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Use of a Portable Greenhouse for Temperature Control in a Small-scale Biogas Production Unit

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Abstract- Biogas yield in anaerobic digesters is negatively affected by low temperatures during cold seasons and nights, temperature fluctuations and inefficient agitation. In this study a 100 ℓ, agitated portable carbon steel digester housed within a greenhouse, whose operation temperature is automatically maintained at 35±1°C by means of an electronic circuit for ventilation control through a suitably sized window and insulation offered by an air film between a double layer of polyethylene plastic covering of the greenhouse, was designed. Analysis of biogas produced from cow dung starting from day 6 of the 31-day retention period showed a specific biogas yield of 0.036 $m^3/kgVS_{added}$ and an improved methane yield of 55% which was higher than 50% achieved by other digester designs. The optimum pH for good buffering capacity and efficient anaerobic digestion was successfully maintained at 7.2 and the chemical oxygen demand (COD) reduction achieved was 61%. The maintenance of a narrow temperature range (34°C-36°C) was successful resulting in solving the challenge of poor temperature control which affects biogas production and methane yield in most small-scale digester designs. This simple, easy to construct, inexpensive and efficient design led to improved biogas yields, quality and faster dissemination of the biogas technology.

Keywords: Agitation; Biogas; Digester; Greenhouse; Portable, Temperature.

1. Introduction

South Africa is experiencing electricity blackouts as a result of energy supply shortages and biogas can provide a solution to South Africa's energy demand [1,2]. In addition, biogas can reduce usage of non-renewable energy sources such as fossil fuels [3, 4, 5]. Biogas is a gas containing between 50-70% methane, 30–50% carbon dioxide, hydrogen sulphide, water vapor and other gases in small amounts. The methane component in biogas is inflammable hence making biogas an inflammable gas that can be used for cooking and other uses just like the non-renewable liquid petroleum gas (LP) and natural gas. In addition, the biogas can be utilized as a vehicle fuel, for heat and electricity production [6]. The production of biogas takes place in air-tight vessels (reactors) called biogas digesters through an anaerobic digestion (AD) process [7]. In an anaerobic digestion process operation, temperature control and substrate slurry agitation are the key factors affecting biogas production of which temperature is the principal factor. These factors affect the physico-chemical properties of compounds present in the digester, kinetics and thermodynamics of biological processes [8,9]. The mesophilic temperature range (30 - 38°C) is commonly recommended for biogas operations since it is more economically feasible than the thermophilic range (49 - 57°C) and is much more efficient in producing biogas than the psychrophilic range (0 -15°C) [10]. A range of 30 - 38°C is however too wide and not ideal for the highest possible biogas production from a substrate due to the fact that the micro-organisms responsible for methane production (methanogens), are very sensitive to temperature fluctuations even as slight as 2 – 3°C and their depletion in an AD process has often led to foam formation and digester souring [9, 11, 12, 13]. This therefore gives rise to the need for the close monitoring and maintenance of a narrow temperature range in biogas production systems.

Another key factor for efficient biogas production is agitation of the digester contents during operation. The purpose of agitation of substrate in a digester is to blend the fresh material with the digestate containing micro-organisms. This operation also prevents scum formation, maintains a chemically and physically uniform slurry enhancing the rapid dispersion of metabolic wastes produced during substrate digestion that could otherwise inhibit methane production, immediately disperses any toxic material entering the tank hence minimizing toxicity, prevents grit deposition and avoids temperature gradients within the digester. Excessive, disproportionate agitation can however interrupt the contact of the micro-organisms to the substrate and decreases biogas production hence agitation can however disrupt the micro-organisms hence slow, occasional and harmonious agitation of the slurry in a digester which increases biogas production is preferred. The type of agitation equipment, rate and amount of agitation varies with the type of reactor and the solids content in the digester. Agitation is also responsible for efficient enzyme activity. Inefficient agitation results in longer retention time, underutilization of digester volume due to formation of dead zones and consequently, decreased biogas production.

