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BIOGAS PRODUCTION IN CONE-CLOSED FLOATING-DOME BATCH DIGESTER UNDER TROPICAL CONDITIONS

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ABSTRACT: The production of biogas from cow dung, pig and chicken manures and from water hyacinth-cow dung mixture in cone-closed gas collector 1.5 mm thick and 0.7 m wide placed in a brick-walled batch-anaerobic digester 1.5 m deep and 0.8 m wide was studied. Samples containing substrate (S) were mixed with water in the ratios of 1:3, 1:4 and 1:5 and left to react with bacteria-dependent enzyme (E) in the digester for hydraulic retention times (HRT) of 10 to 40 days. The results showed that the pH-temperature-dependent reaction followed the Michaelis-Menten mechanism which was reduced to First Order kinetics. The pig and chicken substrates produced higher values of yields (3.08 m^3/ton; 3.88 m^3/ton) at pH range of 6.8-8.0 than the cow dung and water hyacinth-cow-dung mixture (0.92 m^3/ton; 0.64 m^3/ton) at average temperatures of 20-27 ^oC, HRT of 15 days and S level of 25 wt%. It was also observed that the increase in the level of S lowered the yield in all cases of substrates. The yields increased as HRT increased up to 15 days. The highest HRT was found to be 30 days at which the production of biogas slowed down as the bacteria died off slowly. However, the highest yield (5.6 m^3/ton) was produced from chicken dung whilst the lowest production (1.28 m^3/ton) was from hyacinth-cow dung mixture at HRT of 25 days using the same E from cow dung.
Keywords: Biogas-pH; Yield-temperature; Cone-closed-digester; Cow-chicken-pig-dung; Slurry-pH

INTRODUCTION

Biogas, a product from the decomposition of organic materials by methanogenesis, can be the alternative source of energy for most developing countries. Methanogenesis can be carried out in different types of digesters by anaerobic reaction[1, 2]. Field experiences with methane digesters are reported in Kramer (2002)[3], Meyer and Lorimor (2003)[4], Moser and Mattocks (1998)[5], Nelson and Lamb (2002)[6], Jones *et al.* (1980)[7], Engler *et al.* (1999)[8] and Ernst *et al.* (2000)[9].

Mechanism of the reaction is first by the fermentative action of acid forming microbes on the substrate (S) to produce alcohol, hydrogen (H_2), acids and carbon dioxide (CO_2) and second the action of methane-forming bacteria (methanogenesis) to produce methane (CH_4) and CO_2 as indicated in equation (1) where SE is the intermediate product, E is the enzyme, k_1 and k_2 are rate constants (s^{-1}).

$$S + E \xrightarrow{k_1} SE \xrightarrow{k_2} E + CH_4 + H_2 + CO_2 \quad ....(1)$$

The bacteria responsible for the reaction belong to the genera *Bacteriodes* and *Clostridium*. Preeti (1993)[10] reported higher amylolytic bacteria in cow-dung-fed digesters and higher proteolytic bacteria in chicken-dung-fed digesters. The bacteria are highly specific, strongly influenced by pH and temperature[11]. Because of the higher concentration of S than the bacteria concentration in the early stages, the effect of concentration of S on the rate is more pronounced than the bacteria concentration. However the bacteria concentration also builds up as the reaction proceeds[12]. The continuous increase in bacteria concentration leads to an increase in the reaction rate. Therefore, up to a certain value of concentration, the resultant rate will slow the increasing trend. Beyond this point, the resultant rate falls steadily, as the effect of depletion in concentration of S begins to out weigh the effect of increase in bacteria concentration[13]. The anaerobic digestion occurs through hydrolysis followed by a sequence of steps which have been considered together as a pseudo-first order process[14].

