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Shradha Shetty
MVSc Scholar, Department of Livestock Production Management, Kerala Veterinary and Animal Sciences University, Pookode, Wayanad, Kerala, India

John Abraham
Associate Professor, Department of Livestock Production Management, Kerala Veterinary and Animal Sciences University, Pookode, Wayanad, Kerala, India

Balusami C
Associate Professor & Head i/c, Department of Livestock Production Management, Kerala Veterinary and Animal Sciences University, Pookode, Wayanad, Kerala, India

Sabin George
Assistant Professor, Department of Livestock Production Management, Kerala Veterinary and Animal Sciences University, Pookode, Wayanad, Kerala, India

Corresponding Author:
Shradha Shetty
MVSc Scholar, Department of Livestock Production Management, Kerala Veterinary and Animal Sciences University, Pookode, Wayanad, Kerala, India

Effect of digester temperature and digester heating on the production and composition of biogas at high altitude areas

Shradha Shetty, John Abraham, Balusami C and Sabin George

Abstract
In high altitude areas, great variation in the ambient temperature throughout the year affects biogas production. During cold seasons there is either reduction or complete cessation of biogas production. In order to maintain optimum biogas production throughout the year, it is necessary to protect the digesters from cold shock. Thus, the study was carried out to determine the effects of digester temperature on biogas production during summer and winter season. While during monsoon season, the digesters were heated by circulating hot water produced by solar water heater through water jacket which improved the digester temperature to 37.76±0.36 ºC in single stage (D_1) and 36.25±0.31 ºC in two stage digester (D_2), when the mean ambient temperature was 22.18±0.164 ºC. This effect increased the biogas production to 2.51±0.04 and 2.95±0.09 m^3/d. With the increased digester temperature, the composition of biogas improved. Methane concentration increased by 10.22% than in the winter and 6.45% than in the summer season in D_1. While in D_2, the increase was 13.24% greater than in winter and 8.93% greater than in summer season. Thus, heating of digesters prevented heat loss and improved the quality and quantity of biogas.

Keywords: Biogas, digester heating, solar heater, season, methane

1. Introduction

The world is on a paradigm shift towards renewable sources of energy to reduce the effects of global warming and climate change due to fossil fuels. The common renewable sources of energy include solar energy, wind energy, hydro energy and bioenergy. Anaerobic digestion (AD) is one form of bioenergy by which, biogas can be obtained from biomass. The breakdown of complex organic matter to simpler ones with the production of gas rich in methane, by a group of anaerobic bacteria and archaea in oxygen free environment not only helps to recover energy from biomass but also controls pollution by efficient disposal of organic waste and reduced Green House Gas emission (Abdelgadir *et al*., 2014) [1].

Several factors like substrate composition, digester design and operating parameters affect the biogas production with temperature being the prime one (Cioabla *et al.*, 2012) [6]. The digestion process occurs in three different temperature ranges, *viz.*, psychrophilic (0-20 ºC), mesophilic (20-42 ºC) and thermophilic (42-75 ºC), and the rate of degradation of the substrate will be reduced when the temperature falls below 15 ºC (Rajeshwari *et al*., 2000) [19]. But usually, mesophilic and thermophilic temperature ranges are preferred because, higher temperatures increases the rate of degradation of organic matter with improved organic loading rate (OLR) and lowered hydraulic retention time (HRT) along with the destruction of pathogens from the raw materials (Kocar and Eryasar, 2007) [16]. The growth of the methanogenic bacteria is higher at thermophilic range while, that of the acidogenic bacteria at mesophilic range. The sudden fluctuation in the temperature negatively affects the fermentation process of biogas production. As such variations causes microbial imbalance in the digester, the consortia may take a minimum time of three weeks to adapt to the new environmental condition (Adekunle and Okolie, 2015) [2]. The digesters operated at thermophilic temperature range are highly sensitive to the temperature fluctuations and may tolerate a variation of about only +/- 1 ºC while, the mesophilic digesters tolerates a fluctuations of +/- 3 ºC (Weiland, 2010, Dobre *et al*., 2014) [21, 9].

