Investigation of Operating Conditions for Optimum Biogas Production in Plug Flow Type Reactor

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Introduction

With the fast depletion of non-renewable energy sources and high prices, investigation of all possible alternative energy sources especially renewable energy such as solar, biomass, and wind has been increased. In most developing countries biomass waste is abundant source of energy, which can be utilized to generate energy and to produce manure for agriculture as a by product.

Biogas is generated by anaerobic digestion of organic matter. It is composed of methane and carbon dioxide (Goswami, n.d.). Organic matter refers to agricultural residues, manure, and garbage and sewage waste. They originate from wide variety of sources spread throughout the world. Since they can be derived from relatively recently living material than fossil fuel, they are sustainable.

Great potential exists in the Sri Lanka for biogas generation and it is one of the sustainable solutions for the waste disposal problem in the country, for rural development of the country and reduction fossil fuel imports.

Early biogas digesters introduced were continuous flow type digesters. Continuous flow biogas reactors require regular water supply and is preferred for animal and human wastes. Considering these facts a new biogas digester was developed by National Engineering Research and Development Centre of Sri Lanka which is called 'Dry Batch Reactor' (DBR). The preferred feed stock for Dry Batch biogas digesters are straw and animal waste. The moisture content of the input material should be more than 85% while for the continuous type digester the solid content should be 9 to 10% (SLSI, 2006). Disadvantages of the dry batch system are difficulty in loading and unloading , the presence of bio sludge in larger digesters, unstable gas generation rate and the long operating periods. Several parameters affect the optimum performance of plug flow type biogas plants. However, well established information is not available for optimum operation of these types of biogas plants; hence the use of plug flow type has been neglected compared to other types.

Chanakya, et al. (2004) mentioned the failures in converting other types of biomass into manure like slurries for biogas production. This reason has led them to introduce two designs for the successful use of other types of biomass for biogas production. They are plug flow digesters and solid state stratified bed digesters (Chanakya, et al., 2004).

The plug flow type digester has been used to deal with wastes like green leaves and other floating type vegetations which are not generally fed to the other continuous type or batch type digesters. Plug flow reactor is capable of transforming more organic solid waste into biogas. They are capable of converting feed stocks with Total Solids content of 11-14 % (Natural resources conservation service, 2004). There is no longitudinal mixing in ideal plug flow digesters. When the new manure is added the previous feed stocks move in plugs towards the outlet. Operation of plug flow digesters has rather complex behaviour than described above. Some of feed stock will travel faster than the others, and some will settle in the digester (Graves, et al., n.d.). There are a number of installations of plug flow reactors in the country with some having two phase installation design and others using effluent recirculation method. Therefore establishing the parameters which affect the optimum biogas production in plug flow type biogas digester is important for optimum utilization of feed stock resources and of the biogas produced. This will guide the path to sustainable use of bio energy.

Experimental Setup

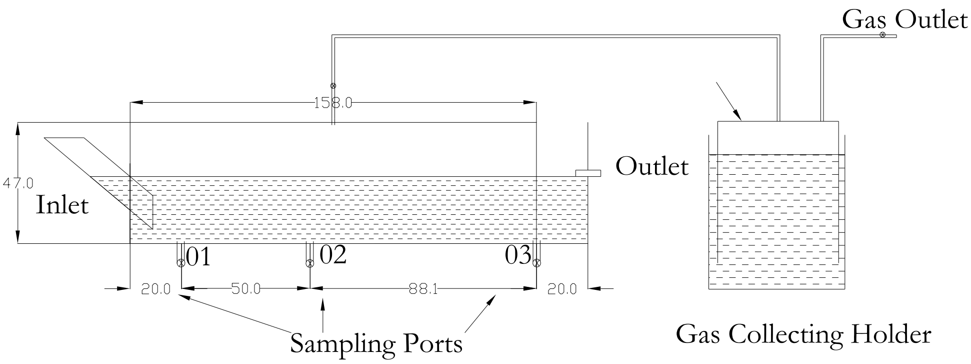
Plastic barrels commonly available in the local market were used for the fabrication of the digester. Diameter of these barrels is 0.47m which facilitates mounting and space requirement to keep the unit. Three barrels were fixed together considering the structural stability and the feasibility in supporting. The length of the digester was 1.58m. The length to width ratio was closer to 3.5:1. This satisfies the length to width ratio defined for manure based on the plug flow digesters (Natural resources conservation service, 2004).

Hence the dimensions and volume of the digester are:

The diameter of the digester	= 0.47 m
Length of the digester	=1.58 m
The digester volume	≈ 0.27 m^3
Working volume	≈ 0.188 m^3

The inlet of the digester was fabricated with a PVC pipe of diameter 11cm. The digester had three windows to observe the inside flow of digestion medium. Three sampling ports were placed in order to facilitate sample the withdrawal.

Figure 1 - Diagram of the Digester



The gas holder was fabricated with another two plastic barrels both of which have one end opened. One barrel was filled with water and the other has an inlet and an outlet dipped in the water. Two plastic tubes of diameter 12.74 mm are used for inlet and outlet. The gas produced in the digester flows to the holder and lifts it up. The produced gas amount can be estimated by the diameter of the barrel and the height of the holder that lifts up. The schematic diagram of the digester is shown in Figure 1.

Two digesters of the same dimensions were fabricated in order to carry out two parallel tests with two loading rates simultaneously.