The rate of reaction is assumed to depend on the concentration of SE, temperature, pH and the geometry of the reactor. Pressure distribution in flat-doomed collectors allows the collector to tip over easily at high gas production rates. Cone-closed gas collectors allow the even distribution of pressure around the cone by venting high pressure into the cone and thus do not allow the collector to tip over easily. The break down of S has been reported to follow the Michaelis-Menten mechanism[15, 16, 17]. The rate of reaction of S can be given by (2), (3) and (4) which yield first order kinetics[15, 18] where t is the time (s), k_{-1} is the rate constant (s^{-1}), R_1, R_{-1}, R_2 are the rates of reaction ($kmols^{-1}$), S_1, S_2 are the initial and final substrate concentration (kmol), K_m is a constant.

$$R_1 = k_1[S][E] = R_{-1} + R_2 = k_{-1}[S.E] + k_2[S.E] \ldots\ldots\ (2)$$

$$\frac{dS}{dt} = \frac{k_2 SE}{(k_{-1}+k_2)/k_1 + S} = \frac{k_2 SE}{K_m + S} \qquad \ldots\ldots\ldots\ldots(3)$$

$$In\frac{S_1}{S_2} = \frac{k_2 E}{K_m + S}dt = kdt \qquad \ldots\ldots\ldots\ldots\ (4)$$

Equation (4) can be used to evaluate the First Order kinetics of biogas production at given conditions of temperature and pH. The purpose of the study was to establish the production capacity from each of the substrates cow, chicken and pig manures and water-hyacinth-cow dung mixture. The specific objectives of the study were to determine the production rate (yield) and favourable pH for different levels of S and to determine whether the breakdown of S follows the modified Michaelis-Menten model.

MATERIALS AND METHODS

Materials

Four organic biomass materials were used separately at different concentrations in separate biogas digesters. Cow dung, chicken manure and pig mature were used in dry form before mixing with water to produce biogas by anaerobic decomposition. The water hyacinth was used in its fresh form, cut into small chips, mixed with cow dung before mixing with water. The substrate was weighed on a scale and mixed with water to form 8 wt%, 15 wt%, 18 wt% and 25 wt% in the ratios 1:3, 1:4, 1:5 etc. The mixture was then placed in the digester and observed for 10, 15, and 25 days depending on the desired period. Feeding the digesters with fresh cow dung was necessary for the water hyacinth biomass in order to kick start the digestion process as the hyacinth does not have anaerobic bacteria.

Equipment

The lay-out of equipment is as shown in Figure 1. A feed port of 300x300 mm, a concrete base of 100 mm and 80 cm wide brick-walled housing that was 1.5 m deep. The gas collector 1.7 m high and 70 cm wide was constructed using 1.5 mm iron sheets, 12 mm deformed bars, 20 mm angle iron, 20 mm central pipe and 16 mm smooth bar to hold the gas collector in upright position. The results are reported for the production of crude biogas from reactors without purification.

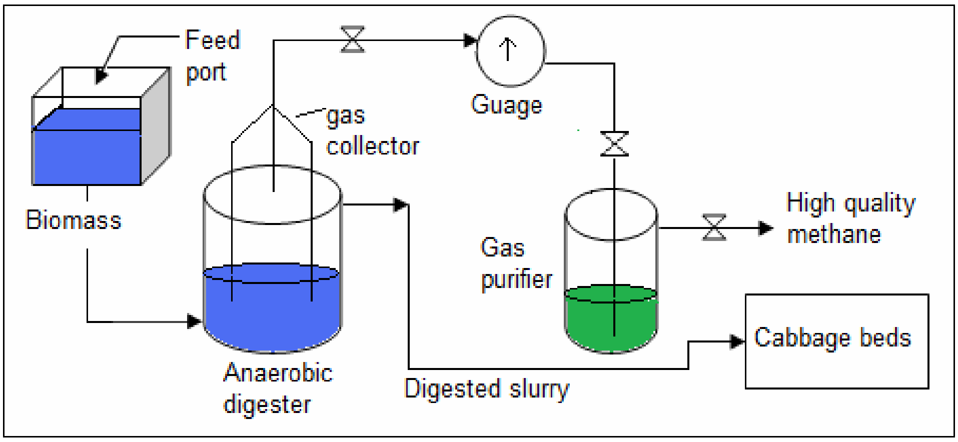

Figure 1: The anaerobic digester plant for biogas production

The samples of slurries were collected at the feed port, in the reactor and gas from the exit pipe for testing to determine the levels of S and gas yields.

