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OPTIMIZATION OF BIOGAS PRODUCTION PROCESS IN SOLID STATE DIGESTERS IN SEMIARID AREAS OF NORTHERN TANZANIA

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ABSTRACT

Solid state digestion process has received much attention due to its low water requirements, making it preferred in semi-arid areas as well. In this study, the performance of the household solid state digesters was evaluated through monitoring of the feedstock mixing ratios and using the digester gas pressure as a measure of performance. Additionally, a batch study to verify the appropriate and optimal mixing ratio of feedstocks was also done. The mixing ratios of cow dung to water were 2:1, 3:1 and 4:1. Total solids determined were 120, 150 and 170 mg/g for the ratios 2:1, 3:1 and 4:1, respectively. Biogas yields for 2:1, 3:1 and 4:1 mixing ratios in laboratory batch mode were 21.4, 22.7 and 46.4 mL/gVS, respectively. These results from a practical scenario show a promising future of the technology which can be adopted by the solid state digester users living in dry areas.

Keywords: Cowdung, Biogas, Mixing ratio, Batch solid state anaerobic digester.

INTRODUCTION

Biogas production and utilization has gained much interest in recent years due to its importance as an alternative and environmentally friendly energy source (Panwar et al. 2011). Biogas technology can be deployed at small and large scales in urban and very remote locations. Varieties of feedstocks and reactor configurations have been tested and proved to be effective in the production of biogas (Brown and Li 2013). Depending on the availability of total solid contents in organic wastes, digesters are categorized into two groups, namely (i) liquid state and (ii) solid-state anaerobic digesters (Brown and Li 2013). The solid-state anaerobic digester is one in which total solid contents range between 10 and 20% while liquid state anaerobic digester is one in which total solid content is less than 10% (Yi et al. 2014). Solid state digestion process has received much attention due to its low water requirements and improved biogas production efficiencies than the liquid state digestion process (Gelegenis et al. 2007).

This study was carried out to determine the operational performances of the Solid State Digester (SSD) installed digesters in Mwanga cluster in northern Tanzania with the aim of improving their biogas production potentials. The prior purpose for establishment of SSD plants was to have a design with low water requirements and high biogas production per unit volume. The estimated biogas production amounts were 1-1.5, 1.5-2.25 and 3 m^3 for digesters with capacity of 4, 6 and 9 m^3, respectively (Kileo and Akyoo 2014). It has been reported that 34.1% of the installed digesters still produce insufficient biogas, the main reason being poor feeding of the digesters using inappropriate mixing ratios of the feedstocks (Kileo and Akyoo 2014). The consequence is that, even communities which could use biogas turn to non-environmentally friendly sources of energy.

Technically, insufficient production of biogas in SSD may be caused by factors such as solid retention time, feedstock quality, feeding frequency, mixing ratios of feedstock, reactor configuration, organic loading rate, inoculation, co-digestion, pretreatment, purification, addition of additives and environmental conditions within the digester (i.e., temperature, pH, buffering capacity and volatile fatty acids concentration) (Lay et al. 1997). Monitoring of the digesters could therefore be done by measuring the daily digester gas pressure, measurements of the total volatile solids degraded and measurements of the amount of biogas being produced. Findings from the field showed that, the often use of mixing ratios such as 2:1 and 3:1 by the household might be affecting the availability of total solids (TS) and volatile solids (VS) in the substrate which consequently affect the biogas production. This corresponds with the study by Yi et al. (2014) who found out that when waste/cowdung is diluted, availability of TS and VS are affected. The more the waste is diluted, VS and TS do decrease. The decrease affects the amount of biogas to be generated since the production depends mostly on the availability of high amount of VS. Factors like breed, growth stage of the animal and diet contributes much on the availability of VS, which vary significantly from area to area (Santana and Pound 1980). Due to variations of VS from area to area, investigation of the right mixing ratio that gives the best and proper VS content for the selected study area (Mgagao) is of great importance. Additionally, this study also provides a basis for improving the biogas digesters planned for construction in similar dry areas such as Oldonyosambu and Ngarenanyuki in Arusha District Councils.

