Performance of Pre-Fabricated HDPE Biogas Plant in Continuous Feed Mode for Hilly Region

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Abstract - **A study was conducted to evaluate the performance of a pre-fabricated biogas plant (2 cub.m) made up of high-density polyethene to observe its suitability for hill region of Uttarakhand. The mean monthly ambient temperature was between 12.53 and 31.95^{0}C during the study period. The ambient temperature was found to affect the slurry temperature inside the bio-gas digester and hence quantity of biogas production. Slurry temperature was higher in the center of the digester compared to the same near the digester wall. The average slurry temperature was higher than the ambient temperature. The average monthly and daily biogas production was lowest (0.57 m^3) during winter months with monthly average ambient temperature of 12.53^{0}C. However, during remaining period of study, the biogas production was higher ranging from 0.810 to1.203 m^3 when ambient temperature ranged between 15.12 and 31.95^{0}C. Other process parameters were observed within the permissible limits.**

Key words: Biogas plant, digester, high-density polyethylene, slurry temperature, total solid, pre-fabricated, ambient temperature

I. INTRODUCTION

Animal dung which is undigested residue of consumed food material being excreted by herbivorous bovine animal species, is considered as a primary fuel source in many parts of rural India and the world and is also a valued fertilizer (Portillo et al., 2017, Lancelotti et al., 2017, Broderick and Wallace, 2016). As per the 20th livestock census of 2019, the national livestock population is about 536.76 million. The collective waste in the form of animal dung and waste water ranges from 3 to 6000 million tons per day (Kaur et al., 2022). India is exporting cow dung to various countries, the top importers being the US, Singapore, China, Nepal, and Brazil (Anonymous, 2024). The people in Indian villages use cow dung for various purposes like cooking food by direct burning it, plastering of walls, floor, as mosquito repellent, and its ash as cleaning agent for kitchen utensils since ages (Gupta et al, 2016). However, considering the continuous depletion of coal and fossil fuels in the country and to reduce dependency on it, the cattle dung can most effectively be utilized to generate biogas, a clean and environment friendly gas, for cooking purposes and for power generation.

India is the second largest country is the world for implementation of biogas programme. According to an estimate, there is a total of about 50 million of micro-scale biogas digesters (plants) operational around the world with 42 million operating in China and another 4.9 million in India (Anonymous, 2019). KVIC, Janta and Deen Bandhu models of biogas plants are the most popular designs being used in the country. Out of these, KVIC model developed in 1962, is a floating-dome whereas later two are of fixed-dome type biogas plant. Janta model of biogas plant, introduced in 1978, became quite popular but like fixed-dome type biogas plant, it is also associated with certain disadvantage like short circulating path of the slurry, escape of undigested slurry from the top and less volume of gas produced due to increased gas pressure (Anjan, 1988). KVIC model is widely accepted and used designs for household purposes in India as it produces biogas at a constant pressure with variable volume (Green et al., 2022). However, the disadvantage with both the designs is that once installed, it cannot be moved to any other place because of underground built digesters. Also skilled technician is required for its construction and installation.

All the three designs of biogas plants have been found more suitable for plain regions basically due to favorable ambient temperature for higher gas production and more floor space available with the famers. Khoiyangbam et. al. (2004) studied the methane emissions from the slurry of different fixed dome type biogas plants having 2 m^3 capacity installed in hilly and plain regions of northern India. The slurry temperature in the biogas plants in the hilly areas remains below the lower mesophilic range (16-25^{0}C) whereas the same was observed higher between 21-33^{0}C in plain regions during most part of the year. It was observed that ambient temperature affected the CH_4 flux. The annual average methane emission from the biogas plants in plain region was 83.1 g m^{-2} d^{-1} as compared to 43.1 g m^{-2} d^{-1} in the hilly regions. Kalia and Kanwar (1998) evaluated a fixed dome Janata biogas plant of 3 m^3 capacity installed in the hilly conditions. The monthly variation in the mean ambient temperature affected its digester temperature and, hence, rate of gas production. The average rate of daily gas production from the plant with daily feed rate of 20 kg cattle dung/m^3 rated capacity of the plant consistently decreased year after year. The decrease in the daily gas production rate was observed more during the peak summer months compared to winter months.