Measurements

The pressure, temperature and pH were monitored using pressure gauges, mercury in glass thermometer, and the pH meter respectively. The composition of the gas was determined using the gas meter. An evaluation of the product yield based on the equation of state was also used to determine the product yield.

Data analysis

The data was analysed using exploration method in excel and SPSS packages where multiple plots were carried out in order to establish the most important trends that would result in the determination of the modified Michaelis-Menten mechanism. The First Order kinetic equation was evaluated using plots of InS versus HRT. The model fitting into data required processing found in such packages.

RESULTS

The composition of biogas was found to be mainly methane and carbon dioxide. There was a little or trace of hydrogen sulphide. The percentage of CH_4 in biogas from cow dung was 50-58 % while the rest was CO_2 (Table: 1). The composition of CH_4 in biogas from chicken manure, pig manure and water hyacinth was 70-85 %, 40-60 % and 45-55 % respectively at pH range of 6-8 and 27 ^oC. The chicken manure yielded more CH_4 than cow dung and pig manure. The alkalinity level was high in chicken manure than the rest of the substrates.

The biogas production from cow manure showed different patterns at different S concentration. As can be observed in Figure 2 the biogas production yielded highest gas volumes at 15 wt% (V15wt%) followed by the 18 wt% (V18wt%). The lowest gas volumes produced were at S concentration of 25 wt% (V25wt%) of biomass. For example, at 10 day HRT, the volumes produced were 0.72 m^3 at V15wt%, 0.64 m^3 at V18wt%, 0.52 m^3 at V8wt% and 0.2 m^3 at V25wt%. It shows that the production of biogas decreases as the S concentration of biomass increases. In another study, cattle slurry and pig slurry showed a linear decrease of methane yield with increasing organic volumetric loading rate over a wide range (Linke, 1997)[19]. It would therefore be appropriate to determine the optimum concentration in order to maximize the use of biomass. The temperature of the slurry changed by 2 ^oC difference (26-28 ^oC) in the hot and cold seasons (17-19 ^oC) at all levels of concentration while the pH changed by 2 units from pH 6 to pH 8.

Table 1: Composition of biogas

Parameter	Units	Cow dung	Pig manure	Chick. manure	Hyacinth-cow dung mixture
Methane	%	50 - 58	40 - 60	70-85	40-50
H_2S (%)	%	0.0	0.06 - 0.12	trace	trace
CO_2	%	42-50	59-94	15-30	40-45
Alkalinity	mg/L	1800-2000	1800-2500	2500-4000	1600-1800
pH	-	6-8	6.4-8.4	6.7-8.0	6-7.5
Temperature	^oC	27	27	27	27
Calorific Value	MJ/m^3	18 - 21	17 -24	18-25	16-18

