-time visualization of the measured data. The reactor operated at 35 °C for this study. The stirrer was programmed to start stirring at 5 rpm for 5 minutes every 2 hours. The produced biogas collected in the bag was automatically measured by wet gas meters. The substrate combinations, OLR (1.2 gVS/L/day), TS (8 %), and mixing ratio 2:1:1 were selected identical to the reactor operating at ambient temperature; however, the BTP-2 operated for a hydraulic retention time of 30 days.

2.3. Analytical method

Total Solid and Volatile Solid content was measured with APHA, 2540 D guideline for TS, and APHA 2540 E guidelines for VS. An Exotech SOL 100 pH meter was used to monitor the pH of the substrates. The composition of the biogas was determined using a Sewerin Multitec-545 gas analyzer. To determine the C/N ratio, the TOC of all the three substrates was determined using the American Society of Agronomy and Soil Science guidelines, and their TON was determined using the APHA 4500-Norg guidelines. To account for temperature variability in the experiment of an ambient temperature condition, a temperature logger was utilized to record ambient temperature at the interval of every half an hour.

3. RESULTS AND DISCUSSION

3.1. Physiochemical properties

The physicochemical properties of a mixture of co-substrates SS, PL, and FW at a ratio of 2:1:1 are shown in Table 2. Since the experiment was conducted at 8 % TS, the co-substrate mixture was diluted to 8 % TS. The pH of the mixture was 7.08, which is in the favorable range of 7-8 [21]. The VS % of the feeding material was 71.7 % of TS.

Table 1. Physiochemical properties of the sample

Co-substrate: SS:PL:FW		TS %	VS %	pH	C:N
		Feeding samples	Feeding samples	Feeding samples	Feeding samples
Mixing Ratio: (2:1:1)	BTP	8.2	71.7	7.08	18.3
	Ambient	8.2	71.7	7.08	18.3

3.2. Composition of biogas

Table 3 presents the composition of the elements contained in the biogas produced in the experiment from ambient and controlled temperature conditions. The composition was determined using Multitec 545 Gas Analyzer (multigas detector with infrared sensors and extended measuring range for Hydrogen Sulfide).

Table 2. Percentage composition of biogas in two different reactors

Constituents	Percentage composition	
	Ambient temperature	Controlled temperature
Methane	50-55	60-65
Carbon dioxide	35-40	30-40
Oxygen	0-5	0-5
Hydrogen sulphide	0-1	0-1
Others (Nitrogen, Hydrogen, Ammonia e.t.c.)	-	-

3.3. Co-digestion at the temperature-controlled condition

Co-digestion of SS, PL, and FW at a ratio of 2:1:1 was carried out in temperature-controlled conditions (35 °C) for about 60 days in a semi-continuous process. Since the reactor was automated, the daily production of biogas was recorded in the system. Figure 3 shows the cumulative biogas production from the BTP 2 reactor. The initial two weeks were an inoculum stabilization period during which no regular feeding was done until the biogas composition was recorded at about 50 %.

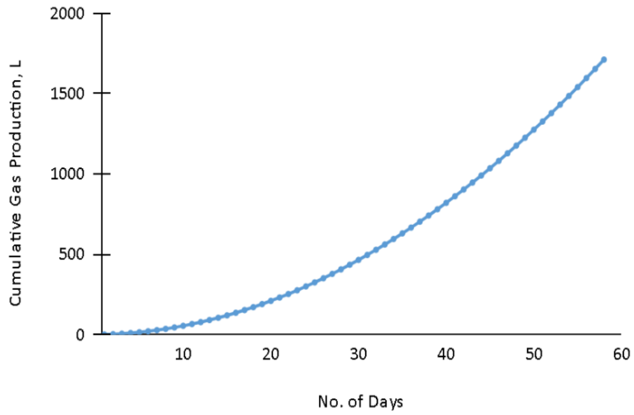

Figure 3. Cumulative biogas production at controlled temperature

The daily gas production was comparatively low in the first two weeks. After stable startup of the reactor, feeding of co-digested substrates was done every alternate day for 30 days. It is evident from Figure 3 that the biogas production exponentially increased upon the initiation of the feeding of the reactor after the 15th day of operation. The pH of the digested substrates ranged from 6.7 to 6.9 throughout the experiment and no significant drop in pH was noted. The average biogas yield was 688.7 L/kg VS_{added} with an average methane content of 60 %.