Biogas could be a good substitute of energy in rural India to meet out the daily energy need especially for cooking purpose. Singh and Gundimeda (2014) reported that majority of the rural households depend on traditional cooking fuels such as firewood (62.5%), crop waste (12.3%) and dung cake (10.9%) whereas households in urban areas depend on LPG (65%), kerosene (7.5%) and coal (2.9%) for cooking purposes.

In terms of energy content, 1.0 m^3 of biogas would save 620 ml of Kerosene, 3.474 kg of firewood and 12.296 kg of cattle dung. In hilly regions of Uttarakhand, people mainly depend upon firewood as cooking fuel. The collection of firewood, from nearby forest, is performed mainly by the womenfolk which is very tedious and time taking operation. Therefore, the use of biogas would reduce the drudgery of womenfolk and would also lower incidence of eye and lung disease due to smoky environment in the kitchen. The farmers in hilly region are categorized as marginal to small and mostly own 4-6 animals for milk as well as farming operations. The amount of cattle dung produced by these animals would be sufficient to set up a small family size (1-2 m^3) biogas plant to meet out the cooking fuel demand of 4-6 persons in family at the rate of 0.24 m^3/day/person.

However, in hilly regions, construction and installation of conventional biogas plant with underground concrete digester is quite difficult mainly due to lesser depth of soil, higher transportation cost of material and space limitations. These problems could be solved by using a pre-fabricated biogas plant made of high-density polyethylene (HDPE). These biogas plants being lighter in weight can easily be transported and installed at desired location. Also, its post installation location can be changed, if need arises. However, the rate of gas production with this kind of biogas plant must be evaluated considering biogas generated from conventional biogas plants. Considering this point in view, the study was carried out with 2 m^3 size of biogas plant made of HDP.

II. MATERIALS AND METHODS

A floating-dome type ready-to-install biogas plant of 2 m^3 capacity (Fig. 1) was taken for the study. The height (H) and diameter (D) of cylindrical digester of the plant was 140 and 180 cm respectively with H/D ratio of 0.78. Similarly, the height and diameter of the gas holder was 117 and 137 cm respectively. The gas holder is pressed down by four helical springs that moves up and down on a central guide. The biogas produced in the digester gets accumulated under the floating gas holder causing vertical movement of gas holder ensuring the supply of gas at constant pressure. The digester and the gas holder both are made from UV stabilized carbon black compound of HDPE. The black color of the digester helps in keeping the slurry temperature warm during the day. The inlet and outlet were made from 100 mm PVC pipe for feeding of fresh slurry and discharge of spent slurry.

The study was conducted at university field laboratory of biogas technology for a period of 8 months during November to June. The study period was chosen in such a manner to observe the performance of experimental biogas plant during winter and summer season.

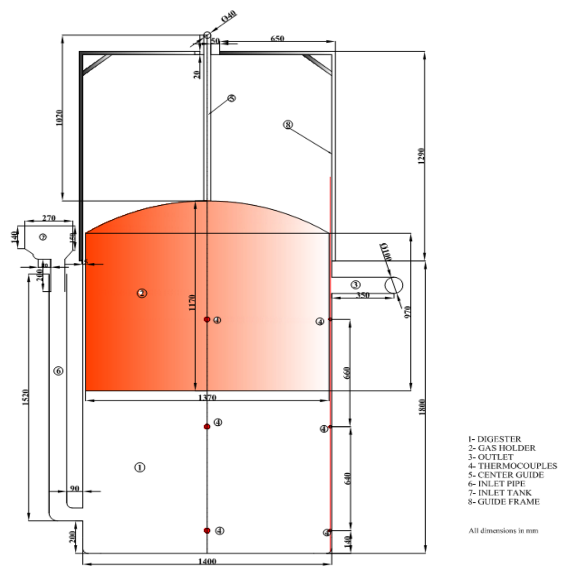

Fig. 1. Schematic diagram of a HDP biogas plant.

The experimental site is located at 29^0 3'0" North (latitude), $79^0$31'0" East (longitude) at an elevation of 243.8 m above msl. The mean ambient temperature of the site ranges between 16-30^{0}C with minimum temperature recorded in between 5-6^{0}C during the months of December-January (Anonymous, 2025).