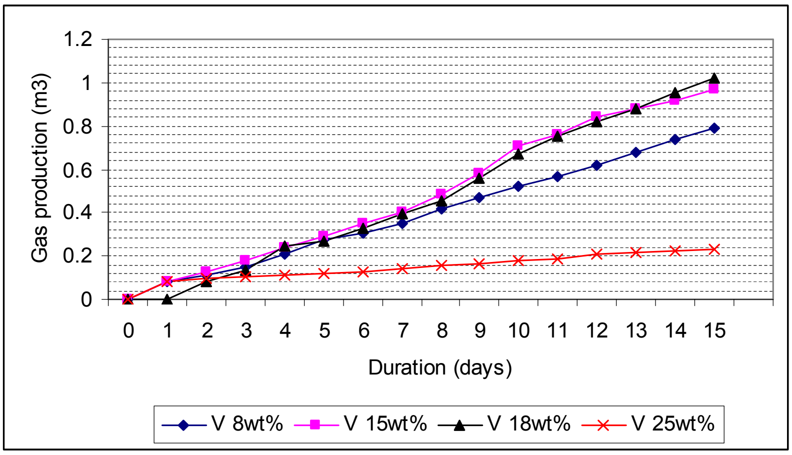

Figure 2: Production of biogas from Cow Dung

The pH change during the production of biogas from chicken manure was 7.2-7.6 for trial 1 (8 wt%) giving a difference of 0.4 units, 6.8-7.2 for trial 2 (15 wt%), a difference of 0.4 units and 6.7-8.0 for trial 3 (25 wt%), a difference of 1.3 units (Figure 3). When compared to gas production values, a jump of 1.3 units of pH produced the highest volumes of gas than a jump of 0.4 units of pH. At 5 days HRT the gas produced were 0.32 m^3, 0.10 m^3 and 0.06 m^3 for trial 3 (Trial 3), trial 2 (Trial 2) and trial 1 (Trial 1) respectively (Figure 4). The values for the 10 day HRT were 0.52 m^3, 0.16 m^3, and 0.14 m^3 respectively.These values give increments of 62.5 % for trial 3, 60 % for trial 2 and 100 % for trial 1.

