Development and Evaluation of a Semi-Automated Stirrer for a Domestic Plug-Flow Biodigester

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Abstract: This paper presents a simple technique to stir substrates and enhance the performance of plug-flow biodigesters. A framework of PVC pipes was constructed and fitted as a semi-automated stirrer in two 2.0 m^3 plug-flow biodigesters fabricated using locally sourced materials. The stirrer in one biodigester was operated while the other biodigester served as the control. Air bags were improvised using a tarpaulin material to collect and store the biogas produced while a locally fabricated double-burner biogas stove was used to utilize the gas for cooking. The biodigesters were loaded to 70% of the capacity on installation and fed every two days with 12 kg (wet weight) of mixed household wastes (dog, chicken and rabbit urine and faeces and left over food). The substrates were stirred three times daily without opening the biodigester. The results showed that the stirrer aided digestion and by implication, prevented a reduction in biogas production by 1.31%/week (R^2 = 0.92) when it was operated. By the end of the 186 day study, up to 41% of biogas reduction was being recorded weekly in the control biodigester, indicating the effect of buildup and hardening of the scum stratum which limited the production and passage of biogas. In addition, effluent drip was observed at the outlet pipe especially in the afternoon around the peak temperatures period when production was high, indicating that the rate of biogas production exceeded the rate of exit thereby resulting in biogas displacing substrates. Bubbling sound that emanated from the biodigester each time the substrates were stirred suggested that trapped gas was released from the strata. The biogas produced from both biodigesters burnt with clear blue flame and was used for domestic cooking. The stirrer was easy to develop, install and operate and can be adapted to different sizes of plug-flow biodigesters.

Keywords: Anaerobic digestion, plug-flow biodigester, stirrer, biogas, air bag

1. Introduction

Biogas is a clean and renewable form of energy that is produced by methanogenic bacteria while acting upon biodegradable materials in an anaerobic condition provided by a biodigester (or bio-reactor). Biogas could very well substitute (especially in the rural sector) for conventional and non-renewable sources of energy (firewood, fossil fuels, crop residues, etc) which are causing ecological-environmental problems and at the same time depleting at a faster rate. Biodigesters have demonstrated considerable socio-economic benefits worldwide and can be constructed in different designs, shapes and sizes using various types of materials. Anaerobic digestion/performance of biodigesters can be influenced by parameters like temperature, pH, particle size, carbon to nitrogen ratio, loading rate, hydraulic retention time, solids content, mixing, etc. While most of the parameters are feedstock or process related, mixing (or agitation) of the substrates in the biodigester is very much related to the biodigester design. Mixing has been reported to enhance biogas production (Baier and Schmidheiny 1997) and ensures efficient transfer of organic materials for the active microbial mass and to prevent sedimentation of denser particulate material (Ward et al. 2008). Mixing can reduce the hydraulic retention time of substrates (Florentino 2003), disrupt scum and facilitate release of biogas trapped within the substrates. However, as important as mixing is to the process of biodigestion, it must be done with caution; light mixing increases the velocity of digestion while heavy mixing decreases the velocity (Florentino 2003), too much mixing stresses the micoorganisms while no mixing results in foaming (Rajendran et al. 1012).

There are several types of biodigester designs (floating-drum, fixed-dome, covered lagoon, plug-flow, etc.) developed particularly for household use (Rajendran et al. 1012). A cheaper and less complex design is the plug-flow biodigester. It is typically a cylindrical tank (with its length greater than the width) in which the gas and other by-products are pushed out one end by new feedstock being fed into the other end. However, it has no means of agitation. In fact, the situation can be more complicated when some parts of the manure travel faster than others on their way through the vessel, or even settle or float and remain in the digester. Apparently, a device for effective mixing is needed to overcome this challenge and improve biogas energy production especially for domestic cooking and lighting. Hence, this study focused on the development and evaluation of a semi-automated stirrer and plug-flow biodigester equipped with the stirrer for household use.