The biogas digester technology potential is however not being fully exploited due to inefficient or a lack of temperature control, the absence and or inefficiency in agitation, gas leakages, unavailability of affordable materials for construction and construction expertise associated with the existing biogas digester designs [14]. There are about 700 digester installations done in South Africa since the introduction of the biogas technology in the country in 1957 by John Fry [15]. For some country rich in biomass deposits like South Africa, this is an unexpected figure as compared to other countries like China with 17 million and India with 12 million installations, and this indicates the need for a closer look at the effectiveness and attractiveness of the technology in the country.

The fixed dome, floating drum, balloon type and several other biogas digester designs have been developed for biogas production over the years and have had many modifications done on them. However, it is still not possible with most of these small-scale digester designs in current use to feasibly control the operation temperature within a narrow optimum range as required by the anaerobic micro-organisms, which get upset by large temperature fluctuations leading to decreased process efficiency and biogas production. Electrical heating is not economical on the small-scale digesters and hence cannot be employed. Low temperatures experienced during cold nights and seasons are the major cause of the undesired adverse temperature fluctuations [16]. Many improved biogas digester designs have been introduced and implemented in the world and currently, over 30 million digesters are in operation across the globe [15].

Designs which deliver lower cost, improved robustness, functionality through integration of other renewable energy sources such as solar, ease of construction, operation and maintenance would aid the market penetration of the biogas technology [17, 18]. Furthermore, to move beyond a dependence on livestock manure, there is a need for small-scale biogas digesters which efficiently digest available substrates in both rural and urban situations. On a domestic level these include kitchen waste, human excreta, weeds and crop residues [19]. This article outlines the design of a small-scale digester with cheap and affordable efficient temperature control facilitated by a regulated greenhouse and agitation system coupled together in a portable unit. The temperature in this digester unit is maintained at a mesophilic optimum of 35 ± 1°C.

2. Materials and methods

2.1. Digester Design

The biogas digester design was based on the specifications of temperature maintenance at an optimum of 35±1°C, manual agitation, portability and simplicity. A batch stirred tank digester was selected since it offers the required reactor simplicity [20]. Fig. 1 and Fig. 2 show the 2D and 3D dimensional views of the proposed design respectively while Fig. 3 shows the fabricated digester. The digester system included a 100 ℓ capacity mild steel cylindrical digester vessel with an internal diameter of 500 mm, a 10 mm thick flat top flange, 3 mm thick cylindrical section and 3 mm thick tori-spherical bottom. This was the minimum workable thickness enabling the vessel to withstand internal pressure to be exerted by biogas during digestion [21, 22]. The thickness was also thin enough to allow for efficient thermal energy transfer across the vessel wall made of mild steel which has a good thermal conductivity of 54 W/mK [23]. The flange top was bolted to the cylindrical section with a corrosion resistant nitrile rubber gasket in-between. The digester vessel was painted black using NS5 METCOTE primer and Duram DTM black, an epoxy-based paint, in order to prevent corrosion and improve absorption of solar and thermal radiation. An anchor impeller with a diameter 95% that of the vessel was designed since it is suitable for the gentle and slow agitation of thick pastes such as most substrate slurries [24]. All the metal vessel dimensions were done according to the American Society of Mechanical Engineers (ASME) standards [21]. A 50 mm PVC slurry outlet pipe was connected to the base of the vessel and it ran through the wooden base on the underside to an exit point on the side of the wooden base while another inlet pipe, gas pipe and agitator handle ran through holes drilled through a vertical wooden support into the metal vessel.

For temperature control, a portable greenhouse with a double layer of UV-inhibited and IR absorbing low density polyethylene (LDPE) transparent polyethylene plastic cover of low cost, high flexibility, high shortwave radiation transmissivity of 60 – 80%, water impermeability and impact resistance [25], for solar radiation transmission and thermal radiation insulation was designed and constructed to house the digester vessel. The greenhouse had a wooden base for thermal radiation insulation and an automated ON/OFF temperature-controlled sliding window to control the greenhouse air temperature through ventilation. The greenhouse design was done is such a way as to minimize thermal energy losses through conduction, convection and infiltration. This was achieved by use of a double layer of polyethylene plastic trapping an air film to provide insulation against heat loss by conduction and convection. Thermal energy loss through infiltration was minimized by ensuring airtightness of the greenhouse structure. When the greenhouse temperature crosses the set point of 35°C, the 12VDC ON/OFF temperature-controlled relay switch actuates a 12VDC motor to open the sliding window and vent warm air out of the greenhouse, replacing it with cooler air hence decreasing the greenhouse temperature. Below the set point, the motor is actuated to move in the opposite direction, hence closing the window. A hysteresis band of 2°C prevented the continuous rapid switching of the relay above and below the set point. This way the greenhouse temperature was maintained within a narrow range of 32-37°C. The slurry temperature in turn was maintained within a narrower range of 34-36°C, giving the desired optimum of 35°C.