During the colder months, the lower ambient temperature lowers the digester temperature which decreases the biogas production (Ferrer *et al*., 2011, Divya *et al*., 2014) [10, 8]. In order to maintain optimum temperature within the digester and to prevent heat loss through the digesters, different techniques like water jacket around the digesters, heating coils within the digester and heat exchangers either within or outside the digester could be adapted (Kocar and Eryasar, 2007) [16]. Some of the other methods include burying the digester underground, use of solar based heating source, coating the top of the digester with charcoal, use of paddy husk to cover the digester top and insulating the inner lines of the gas holder (Rajendran *et al*., 2012) [18]. The temperature of the digester was increased by 3 ºC with a corresponding increase in biogas production by 7-15%, when the top of the digester was coated with charcoal but, the main disadvantage with this method was to repeat the coating once every one and half month (Anand and Singh, 1993) [4]. Alkhamis *et al*. (2000) [3] used water jacket around the digester to circulate hot water from the solar based heating device and results revealed that digester temperature of 40 ºC was achieved in one hour by circulating hot water through water jacket. During colder months of the year, the use of two solar green houses, one surrounding the digester and the other inner greenhouse to heat the contents of the digester improved the digester temperature by 9.8 ºC than the ambient temperature which supported the biogas production throughout the year (Hassanein *et al*., 2015) [13]. Gaballah *et al*. (2020) [11] experimented to check the potential of the solar heating techniques and the results showed that the integrated solar energy of solar greenhouse with that of solar water heater improved the slurry temperature by 9.5 ºC while, the greenhouse alone improved the slurry temperature by 4.9 ºC above the mean ambient temperature.

During winter season the low digester temperature limits the production of biogas, with increased carbon dioxide content and less methane content (Jyothi *et al*., 2017) [14]. They had also reported that in high altitude areas, where the ambient temperature was low, thermal insulation of the digester was essential for optimum biogas production. Thus, this work was carried out to check the effect of digester temperature on biogas production and composition in a single stage digester (D_1) and newly designed two stage digester (D_2) and to study the effect of digester heating on the production and composition of biogas.

2. Materials and Methods

2.1 Experimental setup

The study was carried out at the Biogas Research Laboratory, School of Bio-energy and Farm Waste Management, Kerala Veterinary and Animal Sciences University, Pookode, Wayanad, which is located at an altitude of 867 meters from the MSL. The area is highly humid with heavy rainfall from South West and North East monsoon from June to September and October to November, respectively causing greater variations in the temperature throughout the year. The research was carried out for a year from June 2019 to May 2020 covering all the seasons. The climatic classification of Wayanad as suggested by Danesh and Pavan (2011) [7] was followed in the study as shown in Table 1. The set up included two digesters, solar water heater consisting of collectors, storage tank, heat exchanger, water pumps, the separator and collector for collecting circulated water along with related pipelines. The two digesters were made using fibre glass and both were provided with the water jackets. The solar collectors were placed on the roof of the college canteen. The hot water produced from solar water heater was stored in separate water tank. The hot water was circulated through water jacket using water pump. The circulated hot water was collected separately in a tank and was again subjected for reheating (Fig. 1 and 3).

The water jackets surrounded the digesters in order to provide insulation to them and prevent the heat losses from sides. During winter (October to January) and summer season (February to May), the digester temperature varied depending on the ambient temperature. During monsoon season (June to September), digester heating was carried out by circulating hot water. The temperature of the hot water circulated was 47.2 ºC.

2.2 Digester design

The capacity of both digesters was 3000 l and made up of fibre glass, having a diameter of 204 cm and height of 100 cm. A D_1 had no baffles and all the four stages of anaerobic digestion (hydrolysis, acidogenesis, acetogenesis and methanogenesis) occurred within a single reactor (Fig. 2a). While, D_2 had two compartments within a single digester which separated the acidogenic phase of anaerobic digestion from methanogenic phase. Within each compartment, there were vertical baffles which restricted the flow of the digestate through it thereby, increasing the surface area for the microbes (Fig. 2b).

2.3 Substrate and inocula

The kitchen waste obtained from the college canteen was finely ground and homogenised with a grinder to a size less than 7 mm mixed with tap water. The finely blended kitchen waste was thoroughly mixed in 1:1 ratio with cow dung, using a mixer. The rumen liquor was collected from the nearby abattoirs to be used as inoculum. The D_1 and the acidogenic chamber of D_2 were filled with the rumen liquor and after about 7 days, both the digesters were batch fed with finely mixed kitchen waste and cow dung.