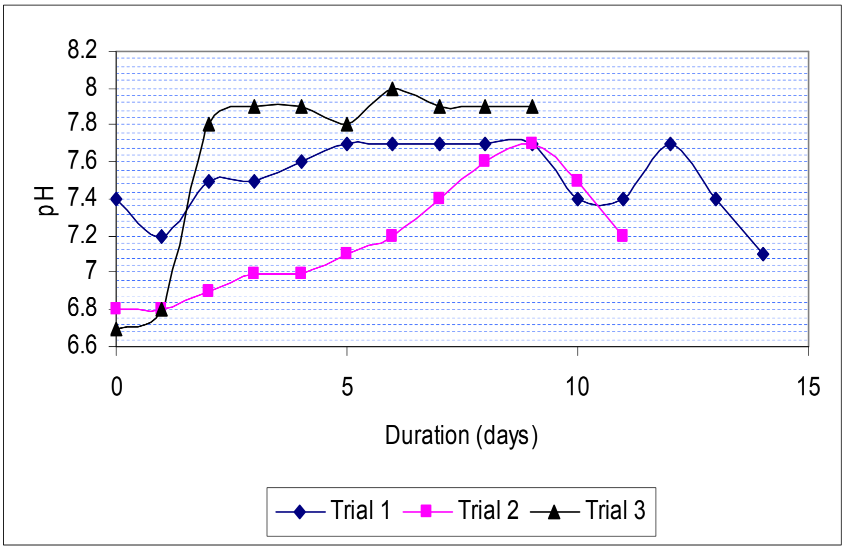

Figure 3: Changes in pH during the production of biogas from chicken manure

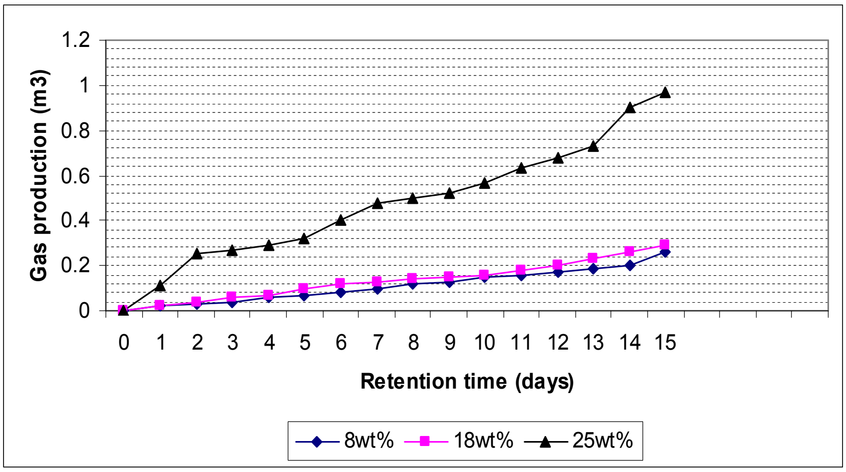

Figure 4: Production of biogas from chicken manure

In the production of biogas from pig manure, the pH dropped from 8.4 to 7 for the 40 wt% of S the first five days and remained at this value during the rest of the retention times. The pH for the 33 wt% (33wt%) solids changed from 6 to 7 during the rest of the HRTs (days). However the pH for the 25 wt% (25wt%) remained at 7 for the duration of the study. The gas production rate for the period 6 to 12 days was 0.05 m^3/day for the 33 wt%, 0.05 m^3/day for the 40 wt% (40wt%) and 0.05 m^3/day for the 25 wt% solids (Figure 5). Therefore the gas production/day was the same regardless of the concentration of solids in the slurry. If the gas production rate is the same, the increase in the level of S does not necessarily improve the yield. It means therefore that biogas yields are high at solids concentration below 25 wt% for pig manure.

The pH in hyacinth-water-cowdung mixture fell in the range 6.5 to 7 for the 1:3 and 1:4 for S:H_2O ratios (pH1:3; pH1:4). The pH for the 1:5 ratio (pH1:5) fell in the range pH 6.7 to pH 8 (Figure 6). The drop in pH was due to the utilisation of acids before the production of biogas began after three days. The production of biogas resulted in the stabilisation pH values to the level below pH 8. The conversion of S by anaerobic bacteria to acids resulted in the lowering of pH to the level where the production was favourable. The optimum pH for the production of biogas was found to be between pH 7 to pH 7.5. It is not surprising therefore that the system adjusted to pH 7 before methanogenesis began. It can also be observed that the pH began to increase on the 30th day. This means that the reduction of acid forming bacteria resulted in the restoration of pH as the production of biogas reduced until the process stopped at some point. The pH was therefore an important element.