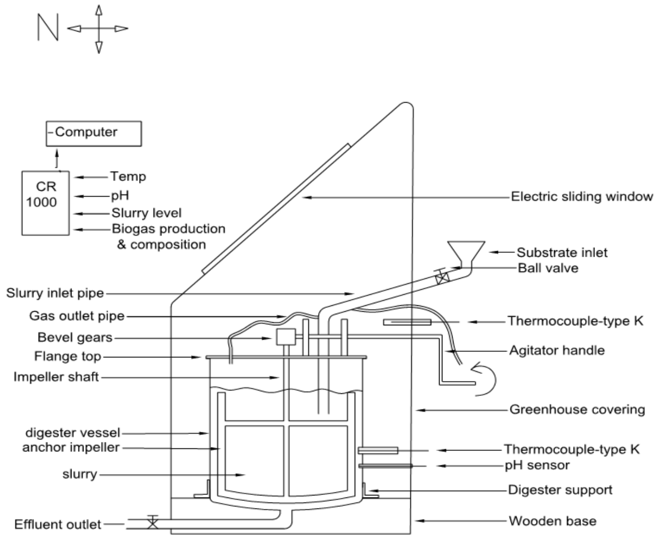

Fig. 1. Schematic of the agitated portable digester under greenhouse-regulated temperature.

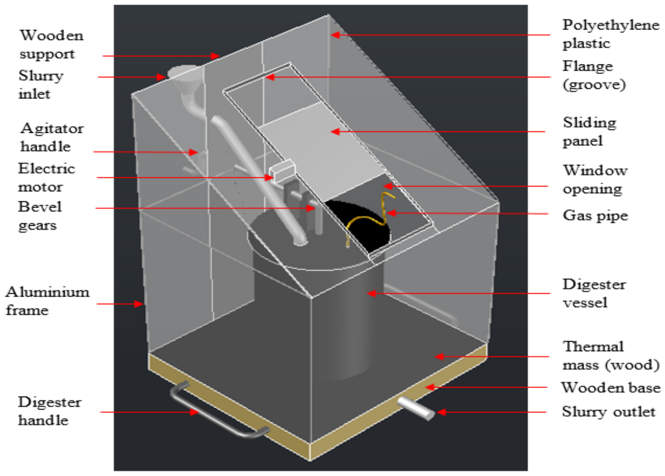

Fig. 2. A 3D view of the proposed agitated portable digester under greenhouse-regulated temperature.

Two type-K thermocouples were air-tightly inserted through the metal wall of the digester and in the space above the metal vessel within the greenhouse respectively so that they could be used to monitor the slurry temperature and the temperature of the air within the greenhouse respectively. A pressure sensor was used to monitor the pressure within the digester vessel.

Fig. 3. Greenhouse regulated temperature biogas digester.

2.2 Digester operation

Cow dung was collected from the dairy farm at the University of Fort Hare. No special inoculum was available to aid the digester start up, hence fresh dairy cow dung (known to contain obligate methane-forming anaerobic micro-organisms), was used to form an improved substrate, which produces biogas within a few days of feeding [26]. Before being fed into the digester, the substrate was analysed for total solids (TS), volatile solids (VS), chemical oxygen demand (COD), ammonia-nitrogen (NH_4-N), total alkalinity (TA), pH and calorific value (CV) using a mass balance and an oven, AL450 Aqualytic photometer which contains a variety of pre-programmed methods based on the proven range of Aqualytic® tablet reagents, liquid reagents, tube tests and powder reagents and a CAL2K bomb calorimeter respectively. An 11% total solids slurry of the substrate was made and fed into the digester as recommended for anaerobic digestion in the mesophilic temperature range [27]. The digester internal temperature, pH, and biogas production rate and composition were monitored as the anaerobic digestion process progressed using a Pasport PS-2125 temperature sensor coupled with a PS-2000 Xplorer, the Serial residential diaphragm biogas flow meter and the SAZQ biogas analyser respectively. Data on the composition of methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S) in the biogas was captured for analysis by a data logger and computer system. Table 1 shows the characteristics of the cow dung fed into the digester for digestion and performance evaluation.