Figure 2- Digester 1

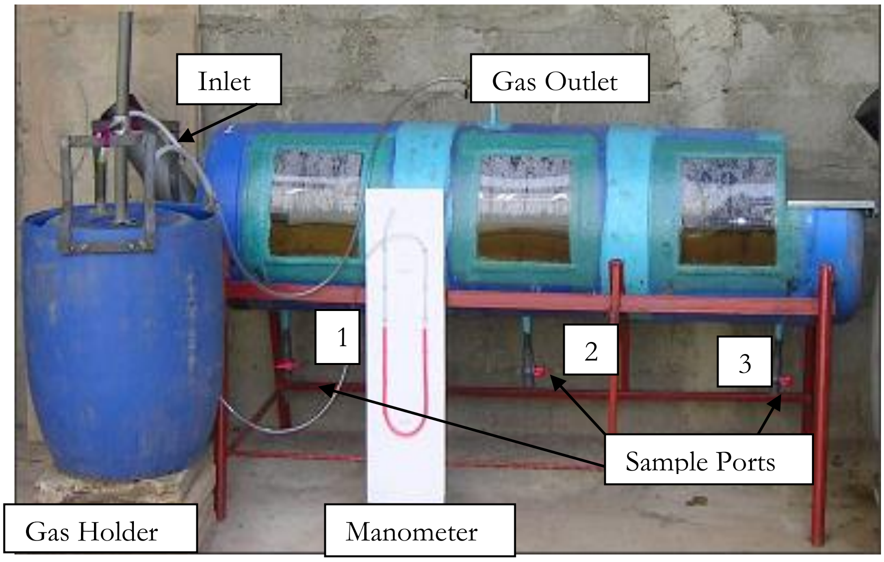


Figure 3 - Digester 2

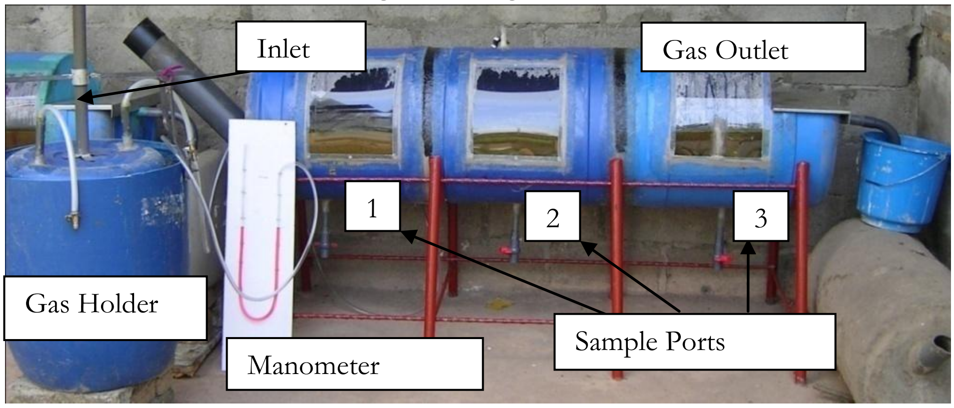


Figure 4 - Inlet of the Digester

Figure 5 - Gas Holder

Initial preparation

Anand et al. (1998) in his research used leaf biomass 50kg/day for 5m3 digester initially and then increased to 100kg/day. The digester 50m^3 for market garbage treatment designed by Sustainable Energy Authority which was intended to feed 1,000kg/day was able to treat 500kg/day at operating conditions. The plug flow digesters developed by the NERDC of Sri Lanka has the capacity to treat 10kg/day for one cubic meter total volume of the digester.

Daily feed stock allowed for the total volume of digester is taken as 10 kg per day per m^3 total digester volume.

The digester volume = 0.27 m^3

Therefore daily feed stock = 10 x 0.27

= 2.7 kg per day

≈ 3.0 kg per day

Therefore, feed rate of 3kg was selected as first feed rate. Other feed rates selected were 0.7kg, 1.4kg and 6kg.

Operating time = 20 days

For the bacteria culture to grow initial preparation of the digester should be carefully done. This was done by feeding cow dung for seven days. The feeding rate of food waste was increased in steps in order to achieve the expected feeding rate and to avoid the acidification. The feed stocks were ground into smaller sizes using a domestic grinder to reduce the particle size. Calcium carbonate was used for the pH adjustment. Temperature variation during day time was between 28^{o}C-31^{o}C.

Composition of feed stocks for 0.7 kg per day in digester no 02:

Food waste & other 350g

Vegetables residue 450g

Composition of feed stocks for 1.4 kg per day in digester no 01:

Food waste 450g

Vegetables residue 900g

Fruit waste 50g

Composition of feed stocks for 3kg per day in digester no 01:

Food waste 450g

Vegetables residue 900g

Fruit waste 50g

Water 1600g

Composition of feed stocks for 6kg per day in digester no 02:

Food waste 900g

Vegetables residue 1800g

Fruit waste 100g

Water 3200g

Table 1 - Feedstock Characteristics

	Digester 01-0.7 kg per day	Digester 01-1.4 kg per day	Digester 01- 3kg per day	Digester 02 – 6kg per day
Average T S Content (%)	21.9	16.1	5.7	5.7
Average V S Content (% VS)	91.9	93.3	92.3	92.3

