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Performance analysis of a new two stage restricted flow anaerobic baffled biogas digester

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Abstract
A newly designed Two Stage Restricted Flow Anaerobic Baffled Digesters (TS-ABD) was compared with that of a Single Stage Non-baffled Digesters (SSD) of similar capacity by co-digesting kitchen waste and cow dung for a period of one year. The pH of methanogenic chamber of TS-ABD was maintained at 8.5 with the addition of sodium bicarbonate. The average biogas production and volatile solid (VS) removal was 15% and 22.5% higher in TS-ABD than the SSD. Digester heating by circulating hot water produced by solar water heater through water jacket improved the biogas production by 70.92% and 67.11% more than that obtained during winter and by 30.68% and 32.88% than that obtained during summer from SSD and TS-ABD, respectively. The Hydraulic Retention Time (HRT) could be reduced to 23.5 days and Organic Loading Rate (OLR) increased to 20 kg VS $d^{-1}m^{-3}$ in the TS-ABD. The methane concentration of biogas was 11% more in TS-ABD than that obtained from SSD.

Keywords: Co-digestion, two-stage digester, biogas, anaerobic digestion

1. Introduction

The demand for energy is increasing day by day and is expected to double by 2050. As of now, most of the energy requirements are met by fossil fuels. This contributes to one-third of the total greenhouse gas emission and cause global warming and climate change. To mitigate the negative impacts of fossil fuels on the environment and also to meet the energy demands of the growing population, it is an urgent necessity to shift towards green renewable source of energy (Martins *et al*., 2019) [19].

Among the renewable sources of energy, biogas which is produced by the decomposition of biomass has significant position. Biogas production has twin advantage of producing combustibles gas; methane along with digestate rich in nutrients to be used as organic fertilisers (Balat and Balat, 2009; Khalid *et al*., 2011; Shen *et al*., 2013) [6, 13, 24]. In India, 32% of the total primary energy is derived from biomass and most of the rural population depends on biomass for energy needs. As per the reports of the Ministry of New and Renewable Energy, the amount of biomass generated in India is about 500 million metric tonnes per year. Additional biomass available from agriculture and forestry comprises of about 120-150 million metric tonnes. All these wastes if efficiently utilised can produce huge amount of bioenergy which can be used for various purposes like cooking, heating and electricity generation.

Globally, the dumping of food waste occupies a space of nearly 1.4 billion hectares leaving behind a carbon footprint of 3.3 billion tonnes of carbon-dioxide equivalent, causing global warming (FAO, 2011) [9]. Incinerating or dumping of food waste in open causes huge environmental and health risks by the release of dioxins and greenhouse gases (Girotto *et al*. 2015; Li *et al*., 2017; Mirmohamadsadegi *et al*., 2019) [10, 20].

The cow dung which is produced in large quantities has good microbial consortia. But, due to lower biodegradability, the cow dung when used as sole substrate reduces the biogas production (Tufaner and Avsar, 2016) [25]. The co-digestion of food waste along with cow dung increased the biogas production by balancing the nutrients and developing a positive synergism between different microbes within the anaerobic digesters (Lisoba and Lansing, 2013) [17].

Anaerobic digestion is a complex bi-phasic process with four steps. The first phase is the acidogenic phase during which hydrolysis, acidogenesis and acetogenesis process occur resulting in the production of organic acids while, the second phase is methanogenic phase during which, the methanogens convert the organic acids into methane and carbon-dioxide

(Adekunle and Okolie. 2015) [3]. The acidogenic and methanogenic micro-organisms differ from each other in terms of physiology, nutrition and sensitivity towards environment (Demirel and Yenigun, 2002) [7]. Thus, when they are together in a single reactor, the microbes will be in direct competition with each other resulting in reduced biogas production. To overcome this limitation, an all-in-one, new Two-Stage restricted flow Anaerobic Baffled biogas Digesters (TS-ABD) was designed where the two phases were separated from each other by a median septum within the digester. Co-digestion of kitchen waste and cow dung was carried out to analyse its performance.