2. Materials and Methods

Fabrication of the biogas plant

The experiment was conducted in a private residence in Ile-Ife town, South-West of Nigeria, between the months of November, 2014 and May, 2015 when the ambient temperature ranged between 22 and 39 ^{o}C. A black plastic drum commonly available and used for water storage was adapted and fabricated as a plug-flow biodigester. Black colour was adopted because a black object (with emissivity ≈1) absorbs all wavelengths of light and converts them into heat, so the drum gets warm and aids digestion. The 2.0 m^3 capacity drum conformed to the specification of a plug-flow biodigester with length>width (1.71 m height and 1.22 m diameter). It was positioned on its side and fitted with 0.10 m and 0.76 m diameter PVC pipes as inlet and outlet pipes, respectively using 45^o elbow joint (Figure 1.1). The inlet was positioned at upper part (0.91 m from the base) for easy feeding while the outlet was at the lower part (0.15 m from the base) to facilitate the outflow of sludge. A semi-automated stirrer (Figure 1.2) was fabricated using 0.025 m diameter PVC pipes, elbows and tee joints and assembled inside the biodigester to form a rigid frame. The height was about 1.05 m such that it cuts through (vertically and horizontally) all the strata inside the biodigester. All the tee joints of each side were looped with a rope and tied to a single rope. The rope from the side facing the inlet was extended outside the biodigester through outlet pipe while that of the side facing the outlet was extended outside through the inlet pipe before the biodigester was hermetically sealed. At the rest position, the stirrer was made to flush with either the inlet or outlet end inside the biodigester. The biodigester was installed in a pit, 1.0 m deep (Figure 1.3) for easy feeding and to give the biodigester walls a firm support and prevent the sides from bulging out due to lateral forces from the substrates. A 1.8 m^3 capacity pillow-shaped airbag was fabricated using a tarpaulin material to provide storage for the biogas produced (Figure 1.4). An air valve was fitted to the airbag at the base for in and out flow of biogas. A double burner table top biogas stove fabricated locally using metal plates, pipes and control valves was used for flame testing and cooking (Figure 1.5). The airbag was located under a shed, 18 m from the biodigester and 5 m from the burner in the kitchen. The biodigester to airbag and airbag to burner connections were done using rubber hoses, PVC pipes and air valves of 0.0127 m diameter. The biogas plant was duplicated and the duplicate served as the control. The stirrer of the control biodigester was not operated throughout the study period.