Table 2 - Feeding Plan

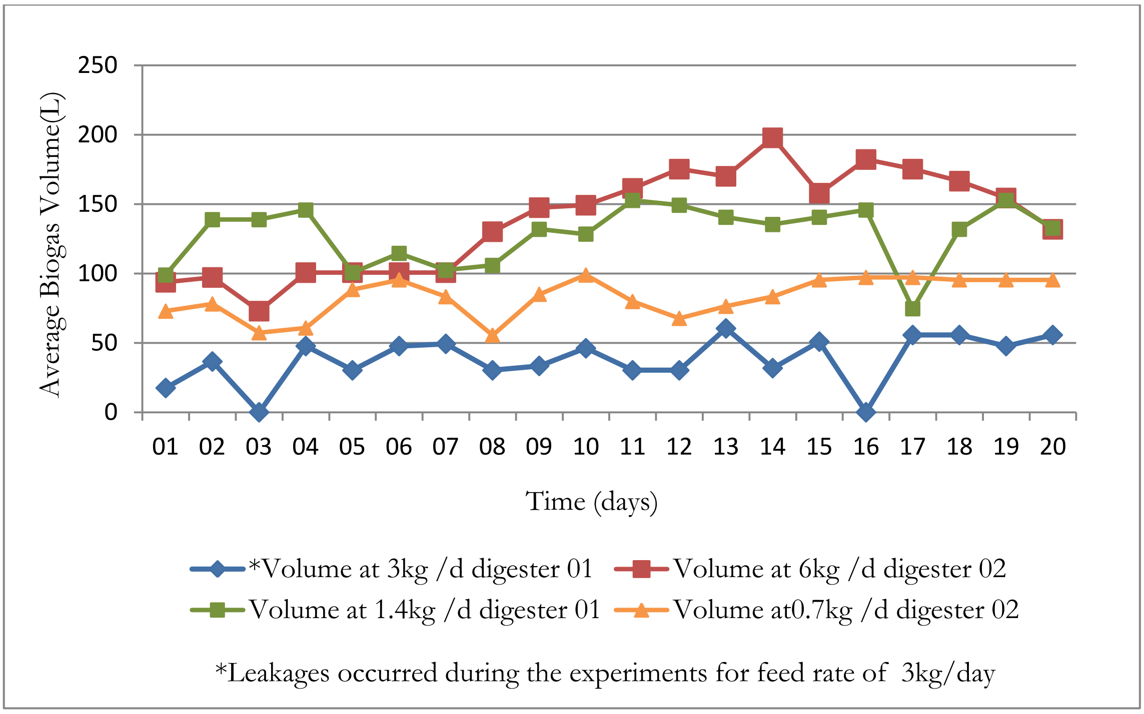
Digester No.	Loading Rate (kg/day)	Organic Loading Rate(kgVS/ m^{3}day)	Operating Time (days)
02	0.7	0.75	20
01	1.4	1.12	20
01	3.0	0.83	20
02	6.0	1.67	20

Analytical procedure

The experiments were conducted during steady period of operation. Feed stocks were analysed for, TS content and VS content. The material discharged from the outlet was in liquid form. Effluent was analysed for COD, TS, VS content. Material obtained from three sample ports along the digester length was tested for VFA content and pH. Daily produced gas quantity was measured from the height of the gas holder that floats up. The gas composition was analysed daily.

Results

Figure 6 - Daily Average Biogas Production



For the 6kg per day and 1.4kg per day higher biogas volume was generated. During the steady state experiments done at 3kg per day leakages occurred in the gas holder, therefore the generated biogas volume is lower than that for the other three feeding rates.

Figure 7 - Composition Variation of Biogas for Feed at 3kg/day and 1.4kg/day Feed Rates in Digestor 1

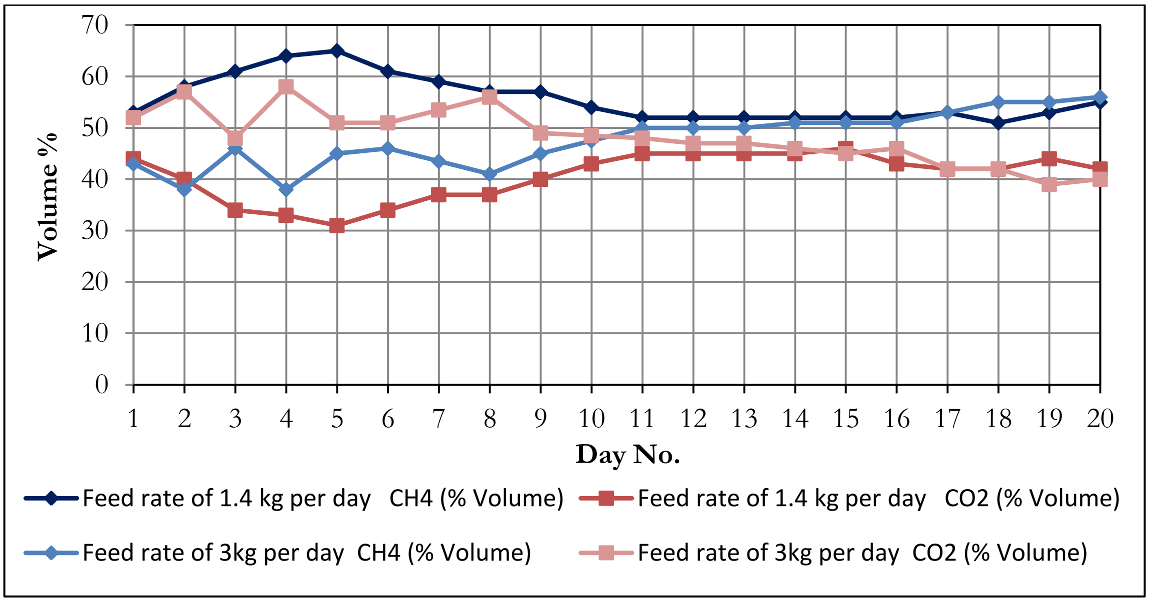


Figure 8 - Composition Variation of Biogas at Feed Rate 0.7 kg/day and 6kg/day in Digester 2