Both D_1 and D_2 were daily loaded with 25 kg of kitchen waste and 25 kg of cow dung diluted in 50 kg of water from June 2019 to May 2020.

2.4 Analytical methods

The important macro-climatic variables like ambient temperature and relative humidity (RH) were recorded daily during the study period using automatic weather station. The digester temperature was recorded daily using digital probe thermometer. The temperature of the digestate was also recorded daily using Digital EUROLAB ST926B multi-thermometer.

The quantity of biogas produced from both the digesters was recorded daily using biogas flow meter (CLESSE CGS-4) and the composition of biogas was analysed once in a month using biogas analyser (Model No. L-314 Precision Scientific) (Plate-1)

The substrate and the digestate from both the digesters was collected once in a week during the entire study period and different components were analysed like moisture, dry matter (DM), total solids (TS), volatile solids (VS), non-volatile solids and carbon-nitrogen ratio (C/N ratio).

3. Results and Discussion

3.1 Climatological data

The climate at Pookode is characterised by high rainfall, high relative humidity and comparatively low ambient temperature. The winter season, had lowest atmospheric temperature ranging from 21.2 ºC to 22.7 ºC, with a mean ambient temperature of 21.63±0.258 ºC, which affected biogas production. During summer season, the temperature varied from 24.9 ºC to 27.2 ºC, and the mean ambient temperature was 26.06±0.359 ºC. During monsoon season, the temperature varied between 21.6 ºC to 22.6 ºC and the mean ambient temperature was 22.18±0.164 ºC.

The south-west monsoon causes high precipitation during monsoon season resulting in high percentage of RH. The highest mean RH during monsoon season was 92.50±1.33 per cent. During winter season, the mean RH value observed was 89.33±0.71 per cent. The lowest mean RH value of 63.33±1.28 per cent was observed during summer season.

3.2 Physico-chemical analysis of substrate and digestate

The substrate had moisture and DM of 79.57±0.34 and 20.43±0.34%, respectively. The volatile solid and non-volatile solid content of the mixed substrate was 93.39±0.51 and 6.61±0.51%.

The presence of baffles and maintenance of different microbial consortia in acidogenic and methanogenic chamber in D_2 improved the utilisation of organic matter thus lowering the DM content in the digestate to 1.07±0.11 per cent. While the DM content of digestate obtained from D_1 was 2.68±1.02 per cent. The values of C/N ratio of digestate collected from D_2 (14.68±0.62: 1) was lower than D_1 (20.58±0.33: 1). The lower the C/N ratio, better the fertilising value of the digestate with better crop yield.

The VS content of the digestate obtained from D_2 was lower (0.46±0.11) than that obtained from D_1 (3.04±0.21). The main reason for lowered VS content of D_2 digestate was because of closer contact between the microbes and organic matter which was mainly due to increased surface area due to the presence of baffles. The VS removal was 96% in D_2 while it was 73.5% in D_1.

3.3 Biogas production and composition during winter and summer season

The temperature of the digesters varied depending on the ambient temperature during summer and winter seasons. During winter season while the digester temperature was 20.56±0.29 and 20.64±0.35 ºC in D_1 and D_2, the biogas production was 0.73±0.03 m^3/d and 0.97±0.03 m^3/d. It was significantly higher (p<0.01) during summer season (1.74±0.05 m^3/d and 1.98±0.06 m^3/d) in D_1 and in D_2, when the digester temperature was 25.05±0.33 and 25.33±0.27 ºC, respectively. Hamad *et al*. (1981) [12] had reported that biogas production increased exponentially with increase of temperature. Sorathia *et al.* (2012) [20] had reported that the lower ambient temperature during the winter season reduced biogas production. The reasons for the increase in biogas production during summer and decreased biogas production during winter were reported by Khalid *et al*. (2011) [15] and Abdelgadir *et al*. (2014) [1]. They reasoned that temperature had great influence on the kinetics of microbial consortia, and there by on the biogas and methane yield. At low temperature the microbial growth and substrate utilisation were lowered. Lower ambient temperature also increased the HRT and affected the activity of microbial consortia resulting in lower biogas production.

