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Experimental and Full-scale Plant Assessment of Biogas Production via Anaerobic Co-digestion

Abdulkadir M. Zabi[1], Abdulfatai A. Adisa[2], Umar A. Aji[3], Vincent C. Ntichika[4], Madu D. Gadzama[5], Ebube P. Nwadiokwu[6]

[1] *Department of Energy Systems Engineering, Cyprus International University, Nicosia, Cyprus*
[2,4] *Department of Chemical Engineering, University of Lagos Nigeria*
[3] *Department of Science Technology, Waziri Umaru Federal Polytechnic, Birnin Kebbi, Nigeria*
[5,6] *Dangote Fertili1ser Company, Nigeria*

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Abstract - Biogas production from anaerobic digestion of organic waste is an important renewable energy source with great potential of replacing fossil fuels for heat and electricity generation. However, efficient anaerobic digestion process and energy conversion technology must be ensured for better biogas yield and energy generation. The present study involves experimental assessment of biogas production from anaerobic co-digestion of biomass feedstock. The experimental stage involves the co-digestion of livestock manure with slaughterhouse waste and vegetable waste, different sets of experiments were conducted at mesophilic condition of 37^o C, 25 days of retention time and utilizing water displacement experimental setup. The biogas yields obtained for the co-digestion of Cow dung + Poultry manure (S1), Cow dung + Sheep manure (S2), Slaughterhouse waste + Poultry manure (S3), Sheep dung + Poultry manure (S4), Poultry manure + Whey (S5) and Vegetable waste + Cow (S6) are 0.0236m^3/kg, 0.0231m^3/kg, 0.0264m^3/kg, 0.0234m^3/kg, 0.0266m^3/kg and 0.0191m^3/kg respectively. These values are acceptable values of biogas yields for livestock manure co-digestion. However the co-digestion revealed that the biogas yields obtained are slightly above the minimum reported value for co-digestion of manure slurry, this is due to the nature of the experimental setup used. According to the simulation conducted with engineering equation solver software on the modeled biogas plant, energy efficiency of 42.55% was achieved by integrating the digestion process to the steam cycle which provides better heat utilization.

Keywords: -Biogas, Biomass, Anaerobic Co-digestion, Livestock manure, Slaughterhouse waste, Vegetable waste, Whey and Energy Efficiency.

I. Introduction

Energy generation and consumption has been a major issue globally for decades, about 80% of the total world's energy generation is from the fossils fuels. Environmental and economic problems associated with the utilization of fossil fuels has make it paramount for each country to search for an alternative source of energy other than the fossil based. The Kyoto protocol and the Paris agreement signed by many countries for the global preservation have shown improvement in many countries in the utilization of the renewable energy sources [1]. These sources are produce naturally and do not have any environment effect upon utilizing, they include solar energy, wind energy, hydro and biomass. Solar, hydro and
wind energy are suitable in certain region of the world and their generation is intermittent with the need. Biomass has great advantage over all renewable sources because of its availability everywhere in the world and round clock generation [2]. Municipal solid waste, agricultural feeds, industrial waste, agricultural waste, sewage sludge, livestock manure etc. are termed as biomass. In the advanced countries large amount of waste are generated due to population and poor recycle, this is a great threat to the wellbeing of both humans and animals. Different energy conversion techniques have developed for the conversion of each biomass to a useful energy. Municipal solids wastes are majorly incineration, pyrolysis and gasification process by generating thermal energy and subsequently electricity using the steam or gas cycles. Livestock manures, sewage sludge and agricultural residues undergo anaerobic digestion process to generate a clean gas called biogas which when properly process can be used in place of natural gas mechanical systems [3]. Anaerobic digestion of biomass is a bio chemical process that involves the conversion of organic feeds waste like livestock manure, agricultural waste, food waste etc to biogas through fermentation process. This fermentation is performed in the absence of oxygen by different bacteria in stages. The process leads to the formation of biogas which primarily consists of methane (CH_4) and carbon dioxide (CO_2) other are like hydrogen sulphide and ammonia gasses are found in traces [4]. Biogas constitutes 50 – 70% methane, 30 – 50% carbon dioxide and small traces of other gases like hydrogen sulphide and ammonia. This gas can be utilized for the production of power in a large scale, for vehicles and also domestic heat source. Biogas if upgraded to 90% methane and compressed can be in internal combustion engines in place of natural gas [5].
Operating factors of the digestion process influences the performance and the productivity of biomass feedstock. Temperature of the process, pH value, retention time, organic loading rate and nutrient ratio are the main factors that affect anaerobic digestion process. Methanogenic bacteria are very sensible to the temperature of the system, temperature range of 35^o C to 37^o C and 45^o C to