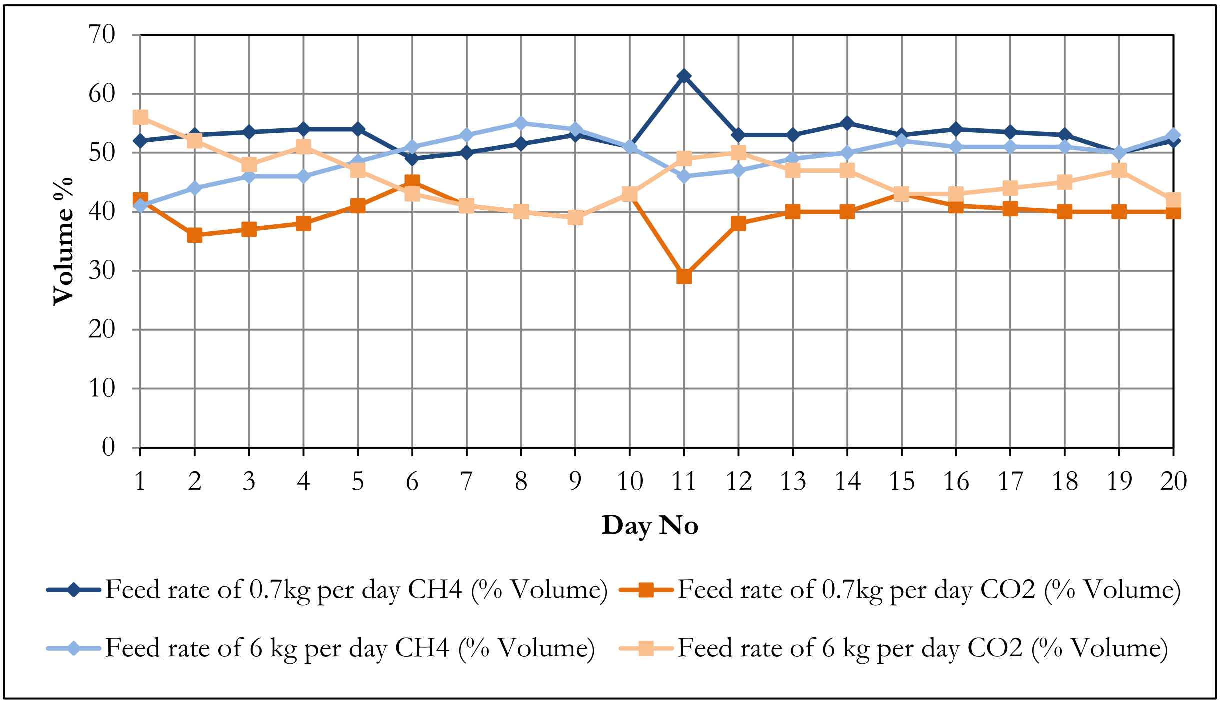


Figure 9 - pH Variation Feed Rate of 0.7kg/day

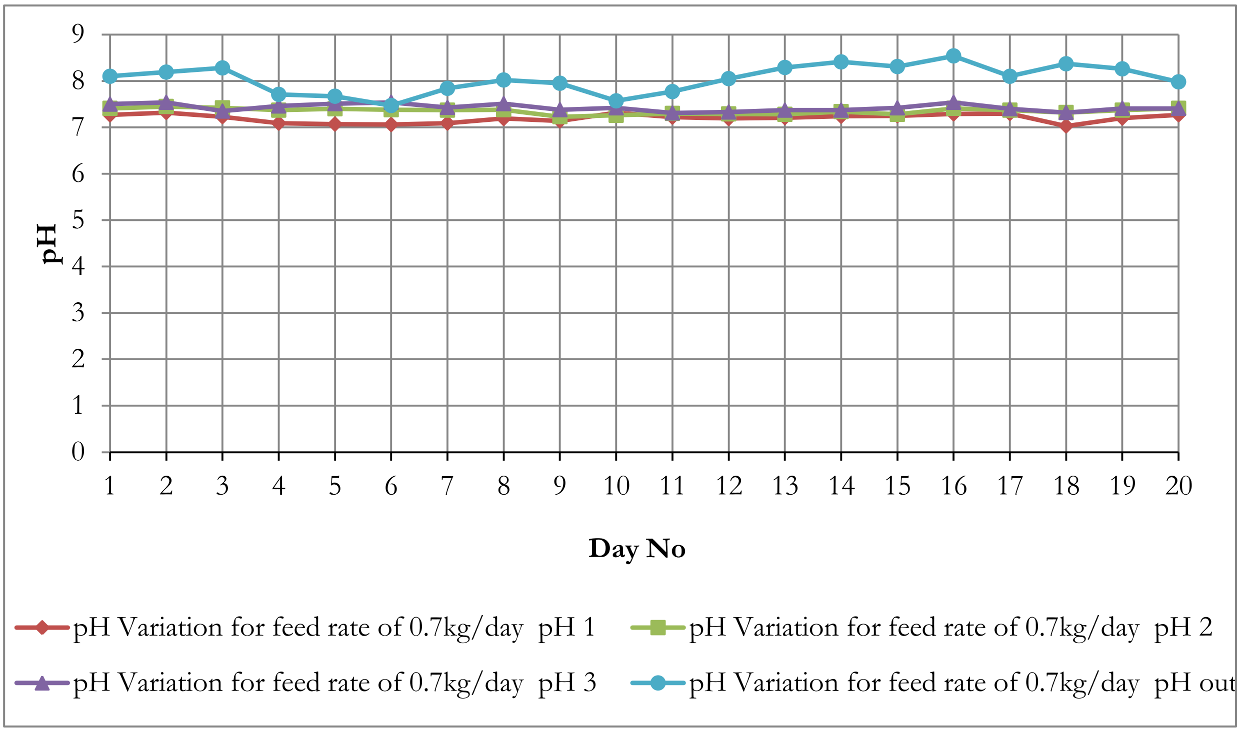


Figure 10- pH Variation for Feed Rate of 1.4kg/day

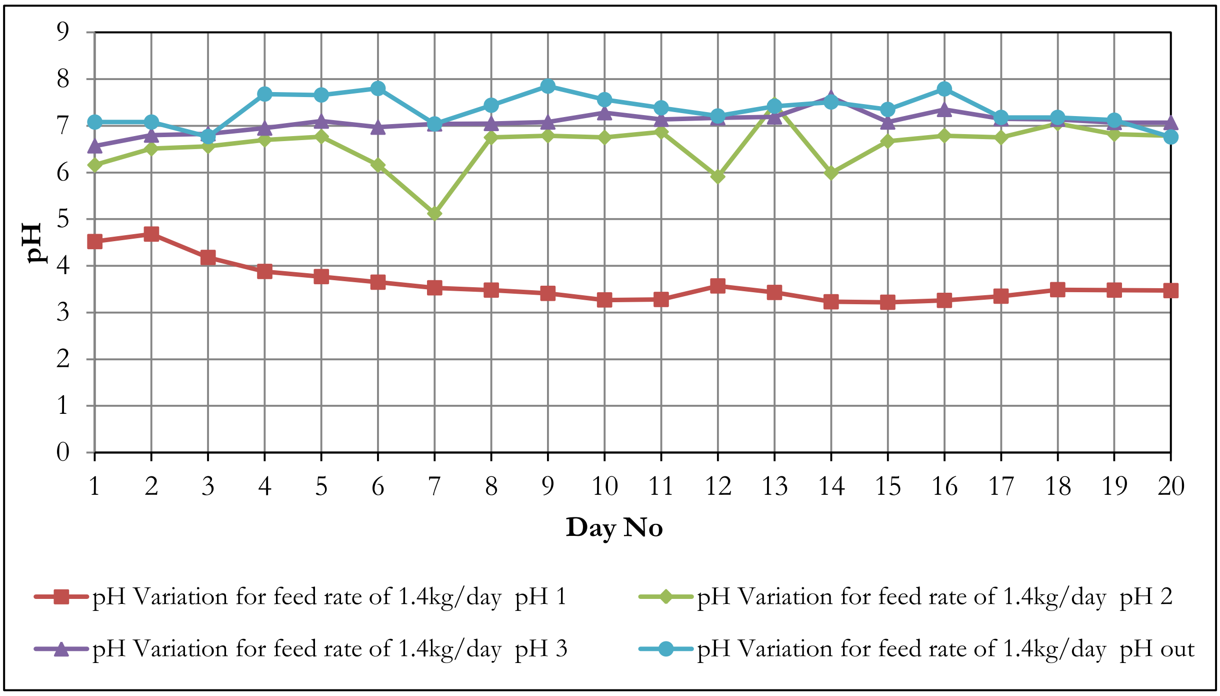


Figure 11- pH Variation Feed Rate of 3kg/day