The experimental biogas plant was charged daily with substrate prepared by mixing 50 kg of fresh cattle dung with 50 liters of water (1:1 ratio) in the morning between 6-7 AM. The ambient temperature was recorded on daily basis using a digital thermometer (model: DTM-100). The slurry temperature was also measured daily with thermocouples (copper-constantan) placed inside the bigas digester slurry at six locations along the depth i.e. three locations in the center and three locations along the digester wall. Three locations selected in the center of digester were near surface (SZC), mid-point along the depth of the digester (MZC) and near bottom surface (BZC). Similarly, three more locations were selected at same heights near the digester wall viz near surface (SZW), mid-point near the digester wall (MZW) and near bottom surface close to digester wall (BZW) respectively. The quantity of biogas produced was also measured daily at 6 AM and 6 PM using a digital gas flow meter (3-liter capacity). Total solids (TS) and volatile solids (VS) were estimated weekly using standard technique. A pH meter was used to monitor the pH of fresh and spent slurry weekly.

III. RESULTS AND DISCUSSION

The data collected during the experiment has been discussed as under:

Slurry Temperature

Fig. 2 and 3 shows the relationship between the ambient and slurry temperatures measured at various points inside the digester slurry. The result indicated slurry temperature inside the digester is either equal or higher than the ambient temperature. The slurry temperature was lower at surface zone (SZC) compared to the middle (MZC) and bottom zone (BZC) along the depth in the center of digester. The slurry temperature was 5.70, 15.10 and 24.86 percent higher than the ambient temperature at all the three locations in the center of the digester.

Similarly, the slurry temperature near wall of the digester was slightly lower than the slurry temperature in the center of the digester. The average slurry temperature near the digester wall was 2.38, 10.73 and 19.68 percent higher near surface, middle and bottom zone along the digester wall respectively as compared to ambient temperature. The average slurry temperature observed was higher at the bottom zone in the center of the digester that may be due to the minimum heat loss. Moreover, the digester wall, slurry and the soil around the digester acted as heat insulator that might has helped in retaining high slurry temperature in the center of the digester.

Fig. 2 and 3 also indicates that the slurry temperature in the center and near the wall of the digester at the bottom zone was higher even when outside ambient temperature was low in the range of 5-21^{0}C. It indicates that HDPE biogas plant have higher favorable slurry temperature, even during winter season when ambient temperature was low, that may yield more biogas. The slurry temperature was measured nearly the same in all the three zones of the digester when the ambient temperature increased beyond 21^{0}C.

Daily Gas Production

Table 1 presents the result of monthly average daily biogas production measured at 6 AM and 6 PM. The daily gas production was observed in range of 0.276-0.592 m^3 and 0.295-0.612 m^3 at 6 AM and 6 PM, respectively, during the study period. The lowest biogas production of 0.276 and 0.295 m^3 was both at 6 AM and at 6 PM, when the mean monthly ambient temperature was 12.53^{0}C in the month of January i.e. during winter season. During this period, the plant was operating under psychrophilic temperature range that lead to low gas production. Guo et al.(2019), Nekhubvi and Tinarwo (2022) have also reported higher biogas production rate with the increase of slurry temperature. Nekhubvi and Tinarwo (2022) further reported a high positive correlation between ambient air temperature and slurry temperature meaning by when air temperature increases, the slurry temperature also increases along with it.

The data also indicated that the average daily biogas production was lower at 6 AM as compared to that of 6PM, which was due to drop in ambient temperature during night. Higher daily mean biogas production of 0.810-1.203 m^3 was during March to June when the ambient temperature was higher i.e. when plant was operating under mesophilic temperature range (20-45^{0}C). Wang et al., 2019 reported that biogas production at temperatures ranging from 25 − 35°C is higher.

It is reported that the methanogens thrive better in mesophilic temperature range resulting in higher biogas production i.e. mesophilic temperature favors the better activity of methanogenic bacteria (Fig.4). During the months of November and December also, biogas production was low (0.826-0.968 m^3) as compared to biogas production during the month of April-June but it was higher than the mean monthly daily gas production between January-February. This may be due to lower ambient temperature of 16-18^{0}C i.e. lower mesophilic temperature range during November-December months resulting into lower slurry temperature and thereby lower biogas production. However, the reason for lower biogas production (0.570-0.608 m^3) in the months of January and February was due to low mean ambient temperature (12.53-15.12^{0}C) meaning by the plant was operating in psychrophilic temperature range (13-14^{0}C) which is not favorable for methanogens resulting into less biogas production (Kalia and Kanwar, 1989). The monthly average daily biogas production per kg of cattle dung also indicated lower gas production in the month of January due to low ambient temperature (Table 1). However, it was higher during other months of the study period because of higher ambient temperature favoring methanogens activities responsible for biogas production.