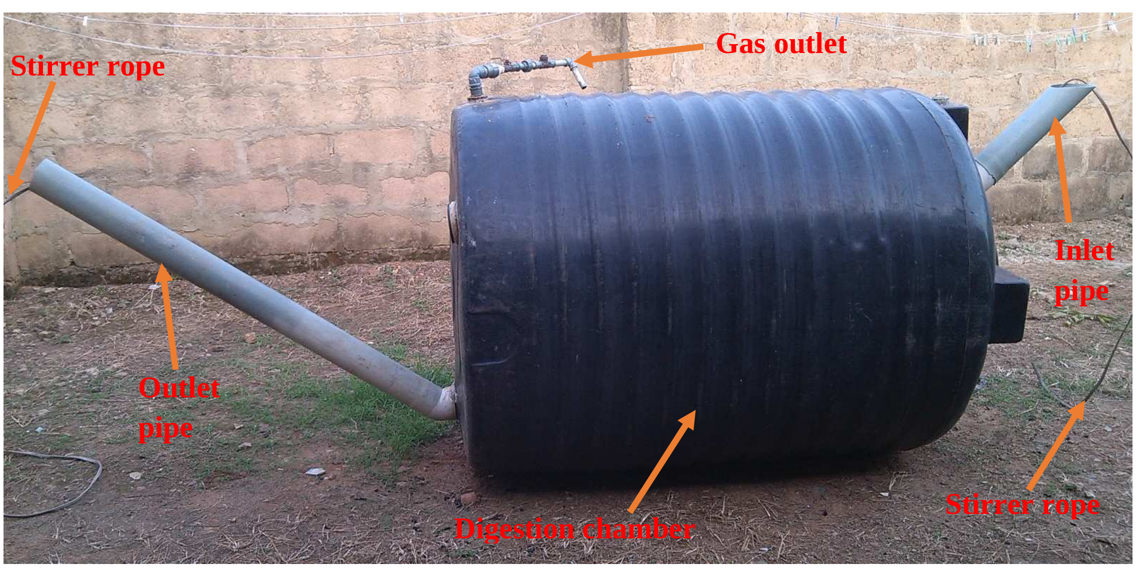

Fig. 1.1: The plug-flow biodigester equipped with stirrer before installation.

Fig. 1.2: The developed stirrer.

Operation and evaluation of the stirrer

The biodigesters were initially loaded to 70% (1.4 m^3) of the total volume with cow dung slurry, to culture the anaerobic microorganisms. Subsequent feeding commenced after the biogas produced had started burning efficiently and was done every two days with about 12 kg (wet weight) of mixed household wastes (dog, chicken and rabbit urine and faeces and left over food) mixed with water to form a slurry mixture prior to loading. The wastes had composition as follows: dog, 5-8%; chicken, 18-24%, rabbit, 60-65%; left over food, 3-5%. Stirring commenced after seven days of loading the biodigester and was carried out by pulling the ropes at the inlet and outlet pipes in succession (five times each) which in turn dragged the stirrer in the biodigester to move through the strata and create turbulent motion of the substrates. At each trip, the stirrer moved a distance of 0.91 m inside the biodigester. With this system, the substrates were adequately agitated and there was no introduction of air or leakage of the biodigester and the anaerobic environment inside was fully maintained. The substrates were stirred three times (6 am, 3 pm and 8 pm) daily.

Assessment of biogas production was carried out daily between 7 and 8 am by placing the airbags on a digital weighing machine. The difference between the present and previous weight was the weight of the biogas produced. The volume of biogas produced was estimated by dividing the weight by biogas density, 1.15 kg/m^3 (Jorgensen, 2009). The airbags were replaced whenever they were full and the gas used for cooking family meals. The biogas was cleaned before it was used for cooking to remove hydrogen sulphide (H_2S) and water vapour using simple technique. Two PVC pipes (2.54 cm inner diameter and 30.48 cm long) were filled with iron fillings and dry charcoal and connected between the airbag and the stove. The iron fillings was to remove H_2S from the wet gas while charcoal was to remove the water vapour. The effluent from the biodigesters was applied to the yard vegetable garden. The biogas production from the two biodigesters was compared using student's t-test in SAS (2002) software. The effectiveness of the stirrer was evaluated as opportunity loss in the control biodigester (reduction in biogas production in the control biodigester) according to the equation:

$$Biogas\ reduction\,(\%) = \left[\frac{V_A - V_B}{V_A}\right] \times 100$$

Where:

V_A = biogas production from biodigester with stirrer

V_B = biogas production from control biodigester

Fig. 1.3: The plug-flow biodigester equipped with stirrer after installation in a sub-surface pit.

Fig. 1.4: Pillow-shaped airbag for storing the biogas produced.

Fig. 1.5. Biogas flame from a table top double burner.