Table 1. Characterisation parameters for dairy cattle dung

Parameter	**Value**
Total solids (mg/ℓ)	162348.67
COD (mg/ℓ)	37 879
Volatile solids (mg/ℓ)	116543.98
Volatile solids / Total solids %	71.79
Total alkalinity (mg/ℓ)	1988 - 2347
Ammonium-nitrogen (mg/ℓ)	128 - 235
Calorific value (MJ/g)	25.29

Anaerobic digestion of the dairy cattle dung was carried out at a temperature range of 35 ± 1°C for a retention time of 31 days. During the 31 days, samples of the slurry were collected through the effluent outlet nozzle for the determination of COD, pH, TS and VS as required since the slurry conditions were uniform throughout the volume of the vessel due to efficient agitation.

3. Results and discussion

3.1 Temperature variation

The ambient temperature, T_{amb}, greenhouse air temperature, T_a, and slurry temperature, T_s variation with time for the month of July 2017 are shown in Fig. 4. This is the coldest month in the climate of the Eastern Cape Province in South Africa [28].

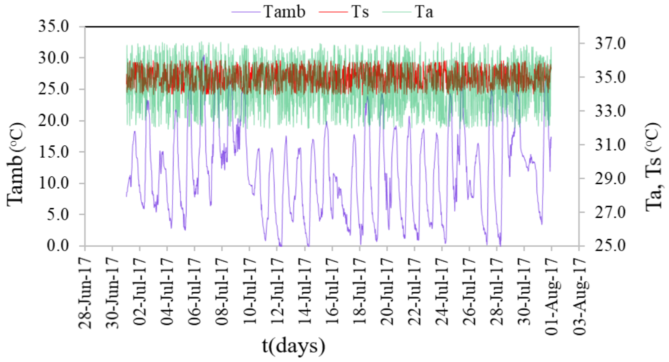

Fig. 4. Ambient, greenhouse and slurry temperature variation for a month.

The inequalities (1) – (3) show the ambient, greenhouse and slurry temperature variations during the month:

$$-0.8^o C \le T_{amb} \le 30.2^o C \quad (1)$$

$$32^o C \le T_a \le 37^o C \quad (2)$$

$$34^o C \le T_s \le 36^o C \quad (3)$$

During this period, it is shown from Figure 4 that $T_a > T_{amb}$ and $T_s > T_{amb}$.

Fig. 5 shows the temperature variations with time measured at 30-minute intervals over a period of two typical days in July. The days were chosen, because they are generally a true representation of the ambient temperature pattern for the whole month at the University of Fort Hare.

Fig. 5. Ambient, greenhouse and slurry temperature variation for 2 days.

During the 2 days;

$$5.4^o C \le T_{amb} \le 23.3^o C \quad (4)$$

$T_a > T_{amb}$ at any given time due to the greenhouse effect and the insulation against heat loss.
$T_s > T_{amb}$ always because of the greenhouse effect and bacterial activity facilitating exothermic reactions within the digestion chamber as stated by [29].

As shown in Fig. 5, the temperature variation behaved differently for different times of the day. Between 0.00Hours and 08.00Hours, $T_s > T_a$ due to the absence of solar radiation in the night. The slurry had a higher heat capacity than the air within the greenhouse therefore it was able to retain heat better than the air. During this period, T_a decreased from 34.8°C to a minimum of 32.1°C at 06.30Hours due to thermal energy losses through infiltration and the fact that there wasn't 100% insulation efficiency. After 06.30Hours, T_a increased gradually and at 08.30Hours, $T_a = T_s = 34.7$ °C. At sunrise $T_a > T_s$ due to the greenhouse effect after sunrise. Between 08.30Hours and 18.00Hours (sunset), $T_a > T_s$ and fluctuated under controlled ventilation. The slurry temperature also fluctuated within its range of 34 – 36°C due to the influence of the greenhouse temperature and the dynamic bacterial activity.