3.4 Biogas production and composition during digester heating

Hot water jacket around the digesters provided thermal insulation and also transferred temperature to the digester through the side walls, when the ambient temperature was low. This resulted in the digester temperature of 37.76±0.36 ºC in D_1 and 36.25±0.31 ºC in D_2, when the mean ambient temperature was 22.18±0.164 ºC. The digester temperature of D_2 was 1.51 ºC less than D_1 because of the presences of fibreglass median septum and baffles even though hot water of 47.2 ºC was circulated through the water jacket in both the digesters. This effect increased the biogas production to 2.51±0.04 and 2.95±0.09 m^3/d in D_1 and D_2, respectively. By providing water jacket in which the hot water produced by solar water heater was circulated by a mono block pump, the heat loss from the digester through the side walls could be prevented. An optimum temperature for biogas production could be maintained in the digester, which resulted in the optimum biogas production, which was 70.92 per cent more than that obtained during winter season in the D_1 and 67.11 per cent more than that obtained during winter season in the D_2. It was also 30.68 per cent more than that obtained during summer season in D_1 and 32.88 per cent more than that obtained during summer season in D_2. Zhang *et al*. (2016) [22] and Mahmudul *et al.* (2019) [17] had stated that temperature played an important role in the efficient performance of the digesters and during winter season, the circulation of hot water produced by solar energy around the digester could maintain optimum temperature with increased biogas production.

3.5 Effect of digester temperature on biogas production

The temperature of the digester had greater influence on the biogas production in both the digesters. The highest biogas yield (2.25-3.15 m^3/d) was during Monsoon season when the digester was heated through a water jacket by solar water heater, when the digester temperature was in the range of 35-40 ºC while, the least biogas yield (0.45-1.15) was observed during winter season when the digester temperature was in the range of 18-22 ºC. During summer, the yield was 1.50-2.20 m^3/d when the digester temperature was in range of 23-28 ºC. The digester temperature influenced the microbial activity of the consortia and thermodynamic equilibrium of the biochemical reactions and thereby affected the biogas production. Chae *et al*. (2008) [5] had reported that digester temperature influenced the CH_4 yield. There was an increase in the biogas production when the digester temperature was in the range of 25-35 ºC but the increase was not linear.

3.6 Composition of biogas during winter and summer season

In both the digesters, there was a significant difference in the composition of the biogas during different seasons. During summer season, the increase in the ambient temperature increased the digester temperature to 23-28 ºC, which resulted in a high CH_4 concentration of biogas in D2, which was 58.91% compared to 52.2% in D_1. During winter season, there was reduction in the methane concentration in D_2 and D_1 digester when the digester temperature dropped down to 18-22 ºC which was 56.53% and 49.73% respectively. In D_2, the concentration of CO_2, H_2O and H_2S during winter was 39.42%, 3.8% and 0.25% while it was 36.68%, 4.1% and 0.31% during summer season, respectively. In D_1, the concentration during winter was 46.80% CO_2, 3.20% H_2O and 0.27% H_2S while it was 43.33% CO_2, 4.20% H_2O and 0.27%

H_2S during summer season. The composition of the biogas varied with variation in the digester temperature (Chae *et al*., 2008) [5]. The higher the digester temperature greater was the methane concentration which might be due to the increased microbial methanonogenic activity which also increases the rate of degradation of organic matter

3.7 Composition of biogas during heating period

The maintenance of digester temperature at mesophilic range of 35-38 ºC increased the methane concentration in both digesters. The composition of biogas obtained from D_1 and D_2 are presented in Table 2. During Monsoon season (June-September) when the digester was heated, the methane concentration increased by 10.22% than in the winter season and 6.45% than in summer season in case of D_1. In D_2, the percentage increase of methane during the same period was 13.24% greater than the winter season and 8.93% greater than the summer season. This conclusively proved that the digester temperature had high correlation with high methane percentage of biogas composition in mesophilic range. As the digester temperature was higher than the ambient temperature, the activity of microbial consortia was higher with higher degradation rate resulting in the increased concentration of methane.