3. Results and Discussion

Biogas production started within seven days in both biodigesters, an indication that the heterogeneous feedstock used had a high degree of biodigestibility and co-digested effectively to improve the efficiency of the anaerobic digestion process. Biogas monitoring commenced from day 11 of loading the biodigesters (therefore, day 11 to 18 = week 1). This was because at day 11, observation from the stove showed that biogas from both biodigesters burnt efficiently and with clear blue flame (Figure 1.5) and so also throughout the duration of the study. It can therefore be deduced that stirring of the substrates did not have effect on the quality of the biogas produced. The results showed that the stirrer aided digestion, resulting in optimal biogas production. It was observed that daily biogas production from both biodigesters picked up gradually and was consistent but fluctuated throughout the study period. This may be due to digestion factors such as feedstock nutrients and temperature. While consistency in gas production may be due to the availability of easily biodegradable nutrients in the feedstock during digestion, fluctuation in gas production may be related to the effect of fluctuating ambient temperatures on digestion. The weekly biogas productions from each biodigester from day 11 are displayed in Figure 1.6. The gradual lower production observed in the control digester in the first eleven weeks may be an indication of the effect of non-transfer of organic materials for the active microbial mass, possible sedimentation of denser particulate material (Ward et al. 2008) and buildup of scum stratum. There was a sharp decline in production between week 11 and 12 from the control biodigester. Afterwards there was further decline to the end with a slight increase around week 17. The sharp and subsequent notable decline in production indicated the strong effect of buildup and hardening of the scum stratum, consequently limiting the production and passage of biogas through the substrates out of the biodigester. The fibre content in the startup feedstock (cow dung) and the high fibre content in the rabbit faeces dominated feedstock used may have highly contributed to the rapid buildup of the scum stratum. Figure 1.7 shows the weekly reduction in biogas production as estimated by the equation described earlier. Between week 2 and 6 (day 25 and 53) of the study, on the average, about 17.5% reduction in gas production was being recorded weekly while the daily production was ($p \leq 0.05$) 1.09 and 0.90 m^3 from the biodigester with stirrer and control biodigester, respectively. Between week 8 and 11 (day 67 and 95), the average daily production of the biodigester with stirrer was about 1.11 m^3 while that of the control biodigester had dropped ($p \leq 0.05$) to 0.84 m^3 and gas reduction had increased to about 23.8% weekly. By week 15 to the end of the study (day 116 to 186), the weekly biogas reduction had further increased to around 39.7% while the average daily production of the control biodigester had dropped drastically ($p \leq 0.05$) to 0.65 m^3 and that of the biodigester with stirrer remained 1.09 m^3. The linear model fitted to the biogas reduction data showed a reduction rate of 1.31%/week (R^2 = 0.92) during the period studied. By implication, the stirrer prevented biogas reduction at the rate of 1.31%/week when it was operated. The daily biogas production range of 1.04-1.10 m^3 from the biodigester with stirrer and with substrate volume of 1.4 m^3 indicated an optimally performing biodigester (Kaltschmitt et al. 2001). At the latter part of the study (around week 14), effluent drip was observed at the outlet pipe of the control biodigester especially in the afternoon around the peak temperatures period when biogas production was high. This may have been caused by the rate of biogas production which exceeded the rate of exit thereby resulting in the gas displacing the substrates. There was no appreciable pick up in gas production after each feeding day suggesting that the loading rate may have been ideal. The bubbling sound that emanated from the biodigester with stirrer each time the substrates were stirred indicated that trapped gas was released from the strata especially the scum. This was confirmed by the fast rate of gas flow through the indicator. The quantities of the effluent collected at each feeding showed slight decrease in the control biodigester compared to the biodigester with stirrer. This can be adduced to the effluent loss discussed earlier. The effluent quality from the biodigesters was not compared but the vegetables harvested from the plot with effluent addition showed an appreciable yield over the ones harvested from the plot without effluent addition. The biogas generated daily from the biodigester with stirrer was, on the average, sufficient to prepare three-square meals for a household of four; regular cooking for breakfast and dinner and light cooking for lunch.

