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Energy Production and Pollution Mitigation from Broilers Houses on Poultry Farms in Jamaica and Pennsylvania

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Abstract - **Increasing energy demands and diminishing fuel supplies have left nations desirous of avenues to minimize their reliance on traditional energy sources and a need to infuse supplementary technologies. Biogas technology is one such trajectory that can contribute to the reduction of dependency on fossil fuel as well as allay environmentally problems. The University of Technology, Jamaica (UTech) and Pennsylvania State University (PSU), in pursuit of investigating the potential of biogas in the agricultural sectors of Jamaica and Pennsylvania, United States, sought to use biogas generated from livestock (chicken, swine and cow) waste as an alternative energy source. A 3^2 factorial design resulted in the construction of seven (7) laboratory scale biodigesters, each with a volumetric capacity of 8 L. Variations of the ratio, (i.e. chicken manure in combination with pig or cow manure) and retention time enabled the monitoring of biogas flow-rates, temperature, pH, residual mass along with percentage methane production. From the data collected mathematical models relating the flow-rate and percentage methane concentration were deduced in order to facilitate the design of a pilot scale digester on the Silverdene poultry farm in the Parish of St. Catherine, Jamaica.**

Index Term **-** Anaerobic digesters, Mathematical models, Chicken, pig and cow manure

INTRODUCTION

Anaerobic digestion (AD) is a natural biological decomposition of organic material in a controlled environment in the absence of oxygen (Matthew et al, 2004). In this oxygen-depleted zone, bacteria are employed to decompose the proteinaceous and carbonaceous materials producing biogas and sludge (Mortley, 1989). Waste from animals such as pigs, cows and poultry are often improperly disposed or used as soil conditioners and fertilizers. Poultry farming is the largest and fastest growing subsidiary within the agricultural sector in Jamaica, consequently, generating large volumes of waste. This combined with manures from cows and pigs, can arguably be a major caused of some of the environmental concerns outlined by the local authorities (Department of Research and Development, Ministry of Agriculture, 1980). As such, this research seeks to design and implement an anaerobic digester that will serve two purposes: reduce environmental pollution by utilizing the waste and produce biogas which can be used to generate energy for the farm.

Objectives

- To evaluate the biogas quality produced from feed variations
- To determine the most suitable mathematical model which satisfies the design parameters and suitably predicts trends of the conversion of organic material to biogas in the anaerobic process.
- To design a pilot scale digester with the aid of a simulation tool

PROPERTIES OF BIOGAS

Depending on the type of raw material, biogas contains on average 50-70% methane, 30-40% carbon dioxide, 1-2% nitrogen, 5-10% hydrogen, and trace amounts of hydrogen sulfide and water vapor (Karki, 1985; Sustainable Development Department (SD) and Food and Agricultural Organization of the United Nations (FAO), 1997). Lusk (1998) indicates that the methane content lies in the range 55-80%. The large percentage of methane accounts for the combustible nature of the biogas. It is invisible in daylight and burns with a clear blue flame without smoke. It produces more heat than wood and kerosene (approximately 22, 9000 kJ/m^3) and is lighter than air (Energy Education Unit, 1984). Table 1 details biogas characteristics (Robbins, 2005).

TABLE 1
BIOGAS CHARACTERISTICS

Biogas	Odor	Exposure Limit (ppm)	Environmental Impact
Methane (CH4)	None	1000	Greenhouse gas; explosive at 15% mixture with air
Carbon dioxide (CO2)	None	5000	Greenhouse gas
Ammonia (NH4)	Pungent	10	Contributes to acid rain when oxidized
Hydrogen sulphide (H2S)	Rotten eggs	10	Highly flammable; acid rain when oxidized to sulfur

The data presented in Table 2 shows the characteristics of biogas for fresh dung in tropical climates (Dornberger et.al, 2005).

TABLE 2
BIOGAS PRODUCTION BASED ON TYPE OF ANIMAL DUNG

Animal Dung	Biogas Production (liters biogas/kg dung)
Cattle	40
Pig	30
Chicken	70

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Loading Rate, Retention Time and Digester Size

According to the FAO (1985) the loading rate is the amount of raw material fed to the digester per day, per unit volume of digester capacity and is usually expressed in volatile solids (VS), total solids (TS) or fixed solids (FS). If the digester is over fed, there will be an accumulation of acidity and the production of gas is inhibited, similarly if the digester is underfed gas production is also repressed (Fry, 1973). Consequently, the loading is dependent on temperature, retention time and digester size. The retention time is simply the average time the material fed remains in the digester. In the case of continuous feed it is calculated by dividing the total volume by the volume of daily inputs (Fogler, 2002).