At 18.00Hours, $T_a = T_s = 34.5$°C, and from then it continued to gradually decrease below the slurry temperature into the night till it reached a minimum of 31.9°C at 05.30Hours and started rising again with the rising of the sun. A linear regression of T_a, T_s and T_{amb} data in Kelvins gave the equation:

$$\ln T_s = 1.043 \ln T_a + 0.064 \ln T_{amb} + 0.8313 \quad (5)$$

Hence:

$$T_s = 0.8313 T_a^{1.043} T_{amb}^{0.064} \quad (6)$$

This implies that T_a, with a higher power of 1.043, affected the slurry temperature more than T_{amb}. This was due to the high conductivity of the mild steel vessel wall separating the slurry from the greenhouse air as opposed to the insulating greenhouse wall separating the greenhouse air from the ambient conditions. The positive relationship however was due to the greenhouse effect. Incorporating the initial slurry temperature, T_{0s} in the linear regression gave equations (7) and (8):

$$\ln T_s = 1.27077 \ln T_{0s} + 0.087894 \ln T_a + 0.003643 \ln T_{amb} + 0.7612 \quad (7)$$

$$T_s = 0.7612 T_{0s}^{1.27077} T_a^{0.087894} T_{amb}^{0.003643} \quad (8)$$

The initial slurry temperature had a higher and more significant impact to the slurry temperature measured at any given point than the greenhouse and ambient temperatures since it has a higher power of 1.27077 as shown in equation (10). This was because the slurry had a high heat capacity and would require more thermal energy before significantly responding to any temperature changes around it.

3.2 Biogas yield

Fig. 6 shows the biogas yield attained during this period. Biogas production started on day 6 where 9.13 litres were measured as shown in Figure 6. This was so because no inoculum was added to start-up the anaerobic digestion process which according to literature might have started gas production as early as day 2 [30, 31].

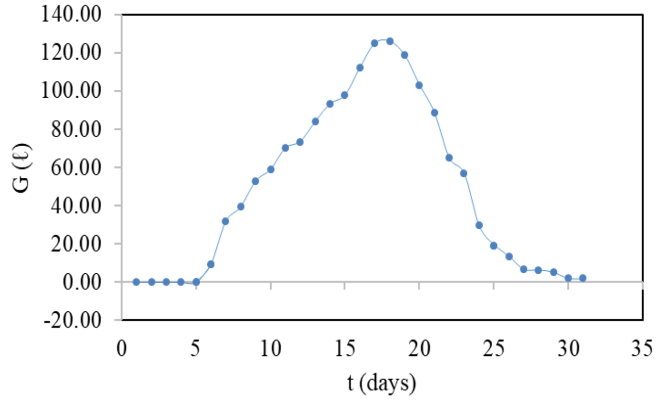

Fig. 6. Biogas yield for dairy cattle dung.

The daily rate of gas production fluctuated between day 6 and day 27 although the general trend was an increase in gas production reaching a maximum value of 125.98 litres on day 18, followed by a decrease to 6.85 litres on day 27. These fluctuations can be explained by the continuously dynamic activity of the anaerobic micro-organisms in response to the slight temperature and pH changes and agitation as fresher substrate was exposed for digestion. Thereafter, an exponential decrease to smaller quantities of gas took place up to day 31 with 2.02 litres. This was a result of the depletion of fresh substrate regardless of agitation and change in temperature, pH, or any other physico-chemical properties.

Fig. 7 shows the cumulative biogas yield over a period of thirty-one days.

Fig. 7. Cumulative biogas production from dairy cattle dung.

It can be observed from Fig. 7 that the total biogas produced over the 31 days of anaerobic digestion of dairy cattle dung was 1491.10ℓ, of which 65.3% (973.78ℓ) was produced between days 6 and day18. During this period the slurry will be rich in the biodegradable organic fraction of the substrate. A cumulative biogas production function, *G(t)* determined from the curve of best fit in Fig. 7 is given in equation (10):

$$G(t) = 0.0011x^5 - 0.0878x^4 + 2.2418x^3 - 18.619x^2 + 61.919x - 61.178 \quad (10)$$

The average daily biogas production $\langle G \rangle$ was determined from equation (11):

$$\langle G \rangle = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} G(t)\, dt \approx 48\,\ell \quad (11)$$

Fig. 8 shows the variation of the production of methane (CH_4) and carbon dioxide (CO_2).