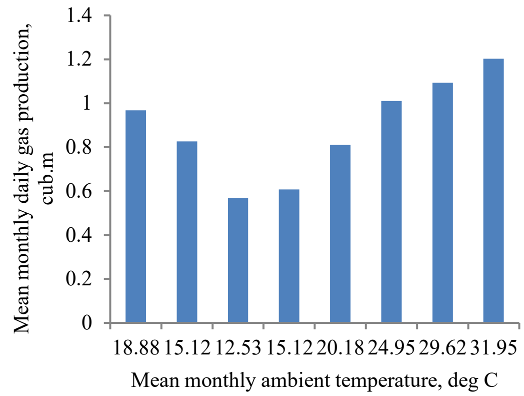

Fig. 4. Effect of ambient temperature on daily biogas production

Cumulative Gas Production

Table 1 also presents the cumulative biogas production observed during the study period of 242 days. The cumulative gas production, in general, was found more in the evening at 6 PM as compared to the same in the morning hours at 6 AM. This is due to higher mean daily gas production recorded at 6 PM. The data regarding percent change (Table 1) indicated that the cumulative gas production was higher for the month of December (82.89%) as compared to the same for the month of November. However, the variation in cumulative gas production was found higher, in general, in the range of 21.67-31.42% during January to June months of the experiment from their previous months. This indicates that during this period the biogas production is almost at constant rate.

Inlet and Outlet Slurry pH

The pH of the inlet and outlet slurry was determined (Table 2) that ranged between 7.18-7.44 and 7.40-7.72, respectively which were within the acceptable ranges. It is seen from the result that pH of the outlet slurry was little higher than the inlet slurry. The variation in pH of slurry is observed between 2.78-5.28 percent with 5.28 percent being the highest during mid of November to mid of February. The ambient temperature during the said period was approximately in the range of 8-20^{0}C i.e. psychrophilic temperature range. The optimum pH range, for anaerobic digestion has been reported between 7-8 (Bamboriya, 2014), however, the process can tolerate a pH range between 6.5-8.0 (Cioabla et al., 2012). The pH value observed indicated that the biogas plant under study was operating stably.

Change in TS and VS

Total solids (TS) and volatile solids (VS) reduction was determined and found to range between 3.92-10.78% and 2.78-17.81% respectively (Table 2). The results indicated that reduction was higher during the digestion period of 50-105 days of starting the biogas plant. Prior and after this digestion period, the reduction in total solids was less. Similarly, the reduction in volatile solid (VS) was observed higher during 0-77 and 106-242 days of study. During the mentioned period, the mean ambient temperature was comparatively higher which provided favorable conditions for methanogens for faster conversion of volatile solid into biogas.

Table 2. Total solids, volatile solids and slurry pH

Digestion period, days	Reduction, %		pH of		Change in pH, %
	TS	VS	Inlet slurry	Outlet slurry	
0-21	7.62	10.96	7.20	7.40	2.78
22-49	8.01	8.39	7.18	7.55	5.15
50-77	10.78	8.45	7.20	7.58	5.28
78-105	10.73	2.78	7.20	7.58	5.28
106-133	5.40	7.83	7.30	7.63	4.52
134-161	6.64	12.59	7.25	7.58	4.55
162-189	7.67	14.57	7.33	7.70	5.05
190-217	4.49	17.81	7.38	7.70	4.34
218-242	3.92	13.84	7.44	7.72	3.76
Mean	7.25	10.80	7.28	7.60	4.52

IV. CONCLUSION

Based on the study, it is concluded that biogas plant made of HDPE can be used for biogas production in hilly areas as it performed satisfactorily both during winter and summer season. The slurry temperature was little higher than the ambient temperature during the winter season of study. The biogas production was higher during summer season due to higher ambient temperature and higher slurry temperature, which was in mesophilic temperature range favorable for biogas production. The cumulative biogas production was215.82 m^3. The ambient temperature also affected the reduction in TS and VS. The inlet and outlet slurry pH was observed within the acceptable limits.