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55^o C is the optimum for gas production at mesophilic and themophilic conditions respectively. pH value is maintained around neutral and alkaline, 6.5 to 8 pH value is appropriate for the digestion process, acidic system inhibits the gas production totally [6]. Loading rate and retention time are dependent on the nature of the feeds stock and the temperature, thermophilic condition supports loading and lower retention time.

Many studies have been conducted over the years on feed pretreatment, co digestion, improvement of gas yield of feedstock, gas purification and upgrade to achieve a better anaerobic digestion process and widen the application of biogas. The most commonly used purification procedures are the Absorption process, Physical process and Hybrid process, these processes involves both physical and chemical cleaning and are reported to achieve 95 to 99% of pure methane, with this quality bio methane are release in natural gas pipelines or filling stations especially in Sweden and Switzerland [7]. A pretreatment process on biomass feedstock before digestion shows improvement in the total yield per unit mass of substrate. Seeding, metal addition, particle size reduction, thermal/thermochemical pretreatment, ultrasonic pretreatment and alkali pretreatment are the pretreatment processes majorly used. These pretreatments improves rate of biogas production and volatile solid reduction.

Biogas generation yield strongly depends on the type and the combination of biomass used for the anaerobic digestion, thus it is essential to study different combination of biomass feed in order to assess the best feed combination. Also, energy efficiency of heat and power generating systems is a very significant measure of assessing the economic feasibility of new or operating plant. The aim of the study is to evaluate the potentials of biogas generation from anaerobic digestion of different biomass feedstock and to conduct energy analysis of a modeled biogas plant using EES software.

II. Materials and Methods

2.1 Biomass Feedstock (Sample Collection and Processing)

The experiment was carried out using six organic material samples namely cow dung, sheep dung, poultry litter, vegetable waste, slaughterhouse waste and whey, all collected in North Cyprus. Cyprus international university research laboratory was used for the purpose of this study.

2.1.1 Manure (Cow, Sheep, Poultry)

Fresh cow dung, Sheep manure and Poultry litter were collected from a dairy farm located in Mandara, lefkoşa. Indigestible parts of the samples were discarded before storing the sample in an air tight container to avoid oxygen penetration. The samples were stored in a refrigerator to strand microbial activities before initiating the experiment.

2.1.2 Vegetable Waste

Vegetable waste sample was collected from Lemar super market located in Cyprus international university, the sample comprises of aged tomato, potato, onions, lettuce, and fruits peelings. The sample was processed and larger parts were cut into smaller pieces for easy fermentation.

2.1.3 Slaughterhouse Waste

One kilogram sample of slaughter house waste was collected from Teşkent slaughter house located in haspolat, North Cyprus. The sample consist majorly intestines which were cut ınto pieces for better digestion and stored in a refrigerator before starting the experiment.

2.1.4 Whey

Three liters of whey sample was collected from Pak Sut, a milk processing company located in haspolat, North Cyprus. The sample was stored in a refrigerator to strand all microbial activities before starting the experiment.

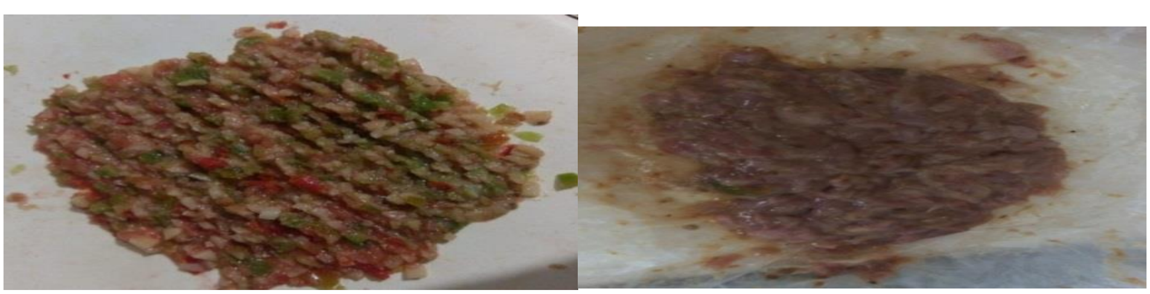

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Fig. 2.1: Biomass Feedstock after processing