3.4. Co-digestion at the ambient temperature condition

This experiment was carried out in the daily average ambient temperature range of 13.5 °C to 28.8 °C with significant fluctuations, as shown in Figure 4. The co-substrates, mixing ratio, and other parameters (1.2 gVS/L/day OLR, 8 % TS) were identical to those in the experiment conducted in the BTP-2 reactor except for 45 days of HRT being used in this case. The digesters experienced significant fluctuation in ambient temperature as observed in Figure 4.

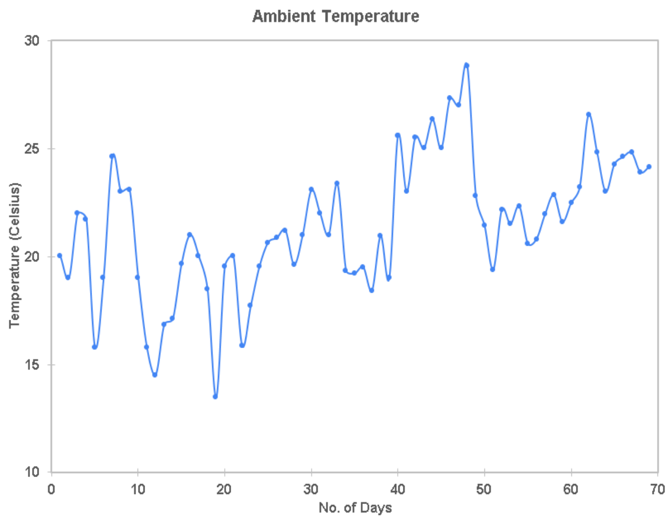

Figure 4. Ambient temperature during the experiment period

Figure 5 indicates the cumulative biogas production from the reactor fed with sewage sludge, poultry litter, and food waste at a ratio of 2:1:1 in ambient temperature conditions. The figure indicates that the reactors took about a month to effectively start up to initiate the feeding process (methane percentage about 50 %) and low gas production can be observed in that period.

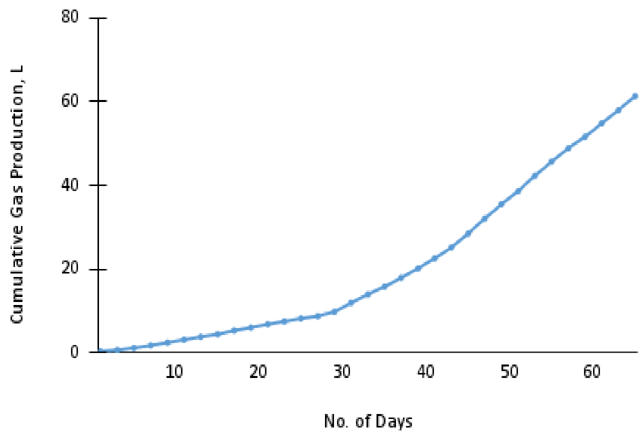

Figure 5. Cumulative Biogas Production in ambient temperature conditions

The exponential increase in biogas production could be observed after feeding was initiated from the 32nd day of operation. The average biogas yield of 462.3 L/kg VS_{added} was obtained from the experiment with average methane composition of 55 %.

It was observed that the startup time was reduced by nearly 50 % when the co-digestion experiment was performed in a temperature-controlled condition (BTP-2) in contrast to the ambient temperature condition (Figures 3 and 5). Figure 6 shows the comparison of biogas yields obtained from reactors operating in ambient conditions and temperature-controlled conditions. Higher biogas yield was obtained from the BTP-2 reactor than that from the reactor operating at ambient temperature. Studies suggest that maintaining a constant digestion temperature is crucial to optimizing biogas production from a biogas plant [22]. If the fluctuations of digestion temperature exceed 5 °C at a short interval, then biogas production could lower considerably; therefore, a constant digestion temperature is crucial to optimizing biogas production [22]. It is apparent from this study that the temperature plays a significant role in increasing the biogas yield from a reactor as 49 % higher biogas yield is obtained in the reactor with controlled mesophilic temperature (Figure 6), which is obvious. A similar study conducted by Lohani et al. (2021) used the identical ratio of 2:1:1, 8 % TS, 1.2 gVS/L/day OLR during the summer season in the ambient temperature range of 22-26 °C, showing a biogas yield of 640 L/kgVSa. However, the same experiment conducted at winter temperatures of 11-19 °C yielded low biogas of 171 L/kgVSa, as shown in Figure 6 [19]. Based on a comparison of this study with a co-digestion experiment conducted earlier in summer in the temperature range of 22-26 °C [19], it can be found that the biogas yield was reduced by nearly 29 %. This study also suggests that biogas yield at summer ambient temperature (figure) is significant if we carefully select locally available substrates for co-digestion. As household biogas plants are serving as an important source of clean cooking energy in rural Nepal [23], their yield can be improved by co-substrate digestion.