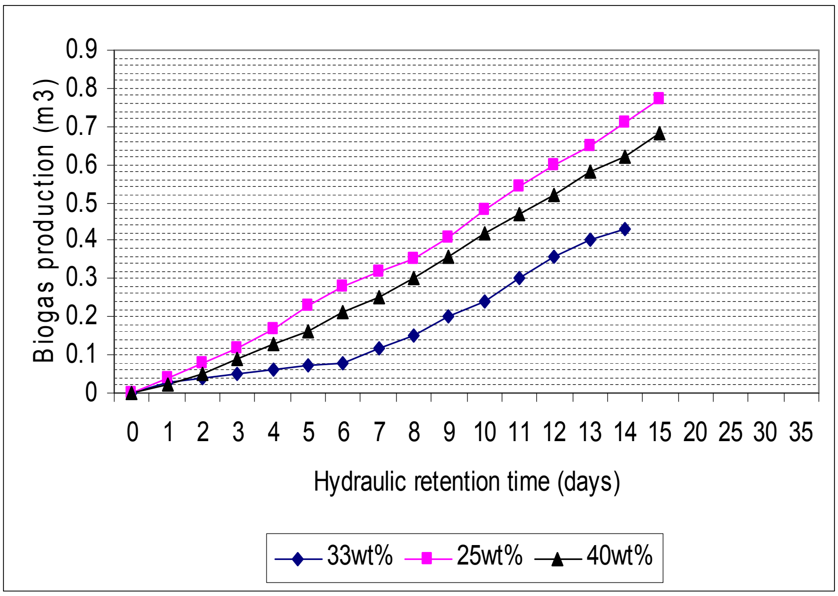

Figure 5: Production of biogas from pig manure

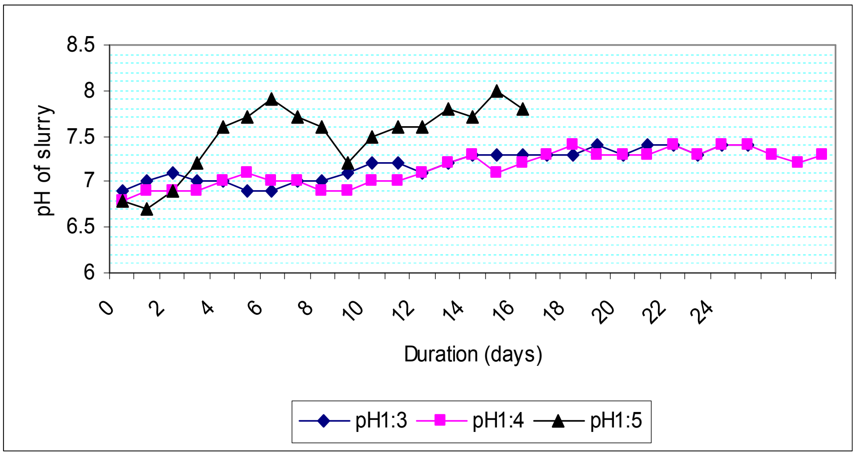

Figure 6: pH changes during biogas production using hyacinth-water-cowdung mixture

The production of biogas in the reactor resulted in the rise in pressure and volume of gas in the collector. But gas production is a function of pressure, temperature and pH. Therefore, the rate of reaction is a function of temperature according to Alhenius Law[20]. By investigating the variations of temperature, one can deduce whether the energy released during the biological reaction is significant or not. The results in Figure 7 show that the increase in HRT resulted in the increase in production. This means that the growth of bacteria increased with increase in HRT. The 1:3 ratio (Vol1:3 ratio) and 1:4 ratio (Vol1:4 ratio) of cow dung to hyacinth produced less gas than the 1:5 ratio (Vol1:5 ratio), which produced more gas. For example, the 1:5 ratio produced 0.56 m^3 than the rest (<0.2 m^3) in 10-day HRT. The presence of cow dung was to seed the process with bacteria. The water hyacinth was the major source of biogas in this mixture. However, there was a time lag before the production of biogas in the reactor could begin. This was due to the delay in the bacteria to multiply effectively in order to break up the hyacinth. A time lag of 14 days was observed in this study.

The results in Figure 8 show the variation of the yields for different substrates at different HRTs. The values of yields from the water-hyacinth-cow-dung mixture (HyacCowM) were the lowest at all levels of HRTs; the lowest value being at HRT of 1 day (0 m^3/ton) and the highest was at the 25th day (1.2 m^3/ton). The yield from chicken manure (ChickenM) exhibited the highest values at all levels of HRTs; the lowest being at HRT of 1 day (0 m3/ton) and the highest was on the 25th day (5.6 m^3/ton).