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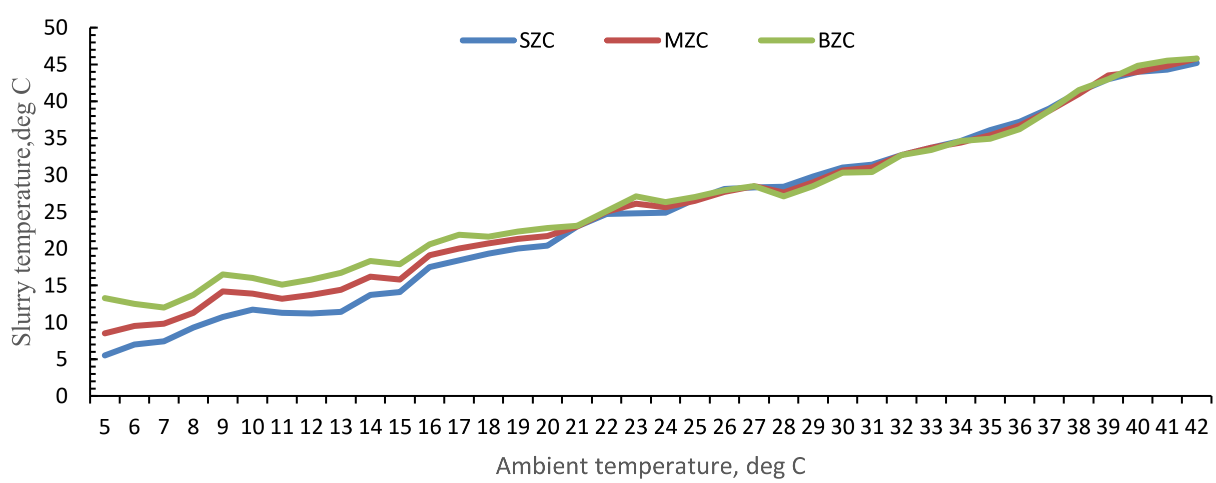

Fig. 2 Effect of ambient temperture on slurry temperature at selected locations in the centre of digester

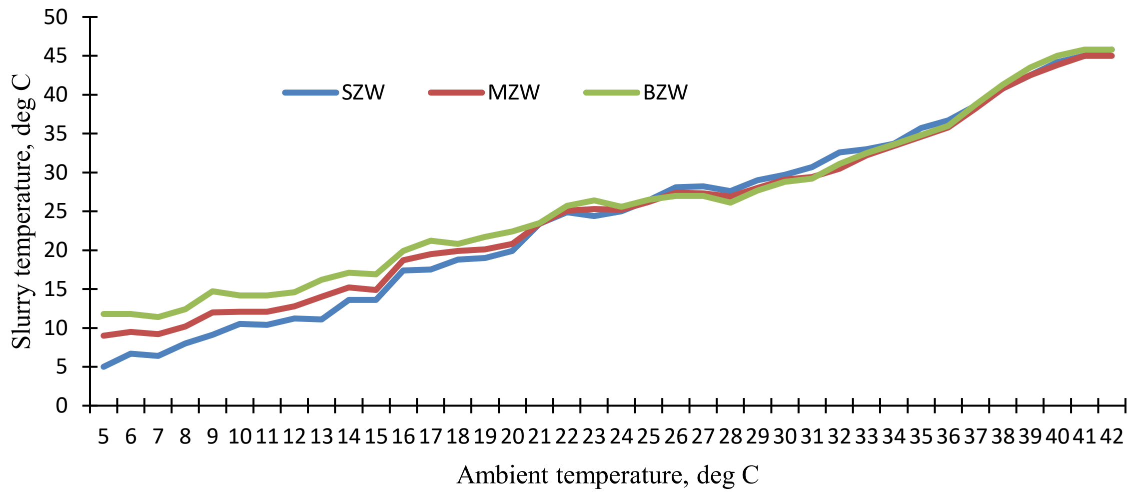

Fig. 3 Effect of ambient temperature on slurry temperature at selected locations near the digester wall