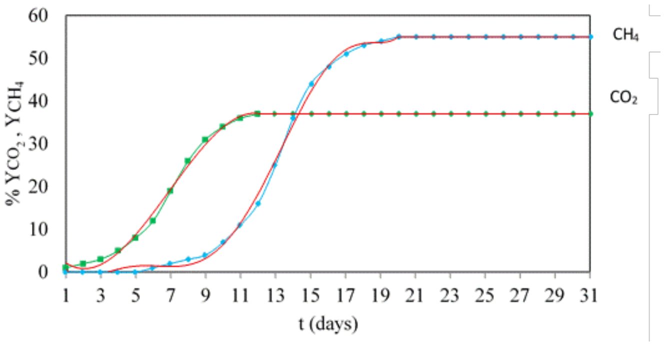

Fig. 8. Variation of the production of CH_4 and CO_2.

With reference to Fig. 8, the CO_2 content was 0.04% (composition in air) on day 1 and it increased starting on day 2 before attaining to a constant value on day 11 and onwards. The CO_2 production pattern followed equation (12).

$$Y_{CO_2} = \begin{cases} 0.04 & if \quad t < 2 \\ -0.0785t^3 + 1.6287t^2 \\ -5.6774t + 6.303 & if \quad 2 \le t \le 11 \\ 37 & if \quad t > 11 \end{cases} \tag{12}$$

The production of CO_2 is due to: (i) the presence of some aerobic bacteria in the digester before the evacuation of air from the digester by biogas formation which facilitated the reaction of O_2 with carbohydrates to produce CO_2 and (ii) the action of acidogenic bacteria in forming fatty acids from the organic feed, which were then decomposed by acetotrophic methanogens to CH_4 and CO_2 according to equation (13),

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{13}$$

The decrease in CO_2 was a result of O_2 depletion in the digester vessel and conversion of some of the CO_2 to CH_4 by the action of hydrogenotrophic methanogens according to equation (14),

$$CO_2 + 4H_2 \rightarrow CH_4 + CO_2 \tag{14}$$

The CO_2 however reached a constant composition after day 11 due to the equilibrium reached between its formation and usage as shown in equations (13) and (14). The CH_4 production pattern followed equation (15).

$$Y_{CH_4} = \begin{cases} 0 & if \quad t < 7 \\ 8\times10^{-5}t^6 - 0.0048t^5 + 0.1082t^4 \\ -1.0937t^3 + 5.2081t^2 - 10.729t & if \quad 7 \le t \le 20 \\ +6.9506t \\ 55 & if \quad t > 20 \end{cases} \tag{15}$$

CH_4 production began on day 6 and increased gradually to attain a constant percentage of 55% on day 20 onwards. There was no CH_4 that was produced before day 6 because the methanogenic bacteria waited till the formation of fatty acids on which they feed in order to produce methane [32, 33]. On day 14, the CH_4 content rose above the CO_2 content since none of the two methanogenic processes uses CH_4 as a reactant unlike in the case of CO_2. The CH_4 content however reached a maximum constant value due to the continual production of CO_2 by the same methanogenic processes which leads to an equilibrium point. The methane yield achieved is higher than the 50% that Mukumba *et al.* found in their digestion of cow dung using a fixed dome batch biogas digester insulated with sawdust [11]. This difference can be attributed to the fact that in the current work the slurry temperature was maintained at 35°C while Mukumba *et al.* used 30°C.

Table 2 shows the final % composition of CH_4, CO_2, H_2S and other gases.

Table 2. Biogas composition after digestion

Gas	**Composition (%)**
Methane (CH_4)	55
Carbon dioxide (CO_2)	37
Hydrogen sulphide (H_2S)	0
Other gases	8

3.3 pH variation

The relationship between the biogas yield and the pH values measured during the anaerobic digestion process is shown in Fig. 9.

Fig. 9. Relationship between COD and pH ranges for dairy cattle dung digestion.