MATERIALS AND METHODS

Study site description

The study was conducted in selected households at Mgagao in Mwanga district (Kilimanjaro region). Additionally, results of the survey in Mgagao are planned to be applied in Oldonyosambu and Ngarenanyuki in Meru district since they have nearly similar climatic conditions as Mgagao. The study areas are as shown in Figure 1.

Site selection and sample size

A survey was done at Mgagao using questionnaires to collect information from selected households. Information collected involved the management of the digesters from biogas users. About ten (10) questions were prepared where the interviewee devoted fifteen minutes to answer the questions. Sample size was determined at precision rate (*e*) of 1% and 99% confidence level as recommended by Dobbin and Simon (2005). The sample size as calculated using equation 1 was 20.

$$\boldsymbol{n} = \frac{\mathbf{N}}{\mathbf{1 + N}(e)^{\mathbf{2}}} \qquad (1)$$

Where: $\boldsymbol{e}$ = Precision rate, $\boldsymbol{n}$ = Sample size, **N** = Total population

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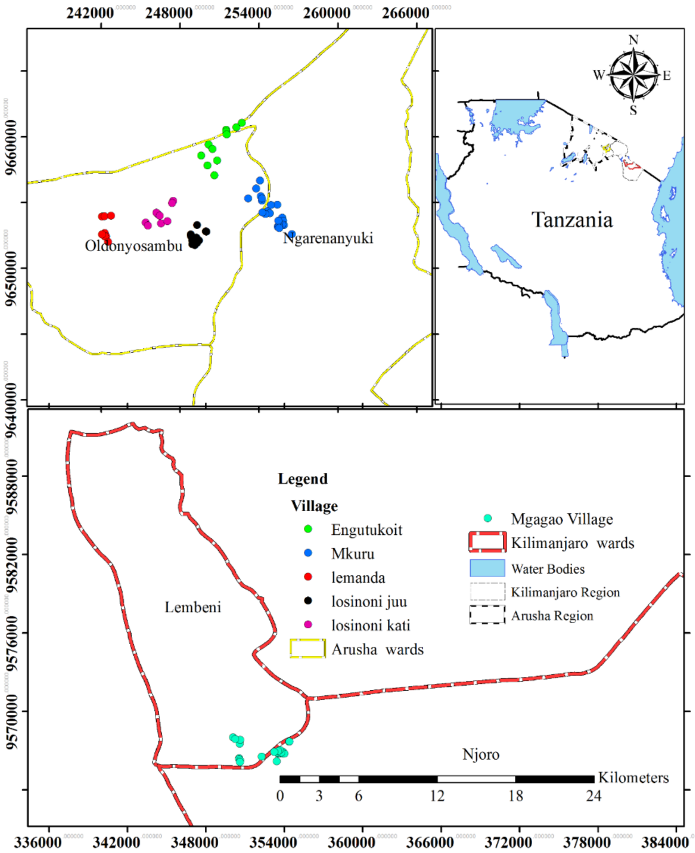

Figure 1: A map showing selected study sites surveyed in Meru and Mwanga districts (Mahushi 2018)

Characterization of the Feedstock

Fresh cow dung from the selected households of Mwanga (Kilimanjaro) and Meru (Arusha), were collected for analysis at the Nelson Mandela African Institution of Science and Technology (NM-AIST). In order to characterize the feedstock and provide more evidence of the best ratio to feed the digesters, experiments were carried out in the laboratory. The cowdung was characterized in terms of total carbon (C), total nitrogen (N), total solids (TS) and volatile solids (VS). Dry weight (TS) was determined at 105 ± 3 °C, VS at 550 °C in muffle furnace and carbon/nitrogen ratio by Thermo Scientific™ Flash™ 2000 Organic Elemental Analyzer operated at 950 °C. Percentage total solid (TS) was determined by drying the fresh sample at 105 °C for 12 hours and calculated using Equation 2 according to Singh et al. (2008).

$$\%\ TS = \frac{\text{Weight of dry sample}}{\text{Weight of fresh sample}} \times 100 \qquad (2)$$

Volatile solids were determined by drying the fresh samples at 105 °C for 12 hours then heated at 550 °C for three hours. The samples were left to cool for one hour, then weight of ash content and weight loss (VS) were calculated as per equation 3 (Singh et al. 2008).

$$\%VS = \frac{\text{Weight loss}}{\text{Weight of dry sample}} \times 100 \qquad (3)$$

For the households in Mgagao, measurements of the performance of the digesters were done by measuring the digester gas pressure using a data logger for a month.