TABLE 3
RELATIONSHIP BETWEEN RETENTION TIME AND TEMPERATURE WITHIN DIGESTERS

Digester Temperature		Retention Times(days)
^{0}C	^{0}F	
16	60	56
27	80	30
37	100	24
48	120	16

MATHEMATICAL MODELLING OF ANAEROBIC DIGESTION

Chynoweth et al. (1998) defines models as mathematical expressions that are used to describe the interactions between various microbial populations involved in the process including: substrate utilization rates, microbial growth rates, product formation rates and physico-chemical equilibrium relationships. However, Hamelers (2004) described mathematical models as ‘black box models’ where the input and output data are known and the transfer function that creates the output must be found. Whatever their description the use of mathematical models produces faster results and are cheaper when modelling systems and simulating their operation than to perform laboratory experiments. The application of sophisticated methods of process control is only possible if mathematical models are available for the system to be optimized (Schuruscher and Wandrey, 1991).

Extensive studies and mathematical techniques have been used to assist the comprehension of microbial processes within reactors, which convert organic material to biogas. According to Florentino, et al. (2000), these models can be used to predict various parameters in the anaerobic digestion process (gas volume, retention time, temperature, etc), which could help biodigester efficiency in methane production.

Martinhão, (1981) indicates that anaerobic biodigester mathematical models were formulated by observing bacteria species and environments and extracting the main variables which influence their growth or reduction. These models describe substrate variation in a biodigester, in which it is assumed that bacteria growth depends on substrate quantity, and that substrate consumption is viable. According to Florentino et al. (2000) it was Merkel, (1981) who estimated approximate theoretical values to calculate mass transfer by analyzing experimental data from a mathematical model which described the anaerobic digestion process. Simple models

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have been studied in order to aid with bio-digestion analysis as well as serve as a process optimization tool to analyze experimental data.

Materials and Methodology

Seven anaerobic digesters were constructed using polyvinyl chloride (PVC) material to accommodate eight liters (8L) of slurry (see Figure 1). The inflow material was diluted on a 1:6 feed to water ratio basis. The digestion is filled to three-quarters (3/4) of the digester volume inclusive of seed material and the remaining quarter (1/4) is empty headspace for the accumulation of gas. A three level, two factors experimental design (as shown in Table 4), was deduced which resulted in nine (9) experiments for both sets of feed variations ('chicken and cow' and 'chicken and swine'). This design was based on possible variables that from literature mainly influenced the system's operation in order to achieve desirable responses such as flow rate of biogas, residual mass (mass in digester during retention time), the methane component of the biogas, pH and temperature.

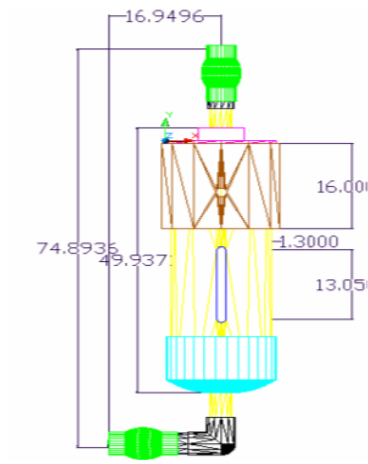

FIGURE 1: SCHEMATIC OF BENCH SCALE DIGESTERS

The pH and temperature were examined on a weekly basis and kept within specific operational conditions. Temperature: 27-35^{o}C (Fry, 1970; Mathew et al, 2004; Mortley, 1986) and pH: 6.6 - 7.2 (Forrest, 1987; Karki, 1985; Robbins, 2005). In addition, adjustments were done to maintain constancy and consistency within the digesters. These included: changing the orientation of digester to obtain maximum sunlight exposure and adding of sodium hydroxide (NaOH) to increase pH. The digesters were also weighed on a weekly basis to ascertain their residual mass. Once in operation, flowrate was recorded three times on a daily basis and averaged to complete the experimental design. The StatEase Design programming software was used to assist in the formulation of design models, which will be used with for scale-up calculations for a pilot scale digester in the next phase of the research.