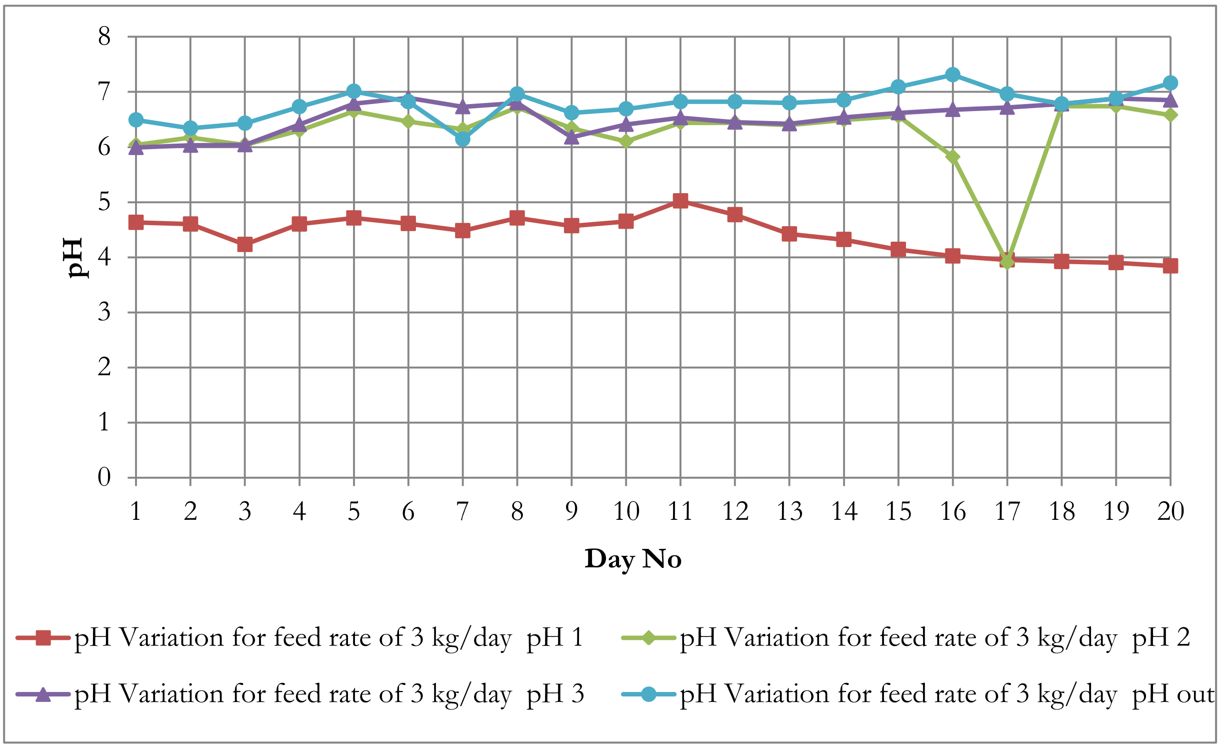


Figure 12 - pH Variation for Feed Rate of 6 kg/day

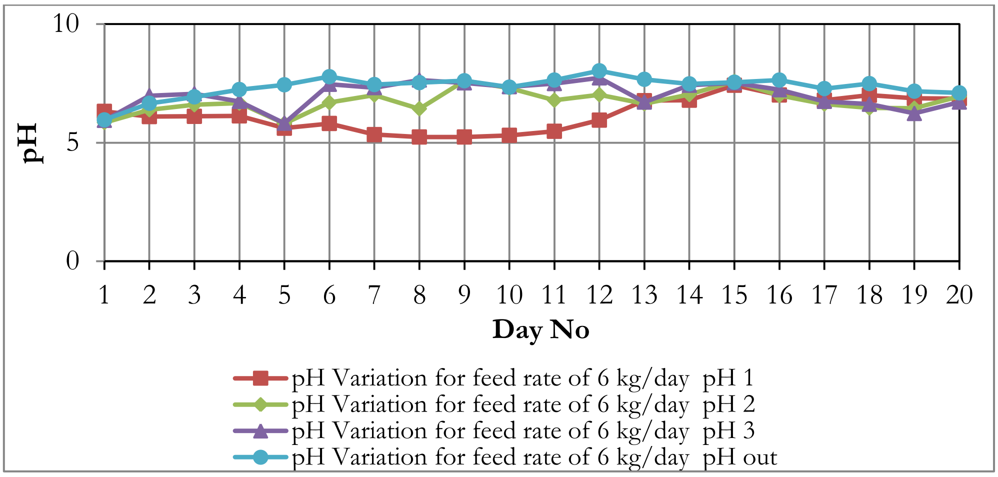


Figure 13 - VFA Variation along the Digester Length for Feed Rate of 0.7 kg/day in Digester 1