For the batch experiment in the laboratory, the feedstock samples were obtained from cattle which are fed/pastured locally. Ratios of cowdung to water of 2:1, 3:1 and 4:1 were prepared in the laboratory. Anaerobic batch mode digesters were made from polyethylene bottles with a capacity of 10 L. The bottles were plugged with rubber plug fitted with delivery tube, the delivery tube were connected to measuring cylinder for biogas measurement. Due to solubility of biogas in water, measuring cylinders were filled with acidified saline water (prepared at pH of 0.5 and 95% NaCl).

During preparation of the feedstock, 2, 3 and 4 kg of cowdung were mixed with one kg of water per each to prepare 2:1, 3:1 and 4:1 mixing ratios, respectively. Batch anaerobic digesters configuration and operation studies were performed to understand the best ratio of the feedstock mixture. Three experimental setups were set at the start of the experiment. The yielded biogas was measured per day by downward water displacement method using calibrated 2 litres cylindrical jar for each reactor. Average values of the results obtained per each setup were calculated. The batch digesters were monitored for 60 days; however, daily production stopped on the 45th day in the 4:1 digester, 30th day in the 3:1 and 2:1 digesters.

RESULTS AND DISCUSSION

Feedstock characteristics (TS, VS and C/N ratio)

TS (%), VS as %TS and CN ratios of fresh (undiluted) samples of the cow dung collected from Mwanga and Meru districts ranged 16-23, 51-83 and 20-41, respectively (Tables 1 and 2). When a sample with 20% TS and 69% VS as % of TS was diluted at ratios of 2:1, 3:1 and 4:1, resulted into diluted samples with TS% and VS (as % of TS) of 12, 15 and 17, and 68.2, 68.5 and 68.7% correspondingly.

Table 1: TS, VS and C/N ratio for samples from semi-arid areas of Meru

Sample name	TS (%)	VS%	C/N ratio
Losinoni Kati	20.0	67.3	25
Engutukoit	22.9	83.2	25
Lemanda	20.0	67.9	25
Losinoni Juu	21.2	76.4	28
Mkuru	20.2	69.5	25

Table 2: VS, TS and C/N ratio for samples collected from biogas users in Mgagao (Mwanga)

Sample Name	TS%	VS%	C/N ratio
Household 1	20.4	69.5	20
Household 2	20.0	69.1	25
Household 3	16.2	51.4	20
Household 4	20.1	69.3	25
Household 5	20.0	69.0	25
Household 6	20.3	69.4	21
Household 7	20.0	68.9	25
Household 8	20.2	69.3	25
Household 9	21.2	73.0	20
Household 10	22.0	83.2	25
Household 11	19.8	68.4	25
Household 12	20.1	69.4	24
Household 13	21.3	73.2	41
Household 14	20.0	69.0	30
Household 15	22.2	79.2	25
Household 16	20.0	68.1	20
Household 17	20.3	69.0	25
Household 18	20.0	69.2	20
Household 19	22.8	83.0	25
Household 20	20.0	68.5	25

The optimal %TS for solid state digesters is reported to range between 10 and 20 (Yi et al. 2014). In this study, feedstock with TS of 17% produced biogas yield of up to 46.4 mL/g VS which was the highest production in all %TS tested. These results were in line with those reported by Budiyono et al. (2010) when cattle manure was used as feedstock. Their results showed the increase in biogas production as %TS was changed from 7.4 to 9.2%. A similar relationship was established by KeChrist et al. (2017) using cattle manure as feedstock, where similar trend of results as of this study were obtained. Comparably Brown and Li (2013) reported an increase in biogas yield from 42 mL/gVS to 72 mL/gVS as %TS increase from 15 to 20 mL/gVS. However, the study by Abbassi-Guendouz et al. (2012) reported contrary results for the effect of %TS on biogas production when similar feedstock as of this study were used.

The CN ratios in this study ranged from 20 to 41 (Tables 1 and 2). The sample with optimal CN ratio (25) in the present study was selected for testing production of biogas in the laboratory. Feedstock with this CN ratio suggests a significant amount of biogas to be generated since the ratio is at its optimal point (Ghasimi et al. 2009).