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TABLE 4
LEVELS AND FACTORS FOR THE FACTORIAL DESIGN

Variables	
Ratio	**Retention Time (days)**
75: 25	20
50: 50	40
60:40	60
100: 0	Control

RESULTS AND DISCUSSION

As is shown in Figure 2, the percentage of methane generally increases with time; however, there is no linear correlation. In experiments (1), (2) and (3) (20 days operation), the biogas flowrate produced is relatively higher with respect to the remaining experiments although the quality of the gas in terms of methane yield was much less. This is consistent with literature, which according to Mortley (1996) suggested that the hydrolytic and acetogenic bacteria are actively converting the substrate during this period. In the later stage of the experimental process the flow rate of the biogas is considerably reduced with higher percentage methane. This period could be attributed to activities of the methanogenic bacteria. The control digester in which, the raw material is maintained at 100 percent chicken manure produced relatively high yields of biogas and methane as tabulated (see Table 5).

The quantities of the sludge that remain in the digester after the fermentation period showed no proportionality with the biogas yield, in general. According to the results shown in Figure 3 only the experiments that are considered in the 40 days retention period demonstrates a linear relationship between the biogas, methane yields and sludge remaining.

The inconsistency of the results may be attributed to the constraints under which the project operated. A constant temperature could not be maintained due to the built of the digesters and as such when it rained the temperature within the digesters were noticeably lower than normal. However, it was desirous to assimilate real conditions therefore no efforts were made change the setup, even though, this would normally be expected at the pilot scale level. Additionally, no assessment of the animals' feeding material was carried out to verify the constituents or whether there were inhibitors present that could have posed difficulty during the fermentation process.

The microorganisms proposed by the literature that would perform the digestion were not verified at each stages of the process and therefore, the consortium responsible for the breakdown remains unknown.

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TABLE 5
RAW MATERIAL – CHICKEN AND COW MANURE

Experiment #	**Ratios**	**Retention Time**	**Biogas Yields- l/day**	**% CH_4 / biogas [a]**	**Sludge Remaining (g)**	**Digester Internal Temperature ^oC**
1	75:25	20	2.73	47	119	27
2	60:40	20	2.61	43	104	28
3	50:50	20	2.19	40	112	25
4	75:25	40	1.41	55	187	29
5	60:40	40	1.52	52	165	30
6	50:50	40	1.89	49	143	32
7	75:25	60	1.31	69	355	29
8	60:40	60	1.27	63	234	27
9	50:50	60	1.30	64	221	29
Control	100:0	20	2.45	51	243	28
Control	100:0	40	2.02	57	334	25
Control	100:0	60	1.14	63	401	31

[a] – Percentage of methane per biogas produced

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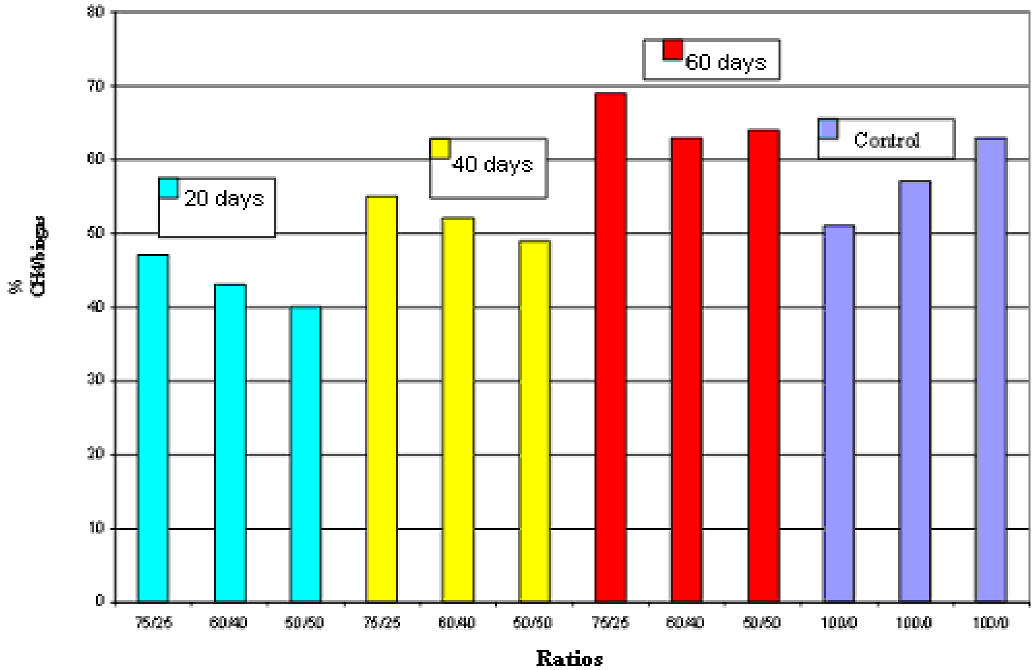