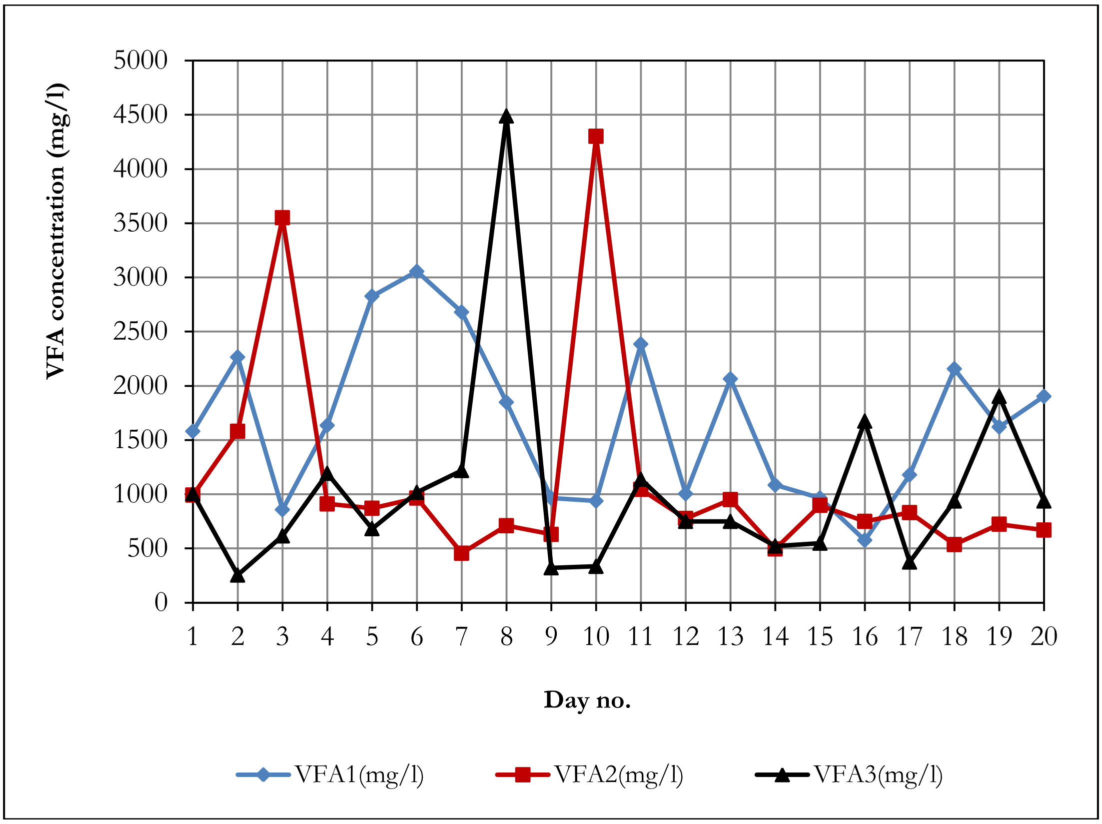


Figure 14 - VFA Variation along the Digester Length for Feeding Rate of 3kg per day in Digester 1

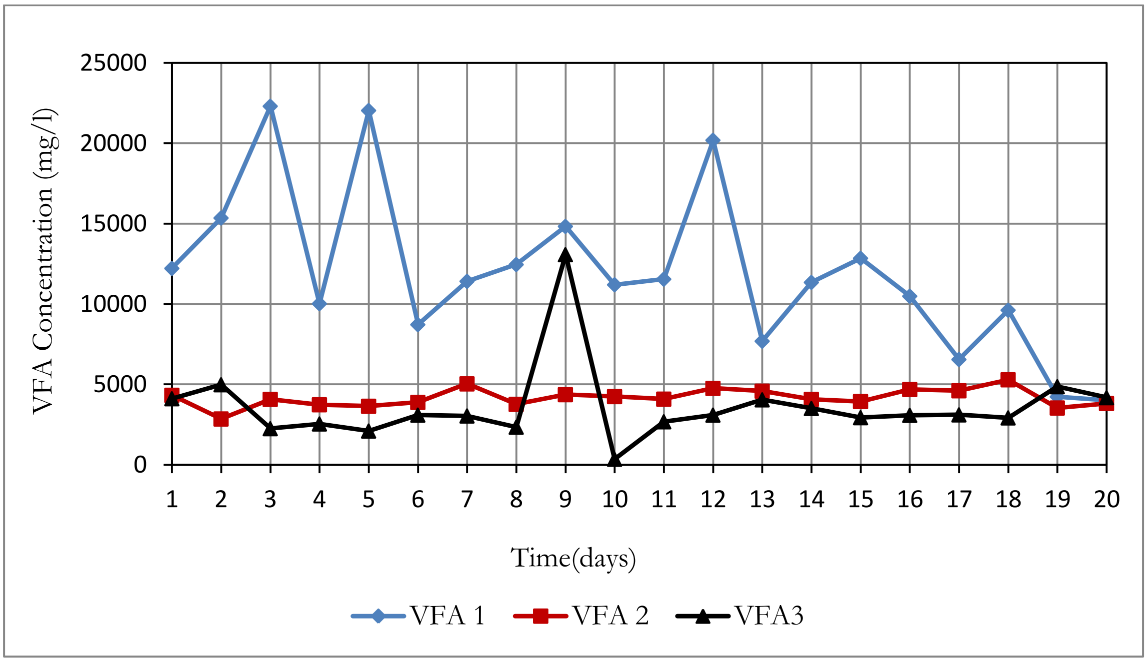


Figure 15 - VFA Variation along the Digester Length for Feed Rate of 6kg/day in Digester 2