When the %VS fall into the optimal range of 28-90% more biogas is produced (Ozturk 2012). The concentrations of VS in this study ranged from 54 to 83%, this is an indication that the feedstock is rich in organic solid content that can be converted into biogas during anaerobic digestion. The substrate with VS (69%) was sampled to be used in this study; however, upon dilution VS slightly changed to 68.2, 68.5 and 68.8% for the 2:1, 3:1 and 4:1, respectively. Biogas production tends to increase when the percentage of volatile solids increases (Gelegenis et al. 2007, Ozturk 2012). This has been confirmed in this study where feedstock with 68.8% generated high amount of biogas than others at 68.2 and 68.5%.

The digester gas pressure

From the household survey it was noted that, at Mgagao, digester users fed their biogas plants using mixing ratio ranging from 1:1, 2:1 and 3:1. The evaluations of the feeding practices in terms of the ratios for the household survey at Mgagao were checked against the digester pressure. Generally, when the digester is fed properly, digester gas pressure corresponds with specific theoretical pressure. The digester of 9 m^3 that was being fed at the ratio of 4:1 was sampled for investigations. Data for digester gas pressures were recorded by the data loggers except where the gas meter was installed in the kitchen. Data were recorded daily for a month. Figure 2 shows the pressure recorded during the respective month. In the month, the digesters were fed with the right proportions of 4:1. The results of the analysis were summarized and presented in weekly basis as per Figure 2. The pressure started increasing at the beginning of week two. This is because during week one, such digesters had not picked up for producing the biogas.

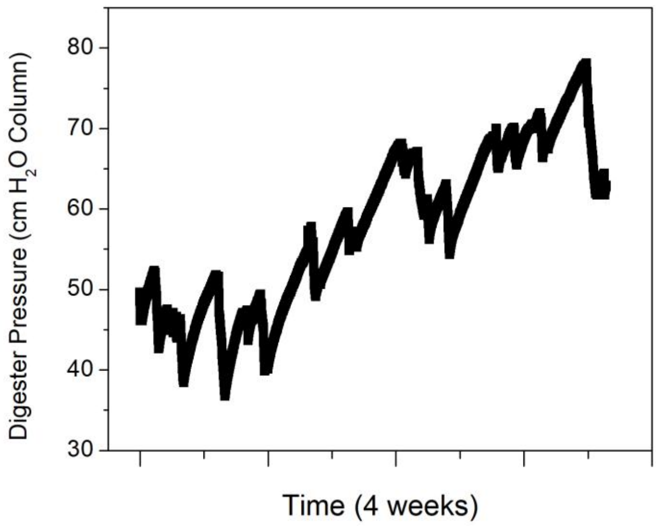

Figure 2: The variation of gas pressure in the digester with time

Digester pressure is one of the best indicators of digester performance and could also measure the level of digester services provided by the households. The theoretical pressure for 9 m^3 digesters is 80-100 cm H_2O column if all conditions are ideal (Zalm

2017). Performance of the digester pressure tested at Mgagao indicated that, higher ratio of cowdung to water lead into more pressure. But, lower ratio of cowdung to water resulted into low pressure. The digester pressure (Figure 2) did vary much from the start until the end of the exercise, with more stable pressure being observed after the first two weeks. The observed pressures for the first week were below the theoretical value since such digesters had not improved much for producing biogas.

Pressure on the fourth week increased nearly to the theoretical pressure since such digesters had picked up for much production of biogas. Therefore, digester gas pressure observed in a month confirmed that the best mixing ratio for optimal biogas production in solid state digesters was 4:1.

The effect of mixing ratio on biogas production

The laboratory experiment carried out revealed that, daily biogas production varied continuously for the 2:1, 3:1 and 4:1 mixing ratios. Figure 3 shows the cumulative biogas production for the reactors operated at three different mixing ratios during the whole experiment. Each curve represents the average of three replicates. The best performance of biogas production was observed in the digester with mixing ratio of 4:1. This ratio provided cumulative biogas of 20.94 L equivalent to 46.4 mL/g VS biogas yield on the 30th day while 3:1 and 2:1 gave 9.08 L (22.7 mL/g VS) and 7.39 L (21.4 mL/gVS), respectively as shown in Figure. 3.