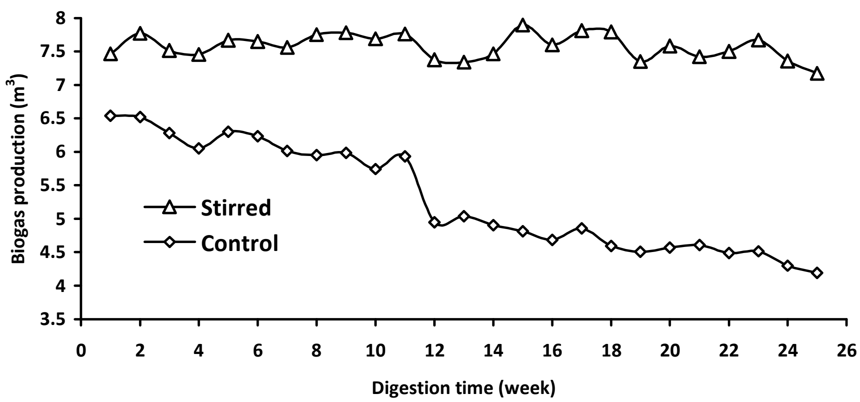

Fig. 1.6. Profile of biogas production from both biodigesters during the experiment.

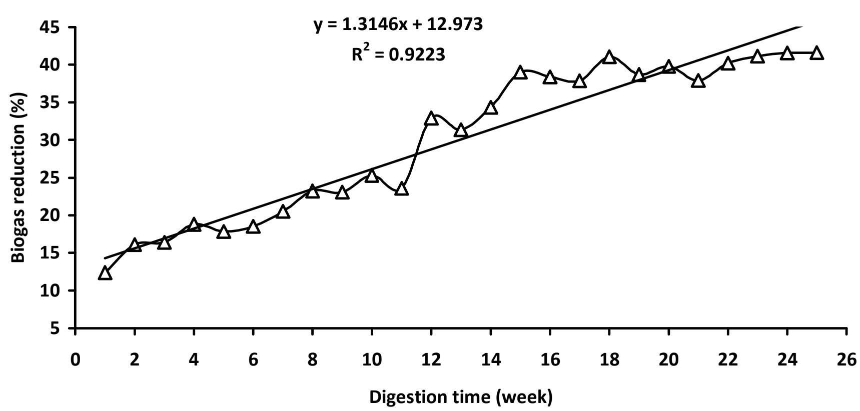

Fig. 1.7. Profile of reduction in biogas production from the control biodigester during the experiment.

4. Conclusions and Recommendations

The developed stirrer improved the performance of the plug-flow biodigester and enhanced domestic biogas production. The stirrer prevented a reduction in biogas production by 1.31%/week when it was operated. By the end of the study, up to 41% of biogas reduction was being recorded weekly in the control biodigester. The biogas produced from both biodigesters burnt with clear blue flame. The stirrer was easy to construct, install and operate and can be easily adapted to different sizes of plug-flow biodigesters. This technology will promote the use of plug-flow biodigesters for cooking energy production thereby making domestic cooking more effective and less costly.

Considering the long term benefits of biogas technology, it is recommended that government should formulate policies and appropriate legislation and adopt advocacy approach to popularize the waste-to-wealth technology and promote its penetration and diffusion into the Nigerian energy market, especially in the rural areas. This could be achieved by setting up youth empowerment/entrepreneurial development schemes whereby fresh and unemployed universities graduates (preferably with technical background) will be trained by experts on the fabrication and commercialization of the technology. Supporting incentives such as soft and revolving loans could be given to the successful trainees to assist them to set up biogas and bio-fertilizer production ventures. In addition, challenged prospective end users of the technology could also be supported with similar incentives from the government or corporate organizations to acquire the technology for their domestic and cottage industrial uses. The expected multifaceted effects on socio-economic life and environment will include job creation, reduction in unemployment, less dependence on fossil fuels, cost savings, improvement in health and hygienic conditions and production of organic fertilizer for crop improvement. Future research should focus on the improvement of the biogas set up: efficient cleaning of the gas produced for possible electricity generation, analysis of effluent quality for crop improvement and commercialization of the set up.

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