3.8 Mean temperature of digestate

The temperature of the digestate was also influenced by the climatic condition of the area. The mean temperature of the digestate was higher in summer followed by winter season when the ambient temperature influenced the digester temperature. As the digesters were heated by circulating hot water through jacket during monsoon season, the temperature of digestate obtained was higher than the ambient temperature. The values obtained during the study period are presented in Table 3.

3.9 Economic analysis

The economic analysis was also carried out during the heating period in order to check the performances of the digesters when they were heated by circulating solar energy based hot water. The economic analysis is presented in Table 4. Both the digesters were made up of fibre glass but they differed in the design. The installation cost of D_1 was INR 98,000 while that of D_2 was INR 1,25,000. The cost of D_2 was higher than D_1, because D_2 involved both horizontal and vertical baffles. The solar water heater along with the monoblock pump used to circulate hot water cost was around INR 36,500.

The operational cost included the cost for maintenance and cleaning of digesters per year. The operational cost was same for both the digesters (D_1 and D_2) and was around INR 5000 per year.

The products obtained from anaerobic digestion of organic waste were biogas and digestate. The biogas produced was used for cooking in the college canteen while, the digestate obtained was used as fertiliser which improved the nutritive value of the soil thereby increasing the crop yield. The biogas output during the heating period which was for around 180 days from D_1 was 360 m^3 while that from D_2 was 420 m^3. The amount of digestate obtained during these 180 days was 1000 kg from D_1 and 750 kg from D_2.

The NPV values obtained for D_1 and D_2 were INR 63,622 and INR 27,077.91, respectively. The positive NPV values indicate that the systems are feasible and will achieve positive economic returns. The NPV value of D_2 was lower than D_1, because of high initial investment cost involved in the installation of the digester. The IRR values were 26.13% for D_1 and 11.42% for D_2.

Table 1: Climatic classification of Wayanad

Monsoon Season	Winter Season	Summer Season
June	October	February
July	November	March
August	December	April
September	January	May

Table 2: Composition of biogas during heating period

Composition	D1	D2
Methane (%)	57.32	62.97
Carbon-dioxide (%)	37.20	31.33
Water vapour (%)	5.20	5.40
Hydrogen sulphide (%)	0.28	0.30

Table 3: Mean temperature of digestate

Seasons	Mean Temperature (ºC) of the digestate-obtained from D1 (Mean±SE)	Mean Temperature (ºC) of the digestate-obtained from D2 (Mean±SE)
Winter season	22.53±0.11	23.02±0.07
Summer season	24.36±0.17	25.44±0.28
Monsoon season	37.28±0.17	36.13±0.08

Table 4: Economic analysis

Category	D_1	D_2
Initial Cost		
Cost of digesters (INR)	98,000	150,000
Biogas stove & pipes (INR)	1,200	1,200
Solar water heater (INR)	35,000	35,000
Monoblock pump (INR)	1,500	1,500
Total	135,700	187,700
Operation cost		
Maintenance cost (INR)	2,000	2,000
Cleaning cost (INR)	3,000	3,000
Total	5,000	5,000
Annual output		
Annual biogas output (m^3)	360	420
Biogas value (INR)	32,400	37,800
Digestate as fertiliser (kg)	1000	750
Digestate value (INR)	10,000	7,500
Total	42,400	45,300
Economic Index		
Payback time (years)	3.32	4.25
NPV	63,622	27,077.91
IRR	26.13	11.42

Fig 1: Solar water heater

Fig 2a: Single stage digester (D_1) and Fig. 2b Two stage digester (D_2)