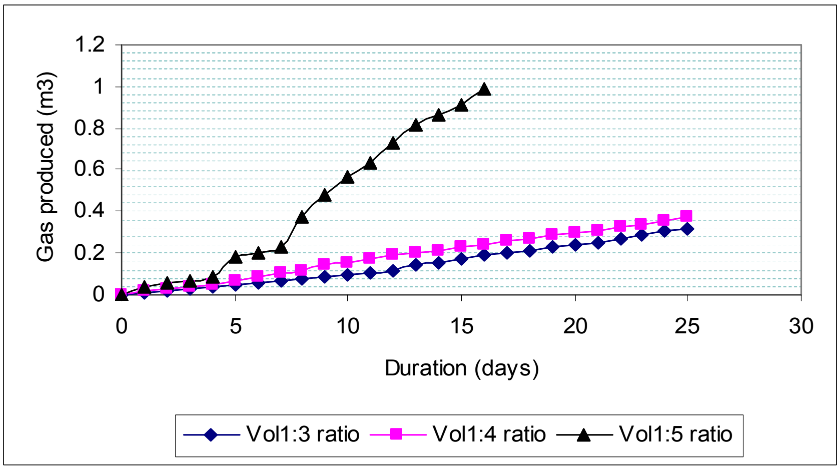

Figure 7: Gas produced from hyacinth-water-cowdung mixture

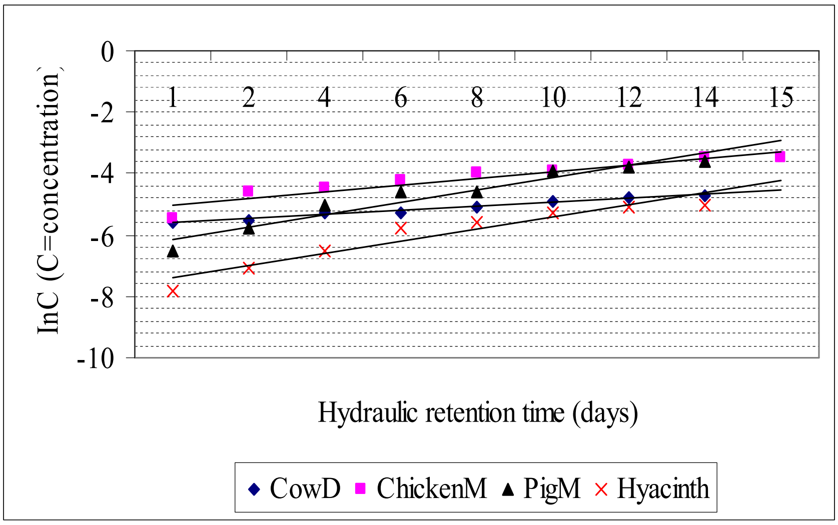

Figure 8: First Order evaluation

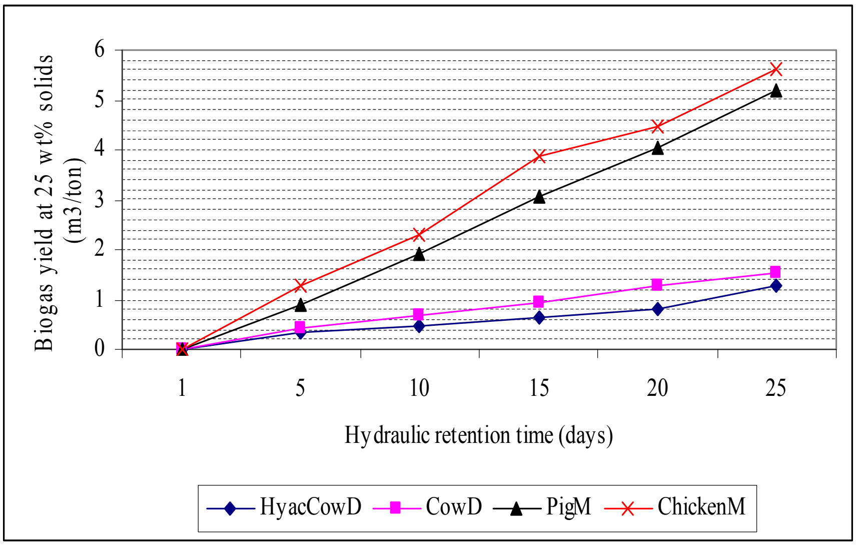

Figure 9 The variation of yield with hydraulic retention time

The reaction in the digesters followed the Michaelis-Menten mechanism as revealed in the plots in Figure 9. The plots showed First Order kinetics for all substrates; cow, pig, chicken manures (CowD, PigM and ChickenM) and hyacinth-cow-manure mixture (Hyacinth)) at desired HRT.

In terms of cost, an estimate of equivalent energy to 1 m^3 of biogas is given in Table: 3. The use of 1 m^3 of biogas would be equivalent to 4.70 kWh which translates to K4, 700. This is the highest cost when compared to that of diesel. However, the fact that there is no cost input into the procurement of organic substrates or manures, the use of biogas technology would be the cheapest at farms producing such substrates.

Table: 3 A comparison of equivalent energy and cost for 1m^3 of biogas

Biogas	Equivalent energy	*Estimated cost (ZMK)*
1 m^3	3.47 kg firewood	3,500
	1.40 kg charcoal	5,000
	0.80 L petrol	4,570
	0.52 L diesel	2,600
	0.62 L kerosene	3,100
	4.70 kWh electricity	4,700

DISCUSSION

Effect of temperature

Methanogenic bacteria, hydrolysis, acidification and methanogenesis were all influenced by temperature fluctuation as reported in another study elswhere[21]. Most of pathogens are destroyed in the thermophilic-anaerobic process which is effective against pathogenic bacteria; *faecal coliform*, *salmonella* and *enterococcus* in sewage sludge through thermophilic anaerobic digestion[22]. *Salmonella* and *Mycobacterium paratuberculosis* are inactivated within 24 hours under thermophilic conditions, while weeks or even months will be needed under mesophilic conditions[23]. Tropical conditions are in most cases favourable to bacteria as the temperatures hardly reach zero level. The temperatures attained in this study (18-30 ^{o}C) were the most favourable for the production of biogas. Any delay in production was due to slow hydrolyzing reaction, improper seeding and the growth of methane forming bacteria which was dependent on the level of solids in the slurries.