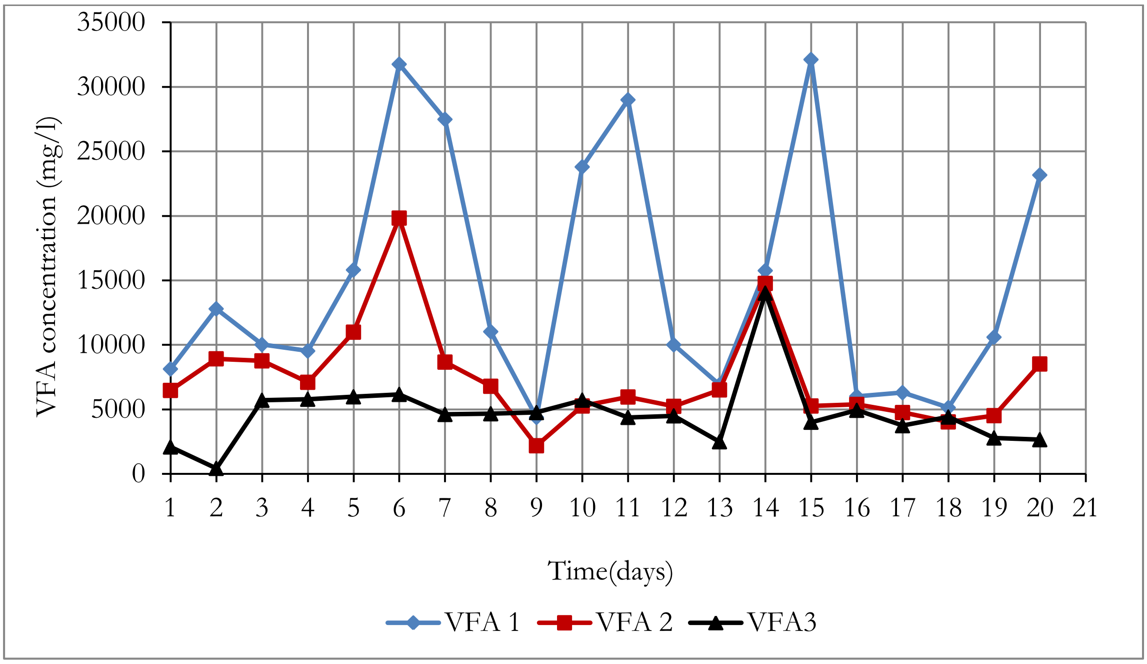


Figure 16 - COD Variation of Effluent for Different Feed Rates

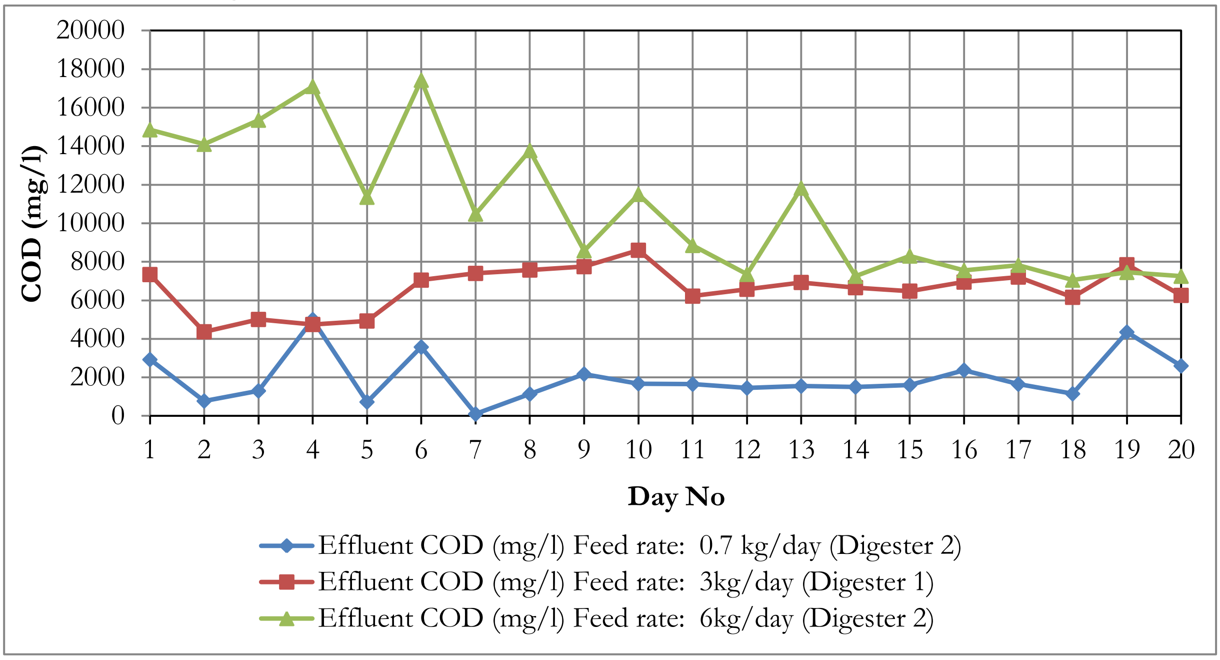


Table 3 - Process Performance

Feed Rate (kg/day)	Average Volatile Solids Reduction (%)	Average Specific Methane Production (m^3/kgVS per day)
0.7	93.48	0.320
1.4	91.37	0.341
3.0	89.36	0.120
6.0	85.92	0.219

The highest average specific methane production was $0.341m^3$/kgVS per day at OLR of 1.12kgVS/m^3 per day. The average specific methane production is 0.120 m^3/kg VS per day for OLR of 0.83 kgVS/m^3day. For OLR of 1.67kgVS/m^3day average specific methane production is 0.219 m^3/kgVS per day. Relatively low biogas yield for feed rate of 3kg per day is due to intermittent leakages occurred during the steady state operating period. Intermittent leakages restrict the successful growth of methanogenisis bacteria culture. Low average specific methane production at feed rate of 6kg per day is due to the insufficient HRT for the larger quantity of feedstock to be digested inside the digester and due to the high VFA concentration produced at higher feed rate.