Due to the presence of the highly digestible organic fraction of the cow dung and the increased rate of COD destruction to form volatile fatty acids (acidogenesis) between days 4 and 6, the pH dropped from 8.0 on day 2 to 6.9 on day 6 and begins to fluctuate between 6.9 and 7.3, giving an average pH of 7.2. This fluctuation was a result of the balance between COD destruction by acid-forming (acidogens) and acid-depleting bacteria (methanogens) since the acidogenesis and methanogenesis processes occur simultaneously [34]. This narrow pH range indicated a good buffering capacity of the cow dung used as a result of its suitable alkalinity (1988 – 2347) [35]. From day 19 the pH began to increase as the fatty acids got depleted. The pH variation with time can be represented by the quadratic function (16):

$$pH = 0.0039t^2 - 0.136t + 8.1018 \tag{16}$$

With reference to equation, the pH decreases then increase within a very narrow range which suggests good buffering capacity and efficient anaerobic digestion. An exponential decrease in COD takes place according to equation (17):

$$COD = 42817e^{-0.039t} \tag{17}$$

This shows that COD destruction was fast and efficient during the digestion period having a half-life, $t_{\frac{1}{2}}$ of 17 days.

$$t_{\frac{1}{2}} = \frac{\ln\frac{1}{2}}{-0.039} = 17days \tag{18}$$

The relationship between biogas yield and pH is shown in Fig. 10. It is clearly shown that the pH drops during the first 6 days i.e. before methanation which depletes the formed fatty acids. The highest biogas yield is obtained at an optimum pH of 7.2 between day 9 and day 24 when the pH is somewhat constant as shown in Fig. 10. After day 19, towards the end of the digestion process, the pH begins to rise again as gas production decreases due to depletion of fatty acids.

Fig. 10. Relationship between biogas yield and pH range for dairy cattle dung.

3.4 COD destruction

Fig. 11 shows the COD destruction rate in relation to biogas yield. Upon entry into the digester, the cow dung had a COD of 37 879 mg/ℓ which dropped to a final value of 14388 mg/ℓ in the effluent. This means that the digester was able to achieve 62 % COD destruction. This agrees with the findings that the maximum COD destruction under mesophilic conditions lies within the range of 60 – 85 % [36]. There was a sharp decrease in COD between days 4 - 7 and 14 - 19 which explains the rapid increase in biogas production on day 6 and 7 and the maximum biogas production on day 18.

Fig. 11. Relationship between gas yield and COD range for dairy cattle dung.

4. Conclusions

The use of a greenhouse temperature regulated, agitated portable biogas digester in the anaerobic digestion of organic waste to produce biogas improved the digestion efficiency and methane yield. The methane yield from dairy cattle dung was 55%, which is comparable to the 50% achieved by other digester designs such as the fixed dome with saw dust insulation, hence the current design becomes a more attractive option since it is portable and can be installed for use in any given location (rural, urban, multi-storey and rocky terrains). The ability to keep the slurry temperature fluctuating within a narrow range of 34°C - 36°C made this design a good option for solving the common challenge of poor temperature control which lead to poor biogas production and methane yield in most small-scale digester designs. In this design, the pH fluctuated within a favorable range of 6.9-7.3, giving an optimum of 7.2, which suggests good buffering capacity and efficient anaerobic digestion. An exponential decrease in COD with a half-life of about 17 days was also achieved and a commendable percentage COD destruction of 62% was realised. Ultimately, the anaerobic digestion process efficiency and utilisation of locally and readily available cheap construction materials make the design quite attractive compared to other designs.

5. Recommendations

The digester developed in this work was only at prototype-scale and therefore it is recommended that a bigger scale digester of a capacity between 1 and 10 m^3 be built and evaluated for performance. A feasibility analysis on the cost of using the mechanism outlined in this work versus other conventional methods of digester heating such as electrical heating, should also be done at the recommended scale in order to more clearly reveal the cost-effectiveness and applicability of the discussed innovation. Semi-continuous digester feeding and use of various kinds of inocula at digester start-up should also be done for further digester performance evaluation since in this work only the batch digestion mode was used for experimental purposes. A mathematical model of this digester design can be developed and used in the determination of optimum biogas production parameters using the design under various feeding and operating conditions.

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