2. Materials and Methods

2.1 Digesters design and fabrication

Six digesters *i.e.*, three Single Stage Digesters (SSD) and three TS-ABD, were fabricated with a diameter of 204 cm and height of 100 cm, each having a volume of 3000 litres. The SSD had a single compartment and all the process of anaerobic digestion (hydrolysis, acidogenesis, acetogenesis and methanogenesis) occurred inside the same chamber as shown in Fig 1.

In the TS-ABD, the whole digester was divided into two halves with an opening at a particular height to optimise the flow of digesta and maximise the control over the bacterial communities living within the digesters. The two halves were provided with vertical baffles which restrict the movement of digesta through it, simultaneously increasing the surface area (Fig 2a &2b). The higher surface area allowed the organic matter to be in close contact with the microbes. The first chamber was the acidogenic chamber where hydrolysis, acidogenesis and acetogenesis occured and the second chamber was the methanogenic chamber where methanogenesis occured. The pH of methanogenic chamber of TS-ABD was monitored continuously and maintained at 8.5 with the addition of sodium bicarbonate. All the six digesters had a water jacket surrounding them, in which hot water produced by solar energy could be circulated to optimise the digester temperature. The digesters design along with the solar panel arrangement was made as shown in Fig. 3.

Fig 1: Single stagenon-baffled anaerobic digester

Fig 2a & 2b: Two stage restricted flow anaerobic baffled biogas digester

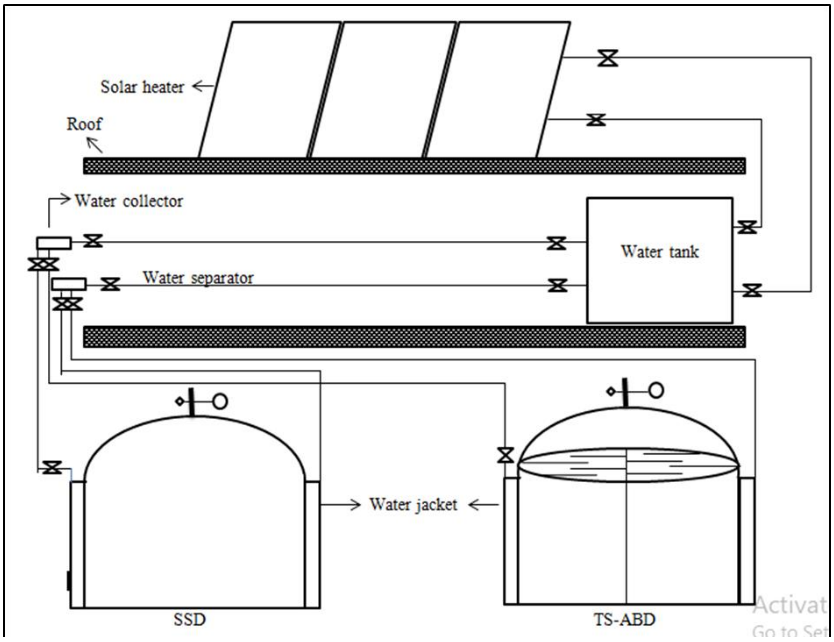

Fig 3: Schematic diagram of SSD and TS-ABD with solar heater arrangement

2.2 Substrate and inocula

The food waste, mixed with tap water was finely ground and homogenised with a grinder to a size less than 7 mm. The finely blended food waste was thoroughly mixed with equal quantity of fresh cow dung, using a mixer. The rumen liquor was collected from the nearby abattoirs to be used as inoculum.

2.3 Operating strategy

The study was carried out at the School of Bio-energy ad Farm Waste Management, Kerala Veterinary and Animal Sciences University, Pookode, Wayanad during June 2019 to May 2020. Initially, the SSD and acidic chamber of TS-ABD were filled with rumen liquor while; the alkaline chamber of TS-ABD was filled only with cow dung. After seven days of filling the digesters, the SSD and TS-ABD were daily fed with ground, mixed and homogenised substrates. All the digesters were fed daily at 2: 00 PM.