OLR of 0.75 kgVS/m^3day showed the highest average volatile solids reduction of 93.48%. OLR of 1.67 kgVS/m^3day showed the lowest average volatile solids reduction of 85.92%.

Highest average gas production was observed for the highest OLR, which is also the highest feeding rate. Low average specific methane production and methane content in biogas was observed at the highest feeding rate. Insufficient retention time and high VFA concentration due to high organic load reduces methane production which results in low specific methane production and low methane content in biogas. Highest average specific methane production was observed for intermediate OLR which is a lower feed rate with high TS content. When the OLR is increased total feed rate is reduced by increasing TS content. At this condition the process is more stable and the hydraulic retention time increases due to lower feeding rate. High COD concentration in the effluent is also an indication of the insufficient retention time.

Table 4 - Comparison between Similar Studies done in Plug Flow Digesters

Waste type	Specific Methane Yield (m^3/kgVS)	Conditions	Reference
Food Waste	0.320	0.75 kgVS/m^3day Temperature :28-31^{o}C	Present Study
	0.120	0.83 kgVS/m^3day Temperature :28-31^{o}C	
	0.341	1.12 kgVS/m^3day Temperature :28-31^{o}C	
	0.219	1.67 kgVS/m^3day Temperature :28-31^{o}C	
Used cooking grease with swine manure	0.310	Cooking grease 2.5%, Temperature: 22-26^{o}C	(Botero, et al., 2010)
Food waste, Anaerobic sludge, Digestate, Cow dung	0.278	Organic loading rate 2.5 kgVS/m^3day Temperature: 55^{o}C	(Chaudhry ,2008)
	0.2259	3.3 kgVS/m^3day Temperature: 55^{o}C	
	0.146	3.9 kgVS/m^3day Temperature: 55^{o}C	
Cassava peel	0.377	3.6kgVS/m^3day Temperature :35-39°C	(Cuzin, et al.,1992)

Cuzin, et al. (1992) reported specific methane production of 0.377 m^3/kgVS for Cassava peel fermentation in a plug flow digester. Chaudhry (2008) reported 0.278, 0.2259 and 0.146 m^3/kg VS production for municipal solid waste for OLR of 2.5, 3.3 and 3.9 kgVS /m^3day respectively.

VFA concentration along the length of the digester shows a large reduction from inlet to the middle span. This is more prominent for feed rates other than lowest feed rate and, at the highest feed rate large fluctuations of VFA was observed for samples taken near the inlet and middle of the digester. Lengthwise VFA variation is an indicator of the biogas production stages along the length of the digester. VFA results show that acidogenisis phase near the inlet and mathanogenisis phase near the outlet. High VFA concentration is a reason for low methane content in the biogas.
Cuzin, et al. (1992) reported acetate accumulation of 10g/l in the feeding box at pH of 5 as a result of acidification due to higher loading rates. At this condition they observed 20% less biogas production than normal biogas production.

VFA concentration exceeded the inhibitory limits mentioned in the literature. This did not cause full process destruction but resulted in low methane content in the biogas. Distribution of biogas production stages along the length of the digester reduces negative effect of high VFA concentrations at higher loading rates.

Highest average VS reduction was observed for the lowest total feed rate with high TS content. Lowest average VS reduction was observed at highest OLR which is the highest total feed rate.

High COD concentrations were observed in the effluent. This is due to insufficient HRT.

Conclusion

Highest specific methane production and high methane content in biogas was observed at 1.4 kg per day which has high TS contents. Although the total feed rate was low, OLR was a middle value at the highest specific methane production. This is due to high TS content of the feed at this feed rate. Highest VS reduction was observed at the lowest feed rate with high TS content which is 0.7 kg per day. Insufficient HRT and high VFA content are reasons for lower specific methane production at the highest feed rate. The VS reduction was also the lowest for the highest feed rate.

At 1.4kg per day OLR is an intermediate value while at 0.7 kg per day OLR is lowest. These low feed rates which have high total solids content showed more stable operation and high specific methane production. Increment in HRT at lower feed rate increases specific methane production. Further studies should be conducted to study the effect of TS content in the feedstock.

Although the VFA concentration near the inlet was much higher than the inhibitory levels it did not lead to full process destruction. The VFA variation along the digester shows the variation of acidogenisis to methanogenisis stages along the digester length which is more prominent at intermediate feed rates. At higher feed rates high VFA concentrations were observed along the digester length with large fluctuations in VFA content. Higher VFA content and VFA fluctuations lead to process instability. Co digestion of food waste with cattle dung, sewage waste or other suitable sources help to control the high VFA concentrations.

High COD content in the effluent is an indicator of the presence of undigested organic material in the effluent. The COD levels observed in the effluent for all feed rates are much higher than recommended levels for discharging effluent. This COD content can be treated in a second digester or the length of the digester has to be increased to convert COD in the effluent to biogas. Other reason for lower gas quality is the high VFA production in the digester.

Further studies should be conducted to study the effect of TS content in the feedstock for biogas production. Future studies should be focused on importance of flow induced by the effect of pressure inside the plug flow digester on biogas production and its composition.

Effluent nutrient content should be tested to be used it as an organic fertilizer. This source supplies high quality fertilizer which increases resistance of the plants to diseases and increase the richness of soil.

GHG potential of methane in the biogas is 20% (Wightman, 2005) higher than carbon dioxide. Therefore it should be carefully trapped and used to avoid leakages.

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