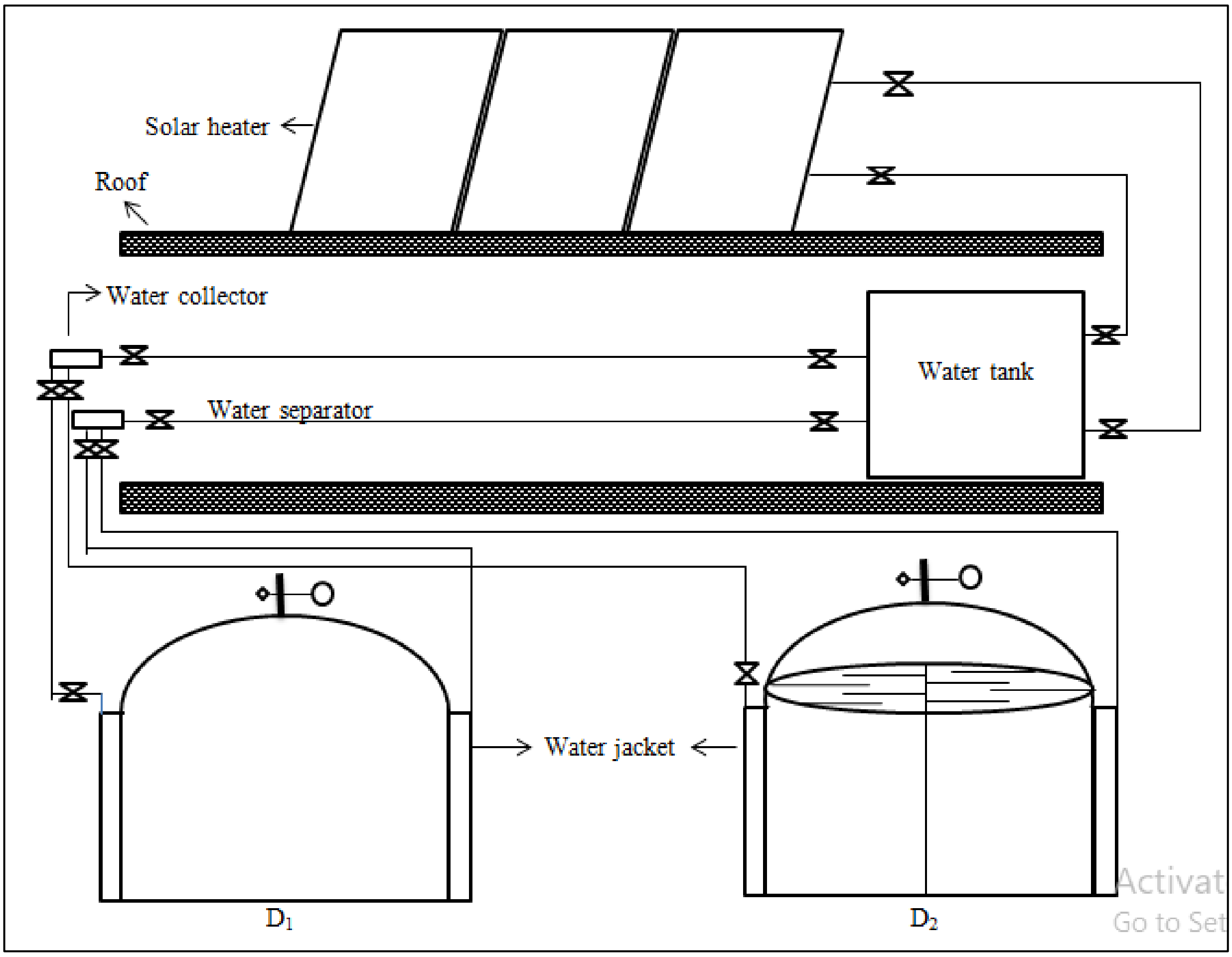

Fig 3: Schematic diagram of digesters with heating system

4. Conclusion

During summer and winter seasons, digester temperature was influenced by ambient temperature and it was seen that the biogas production was significantly ($p<0.01$) higher during summer (1.74±0.05 in D_1 and1.98±0.06 in D_2) when the digester temperature was 25.05±0.33 ºC and 25.33±0.27 ºC than winter season, when the digester temperature was 20.56±0.29 ºC and 20.64±0.35 ºC in D_1 and D_2, respectively. When digester heating was carried out by circulating hot water produced by solar water heater through the water jacket, the biogas production was highest compared to summer and winter. The biogas production in D_1 and D_2 stage digester was 2.51±0.04 and 2.95±0.09 m^3/d and the digester temperature was 37.76±0.36 ºC and 36.25±0.31 ºC, respectively. The composition of biogas also varied depending on ambient temperature. An optimum biogas production of 2.95±0.09 m^3/d with highest concentration of 65.67% methane could be obtained at a digester temperature of 35-38 ºC from D_2. This was 14.91% more than D_1 at similar digester temperature.

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