FIGURE 2: PERCENTAGE METHANE VERSUS RATIO

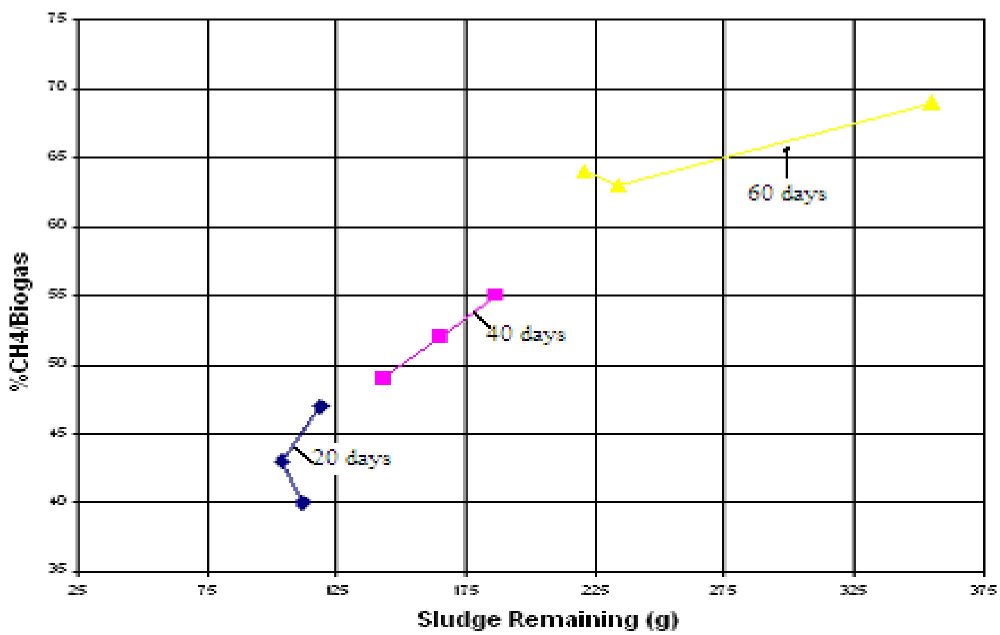

FIGURE 3: RELATIONSHIP BETWEEN METHANE PRODUCED AND SLUDGE REMAINING FOR EXPERIMENTS WITH CHICKEN AND COW MANURE

The chicken and swine experiments showed contrary results to that of the chicken and cow combinations as depicted in Figure 4. The results suggested that the biogas and methane yields exhibit proportionality to sludge residue. The contents of the manure from pig may be responsible for such an action however; this is yet to be proven. With careful analysis of the manures as well as the animals' daily nutrition more conclusive data could be displayed, thus making a link between the behaviour of manures when digested. It is also possible that chicken and swine manures in combination contain inhibitors that retard their breakdown.

TABLE 6
RAW MATERIAL – CHICKEN AND SWINE MANURE

Experiment #	**Ratio**	**Retention Time (days)**	**Biogas Yield - L/d**	**% CH_4 / biogas [a]**	**Sludge Remaining (g)**	**Temperature ^{o}C**
1	75:25	20	2.78	41	110	27
2	60:40	20	2.92	51	124	28
3	50:50	20	3.01	43	121	25
4	75:25	40	2.23	57	182	29
5	60:40	40	1.30	68	175	30
6	50:50	40	1.49	58	167	32
7	75:25	60	1.12	65	281	29
8	60:40	60	1.27	59	209	27
9	50:50	60	1.25	72	261	29
[b] Control	100:0	20	2.45	62	265	28
[b] Control	100:0	40	2.02	59	258	25
[b] Control	100:0	60	1.14	63	423	31