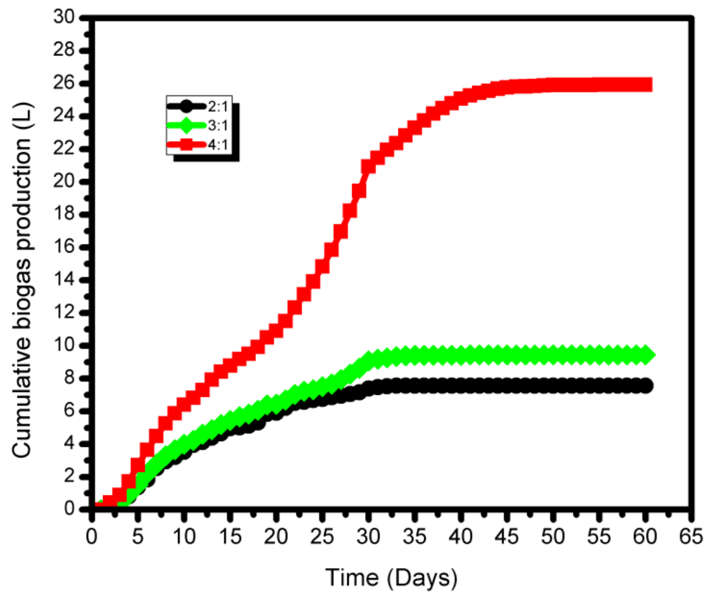

Figure 3: Effect of mixing ratios of cowdung to water on biogas production

Working with cowdung/water feedstock, Adelekan and Bamgboye (2009) reported an increased biogas yield that was directly proportional to the increase in mixing ratio. Similarly, Haryanto et al (2018) using comparable feedstock reported a potential increase in methane yield of up to 122 mL/gVS at 2:1 mixing ratio of waste/water as compared to 1:1 that produced only 78 mL/gVS. The results obtained in this study clearly illustrate that, increase in substrate/water mixing ratio gives enhanced biogas production. This could be explained by the fact that, as substrate mixing ratios increase, volatile solids also increase resulting into higher production of biogas.

Statistical analysis

In order to describe the relationship between the 2:1 and 3:1 ratios, 2:1 and 4:1 ratios, and 3:1 and 4:1 ratios on biogas production in SSD, Pearson correlation was used. The variables were classified as per Guildford's rule of thumb for interpreting correlation coefficient (Guilford and Fruchter 1965). The interpretation was based on correlation coefficient value (r), where 0.0 to 0.29 indicates negligible or little correlation, 0.3 to 0.49 indicates low correlation, 0.5 to 0.69 indicates moderate or marked correlation, 0.7 to 0.89 shows high correlations and 0.9 to 1.00 shows very high correlations. The significance level (or p-value) is the probability of obtaining results as extreme as the one observed. If the significance level is very small (less than 0.05) then the correlation is significant and the two variables are linearly related. If the significance level is relatively large (for example, 0.50) then the correlation is not significant and the two variables are not linearly related (Guilford and Fruchter 1965).

Very high positive correlation existed between the 2:1 and 3:1 ratios ($r = 0.96034$, $p = 0.0$). Very high positive correlation also existed between the 2:1 and 4:1 ($r = 0.99225$, $p = 0.0$). A very high positive correlation ($r = 0.92128$, $p = 0.0$) occurred between 3:1 and 4:1 ratios. All mixing ratios displayed a linear relationship ($p = 0.0$) meaning that results were linearly related.

CONCLUSION AND RECOMMENDATION

Cowdung/water ratio of 4:1 showed high production of biogas than that of 3:1 and 2:1 ratios. Feeding lower ratios would result into low production of biogas as reported elsewhere. Solid state digesters are best fit for areas where there is insufficient water supply. Digester pressure best provides for the health of the digester as a performance evaluation parameter. Sensitization of the communities to use appropriate and recommended ratios is important and calls for implementation if we are to make the communities use efficiently the biogases. Investigation of the frequencies of feeding especially for SSD needs further investigation.

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