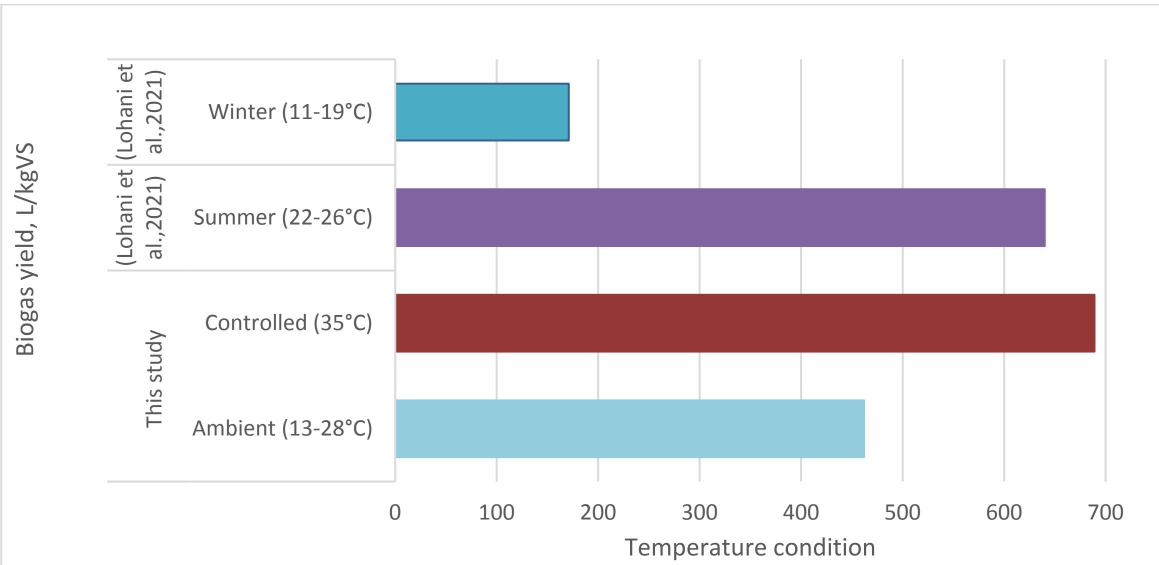

Figure 6. Biogas yields in different temperature conditions

4. CONCLUSIONS

In this study, the performance of bio-reactors co-digested with locally available substrate sewage sludge, poultry litter, and food waste at a mixing ratio of 2:1:1 was observed at both ambient summer temperature and controlled mesophilic temperature. The mixture of SS:PL:FW at a ratio of 2:1:1 had the highest biogas yield of 688.7 L/kg VS_{added} with a nearly 49 % higher value than the one operating in ambient temperature conditions at a similar mixing ratio and OLR. A reduced biogas yield of 462.3 L/kg VS_{added} was observed from the reactor operating in ambient temperature conditions. The average methane content in the controlled temperature and the ambient temperature was 60 % and 55 %, respectively. The study suggests that temperature plays a vital role in biogas production efficiency and enhanced temperature condition and desired biogas yield can be obtained. Furthermore, the efficiency of the digester was affected by the temperature fluctuation in the ambient environment, thus reducing the biogas production by 49 % in comparison to the controlled temperature condition. From the result, it is apparent that the implementation of locally available temperature control and enhancement techniques such as canopy or greenhouse could be useful for optimized biogas production from the digesters operating under ambient conditions. Biogas production with all the locally available resources can surely be one of the best ways to achieve sustainable waste management and it also contributes to the enhanced synergistic effect of anaerobic digestion. This study helps plan effectively towards sustainable development and circular economy by valorizing waste to energy conversion on the community and commercial scales.

5. ACKNOWLEDGEMENT

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