Performance of biogas reactors

A relatively lower performance was observed for the high organic loading rates per gram of volatile solids (VS) (20-30 g VS dm^{-3} day^{-1}) used which was attributed to the possible wash-out of the acidifiers at the considerably low retention times (1.25-4 days) used[24]. The anaerobic reactors can achieve chemical oxygen demand, biochemical oxygen demand, total solids and VS removal efficiencies of 55–65 or 59–68 % at HRT of 15 days with the corresponding average CH_4 production value of 0.191 l/g VS added[24]. The results of the effect of retention period on cow dung material showed that gas production was optimum at 4th and 7th weeks of production[25]. This study produced comparable result at HRT of 2 weeks.

However, digestion stability decreased when an HRT of 8 days was used (Kim *et al.,* 2006)[27]. In this study the longer the HRT the increased was the production and stability of pH at optimum concentration of solids (8-18 wt%). Pig manure can effectively be stabilized using anaerobic digestion as was observed by the reduction in smell from the digested slurry. The methane content of biogas from pig manure varies from 55 to 65% and stabilized sludge present good characteristics for use in agriculture[28]. The findings in this are in agreement with this finding. Although stored animal manures are significant sources of methane and N_2O, which have 23 and 297 times higher global warming effects when compared to carbon dioxide[29], the digested sludge is a suitable product for agricultural use particularly as fertilizer.

The biogas production was different for different substrates because the bacteria responsible for the breakdown of substrate were different. While amylolytic bacteria is good for cow dung, proteolytic bacteria is best for chicken and pig manures[31]. What is good for the farmers, based on this study, is chicken and pig manures but the supply of these substrates can be a problem at times. Cow dung users can have a continuous supply of substrate from animals on a daily basis. This is one reason that the use of cow dung can be recommended for the long term use. For large farms where there is continuous process of rearing chickens and pigs, biogas production by this method would be the best as continuous organic loading of reactors would make available adequate biogas for lighting, cooking and other uses.

First order kinetics

The results fitted well in the modified Michaelis-Menten mechanism. In all the four substrates a plot of InC versus HRT was linear with negative slope in the fourth quadrant. In a study elsewhere, when operation temperature was adjusted from 30 °C to 55 °C and the HRTs ranged from 8 to 12 days, the rate of soluble chemical-oxygen-demand removal correlated with digestion time according to the first-order kinetic model developed by Grau *et al.* (1975)[26]. In this study, the production of biogas followed the modified Michaelis-Menten model which was first order kinetics model. If the increase in production of biogas resulted in the increase in rate of soluble chemical-oxygen-demand removal then the results are in agreement.

Effect of pH

The self-adjustment of pH to levels from 7 to 8 by the slurries signified that this is the optimum pH range for the production of biogas from given materials. When the biogas production stops the volatile fatty acids begin to accumulate rapidly accompanied by pH decrease[21] as was observed towards HRTs of 10 to 15 days in the case of chicken manure and 20 to 25 days for hyacinth-cow-dung mixture. Organic loading increases acidification of slurries while the degree of acidification increases as HRT decreases[30].

CONCLUSION

Anaerobic digestion is the best method for biogas production from cow dung, chicken and pig manures and water hyacinth. The generation of biogas from biomass is dependent on the amount of acids formed which depends on the type of biomass used. The biogas production rate was found to be different for different biomasses. The yields were temperature and solids-concentration and pH dependent. The chemical reaction followed the modified Michaelis-Menten mechanism which was first order at mesophillic and psychrophillic temperatures. Biogas technology can be a viable development option for developing countries for energy production and substitution if properly managed and marketed.

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