During summer and winter seasons, the digesters temperature varied in accordance with the ambient temperature. During monsoon season, the digesters temperature was kept optimum in the range of 35-37 ºC (Alkhamis *et al*., 2000 and Mahmudul *et al*., 2019) [4, 18] by circulating hot water produced by solar water heater through water jacket around the digesters.

2.4 Analysis and calculations

Weekly analysis of the input substrates and output digestate were carried out to determine the Total Solids (TS) and Volatile Solids (VS) as per AOAC (2016). Nitrogen (N) was estimated by Kjeldahl's method and Carbon (C) by Walkley and Black method. The temperature and pH of the substrate and digestate were recorded using Digital EUROLAB ST926B multi-thermometer and Eutech digital pH tutor instrument, respectively. The quantity of biogas produced per day was recorded using biogas flow meter (CLESSE CGS-4). The composition of the raw biogas produced was analysed weekly using a biogas analyser (Model No. L-314 Precision Scientific). The values obtained were statistically analysed using Independent t-test and General Linear Model (GLM) using SPSS version 24 ® software.

3. Results and Discussion

3.1 Physico-chemical characteristics of kitchen waste, cow dung and their equal mix

The pH of the kitchen waste and cow dung was 5.79±0.17 and 7.73±0.03. The moisture and Dry Matter (DM) content of kitchen waste was 78.78 ±0.31 and 21.22±0.31%, while that of cow dung was 82.83±0.34 and 17.17±0.34%, respectively. The DM content of kitchen waste varied depending on its origin, eating habits and season. The DM content of cow dung was lower than that of kitchen waste, mainly due to partial digestion of feed materials in the rumen of the cattle which in turn, reduces the organic matter content of the dung. The C/N ratio of kitchen waste and cow dung was 16.10±0.51 : 1 and 22.61±0.31 : 1, respectively. The combination of substrates with lower and higher C/N ratio was suggested for optimum biogas production by Orhorhoro *et al*. (2016) [22]. The VS content of kitchen waste was higher (93.49±0.58% of TS) than that of cow dung (82.03±0.46% of TS). VS is that portion of TS, which undergoes anaerobic fermentation to produce biogas while, the non-volatile solids remain unaffected (Awasthi *et al*., 2017; Khoiyangbam *et al*., 2015) [5, 14].

The pH of the mixed substrate was towards neutral (6.75±0.15). The mixed 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 cow dung and kitchen waste could be used individually as sole substrate for biogas production, but the co-digestion of both together yielded higher methane than each substrate alone, mainly by balancing the nutrients in the digesters (Li *et al*., 2009; Otun *et al*., 2015) [23].

3.2 Physico-chemical characteristics of digestate

The pH of the digestate obtained from SSD and TS-ABD were 7.99±0.18 and 8.47±0.05. Jain *et al*. (2015) [11] had reported that an optimum pH of 6.5-7.5 was required for efficient biogas production. While, Nijaguna (2016) [21] reported that, the methanogens were highly sensitive to the environmental variations and worked efficiently when the pH was in the range of 6.8-8.5. In the acidic chamber, the production of volatile fatty acids reduced the pH to 6.5.To optimise methane production, the pH of the methanogenic chamber was maintained at 8.5 using sodium bicarbonate as per Jurgensen *et al*. (2018) [12].

The DM of the digestate of TS-ABD (1.07±0.11) was less than SSD (2.68±1.02), which might be due to the increased utilisation and conversion of organic matter to biogas by the different microbial consortia in the two chambers.

The C/N ratio of the digestate obtained from TS-ABD was lower than SSD. The values were 14.68±0.62: 1 and 20.58±0.33: 1, respectively. Nijaguna, (2016) [21] had reported that the digestate with lower C/N ratio had better fertilising value and resulted in a better crop yield of 5-15%.

The VS content of the digestate from the TS-ABD was lower (0.46±0.11) than that obtained from the SSD (3.04±0.21). This was because of the higher biodegradation of VS as the organic matter was in close contact with the microbes due to the increased surface area, brought about by the baffles. The VS removal was 96% in TS-ABD while it was 73.5% in SSD.