[b] – The control experiments are the same as those represented in Table 2

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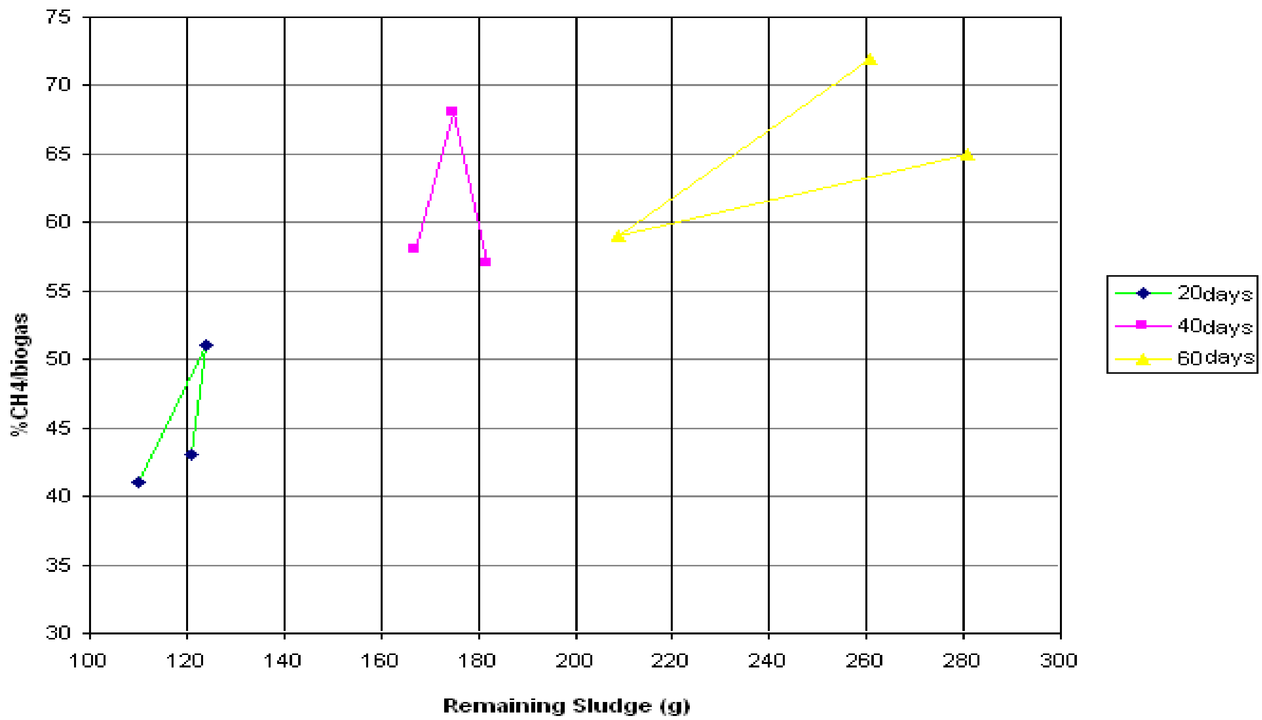

FIGURE 4: RELATIONSHIP BETWEEN METHANE PRODUCTION AND REMAINING SLUDGE FOR CHICKEN AND PIG

Models

The models developed for chicken and cow experiments using StatEase, suggested that both the methane production and flowrate varied linearly with respect to retention time and ratio. This confirms the hypothesis and concurs with literature, when particular operational parameters are managed properly. In the case of the methane production both retention time and ratio significantly contributed to the outcome, that is with a higher retention time and ratio of chicken manure (main feed material), the methane production would be higher as explained by the linearity. However, for the flow rate, only the ratio is significant. It was expected that the both retention time and ratio would influence the flow rate, but the results conflicts with this theory thus more experimental and statistical analysis may have to be done to confirm or deny the results presented.

The combination of chicken and swine, showed that both retention time and ratio are significant for methane production but a significant model for flowrate could not be deduced, possibly due to experimental errors or limitations of the software used.

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The models deduced are:

Chicken and cow:

Methane Production = 44.90351 + (0.066667 ×Retention time) + (40.877193 Ratio)
Flowrate = (- 0.051740) + (2.6097×10^{-4} × Retention Time) + (0.1311913 × Ratio)

Chicken and pig:

Methane Production = 40.37719 + (0.16667 ×Retention time) + (42.63158 ×Ratio)

Digester sizing:

Volume = 70.21m^3
where S_d = loading rate of slurry and
R_T = Retention time (optimum - 60 days)
Since the volume and the retention time are known then S_d may be calculated

$$S_d = V_d / R_T = 70.21\,m^3 / 60\text{days} = 1.17\,m^3 / day$$

Conclusions

This investigation emphasizes the concept of animal waste combinations for biogas production outlining its feasibility and potential for a viable alternative source of energy. The findings indicate that with optimal operating conditions for the bio-digesters, chicken manure in combination with other animal waste (cows and pigs) may be used as a means of producing electricity. This would aid in the reduction of environmental pollution as well as expenditure on electricity. There would, however have to be more extension research in this area based on the limitations identified. This fused with the efforts of the community in and around the farm to practice good disposal and/or usage of the abundantly useful material, animal waste.

The design (as shown above) and construction of a pilot-scale bio-digester will be done to confirm the findings of this investigation in order to fully explore the potential of waste combination for confirm energy production.

Recommendations

Other experiments must be carried out using animal waste in combination with vegetative material to determine whether satisfactory methane production can be achieved.

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