3.3 Hydraulic Retention Time (HRT) and Organic Loading Rate (OLR)

The TS-ABD with separate acidogenic and methanogenic chambers and the restriction of the flow by alternately arranged baffles, increased the surface area and digestion of organic matter, which resulted in a significantly ($P<0.01$) reduced HRT of 23.5 ± 0.43 days, while it was 30.17±0.48 days in the SSD. The OLR was 12.07±0.32 kg VS $d^{-1}m^{-3}$ for the single stage digester while it was 20.01±0.36 kg VS $d^{-1}m^{-3}$ for the two stage digesters. There was a significant difference ($p<0.01$) in the OLR between the two digesters.

3.4 Biogas production

The biogas production varied throughout the year depending on the variation in the ambient temperature. The average biogas production in SSD and TS-ABD was 1.66±0.51 and 1.96±0.57 m^3/d respecteively. The biogas production was highest in TS-ABD which might be due to the fact that the phase separation of acidogenic microbial consortia and methanogenic consortia protected the methanogens from the shock of low pH, providing high OLR and low HRT. This also favoured the growth of methanogenic bacteria in the methanogenic chamber and acidogenic bacteria in the acidogenic chamber (Demirel *et al.*, 2005) [8]. The baffles of the TS-ABD provided templates on which the microbial sheets were formed, bringing about higher level of biodegradation of volatile solids than the SSD resulting in higher biogas production.

3.5 Seasonal effect on biogas production
During summer and winter season, the digester temperature varied depending on the ambient temperature, which affected the biogas production. As shown in Fig. 3, during winter season, while the digester temperature was 20.56±0.29 and 20.64±0.35 ºC in the SSD and TS-ABD the biogas production was 0.73 ± 0.03m^3/d and 0.97±0.03 m^3/d, but it was significantly higher (p<0.01) during summer season (1.74± 0.05m^3/d and 1.98± 0.06m^3/d)in SSD and in TS-ABD, when the digester temperature was 25.05 ± 0.33 and 25.33±0.27 ºC, respectively (As shown in Fig. 4). During both summer and winter season, biogas production was more in the TS-ABD than in SSD. Temperature had great influence on the kinetics of microbial consortia, and there by on the biogas and methane yield. At low temperature, the microbial prolifereation and substrate utilisation were lowered. The lower ambient temperature also increased the HRT and affected the activity of microbial consortia resulting in lower biogas production (Khalid *et al.*, 2011 and Abdelgadir *et al.*, 2014) [13, 2].

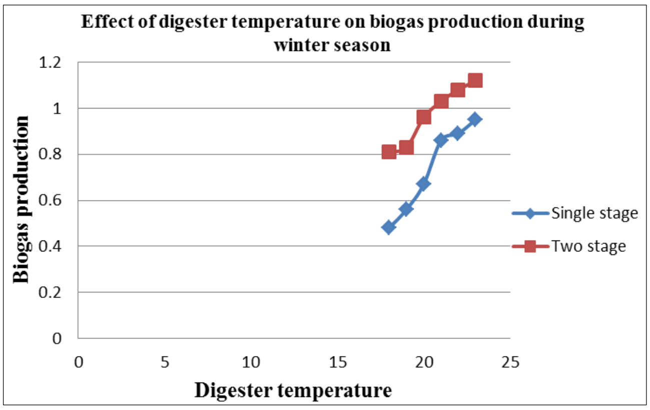

Fig 3: Effect of digester temperature on biogas production during winter season

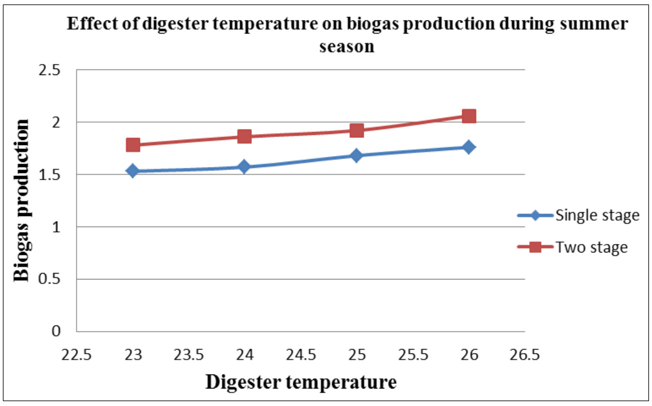

Fig 4: Effect of digester emperature on biogas production during summer season

3.6 Effect of digester heating on biogas production
During monsoon, the hot water circulated through the water jacket around the digesters provided thermal insulation and also transferred temperature to the digester even when the ambient temperature was low. This resulted in an optimum digester temperature of 37.76±0.36 ºC in SSD and 36.25±0.31 ºC in the TS-ABD, while the mean ambient temperature was 22.18±0.164 ºC. This effect increased the biogas production to 2.51±0.04 and 2.95±0.09m^3/d (as shown in Fig. 5). Digester heating resulted in higher biogas production, which was 70.92% more than that obtained during winter season in the SSD and 67.11% more than that obtained during winter season in TS-ABD. It was also 30.68% more than that obtained during summer season in SSD and 32.88% more than that obtained during summer season in TS-ABD. Zhang *et al.* (2016) [26] and Mahmudul *et al.* (2019) [18] had stated that during colder days, the circulation of hot water produced by solar energy around the digester could maintain optimum temperature, with increased biogas production.

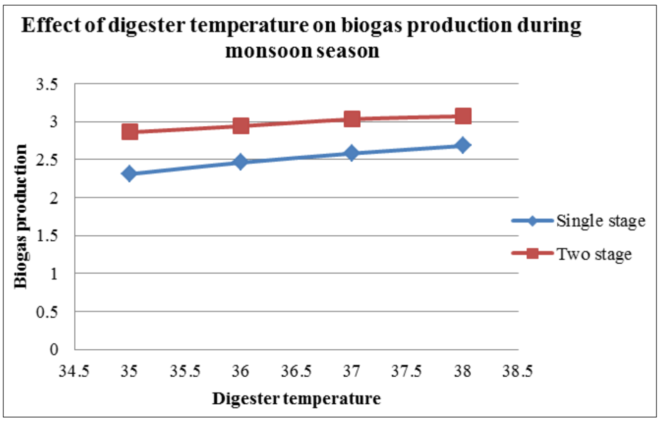

Fig 5: Effect of digester temperature on biogas production during monsoon season

3.7 Composition of biogas in different digesters
Between the digesters, there was a significant difference (p<0.01) in the composition of the biogas produced. The biogas obtained from TS-ABD had higher methane content (60.25%) than that obtained from SSD (53.62%). The main reason for enhanced methane production in TS-ABD was due to increased rate of degradation of the substrate which provided higher amounts of readily available VFAs to the methanogens in the second chamber and also due to the maintenance of pH of 8.5 in the second chamber, which caused multiplication of methanogens in large number increasing methane production than the SSD. The percentage of methane in TS-ABD was 11% more than that of SSD. The composition of biogas obtained from different digesters is presented in Table. 1.

Table 1: Composition of biogas from SSD and TS-ABD

Composition	Biogas from SSD	Biogas from TS-ABD
Methane (%)	53.63	60.26
Carbon-dioxide (%)	41.77	35.26
Water vapour (%)	4.33	4.2
Hydrogen sulphide (%)	0.273	0.286

4. Conclusion
The newly designed TS-ABD performed more efficiently than the common SSD. The average biogas production and VS removal was 15% and 22.5% more in TS-ABD than the SSD. Digester heating by circulating hot water produced by solar water heater through the water jacket around the digester optimised the digester temperature. The biogas production was 70.92% and 67.11% more than that obtained during winter and 30.68% and 32.88% more than that obtained during summer from SSD and TS-ABD, respectively. The

newly designed TS-ABD also decreased HRT to 23.5 days and increased OLR to20 kg VS $d^{-1}m^{-3}$, with higher percentage of VS removal. The concentration of methane in the TS-ABD was 11% more than that in the SSD.

5. Acknowledgement
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