2.2 Experimental Setup

The setup consists of three conical flasks, measuring cylinder, connection tubing and stoppers. 500ml conical flask was used as the digester; 250ml conical flask was used as hydrogen sulphide removal unit and water displacement unit. The measuring cylinder was used to measure the amount of water displaced. The experimental technique employed for this study is the water displacement technique. Evolved biogas from the digester moves through the hose to the next conical flask which contained 200ml of 3M NaOH solution, the biogas bubbles through the solution with hydrogen sulphide and part of carbon dioxide trapped. The biogas then moves to the next conical flask containing water and displaced it. So the amount of biogas produced is determined by the quantity of water displaced by the biogas.

Fig. 2.2: Experimental Setup

2.3 Methodology

The experiments involves six sets of setup; Cow dung + Poultry manure (S1), Cow dung + Sheep manure (S2), Slaughterhouse waste + Poultry manure (S3), Sheep dung + Poultry manure (S4), Poultry manure + Whey (S5) and Vegetable waste + Cow (S6) co-digested in 1:1. Sixteen (16) grams each of cow and poultry manure were weighed on a measuring scale. The two samples were mixed together and diluted with 368ml distilled water to achieve 8% total solid dilution [8]. The sludge was stirred vigorously to ensure homogeneity. pH value and COD of the sample were measured before starting the digestion. The sample was transferred to a 500ml conical flask which was used as the digester and air was flushed out of the system using nitrogen gas. Temperature of the digester was maintained at 37^{o} C using hot plate. The same procedure was employed for all the six setups.

2.4 Pre-Digestion Test

2.3.1 Total Solid (TS) Analysis

This test measures the actual total solid content of the samples; it involves evaporating the sample in a weighed dish and drying in an oven at 105^{0}c for 1 hour. The total solid content is the weight of the sample after the drying.

$$\% \text{ Total solids} = \frac{(A-B)}{(C-B)} \times 100 \quad (1)$$

Where; A = weight of dried sample + dish (g)

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B = weight of dish

C = weight of wet sample + dish

2.3.2 COD Analysis

This test was conducted using the COD test kit (LCK 514), the kit contains 25 bottles of dichromate reagent which are automatically detected by the spectrophotometer with the help of the barcode on them. The test was carried out by injecting two milliliter (ml) of the organic sample into the COD test bottle. The bottle was then heated for two hours at 148°C. After the heating, the bottle was carefully clean and inverted twice. Sediments in the bottle were allowed to settle before inserting the bottle in the spectrophotometer. The bottle was automatically detected and the COD value of the sample displayed digitally in mg/l. The same test procedure was done for all the samples.

2.3.3 Daily pH and Biogas Production Measurement Procedure

5ml of the sample is withdrawn from the experimental setup daily for pH measurement using syringe. The pH is measured and recorded. The 5ml sample is injected back to the experimental setup after measurement. Biogas daily production was measured by checking the change in the amount of water displaced by the gas daily. The same procedure was repeated daily across the retention time.

2.4 Full-Scale Biogas Plant Energy Efficiency Analysis

Large scale biogas systems requires external heat source for maintaining the required digestion temperature. The modeled biogas plant used for this study involves integration of biogas generation unit with energy conversion system. Energy analysis of the modeled biogas plant was conducted using EES software by considering energy balance of each stream involved in the system.

2.4.1 Full-Scale Biogas Plant System Description

The modeled system consists of mixing tank, anaerobic digester, biogas boiler, pumps, steam turbine, condenser and one open feed water heater (OFWT). Biogas generated from the digester was used as fuel in the biogas boiler to generate steam. The steam generated was used to drive a steam turbine, extraction of steam from the turbine was used for maintaining the digester temperature.

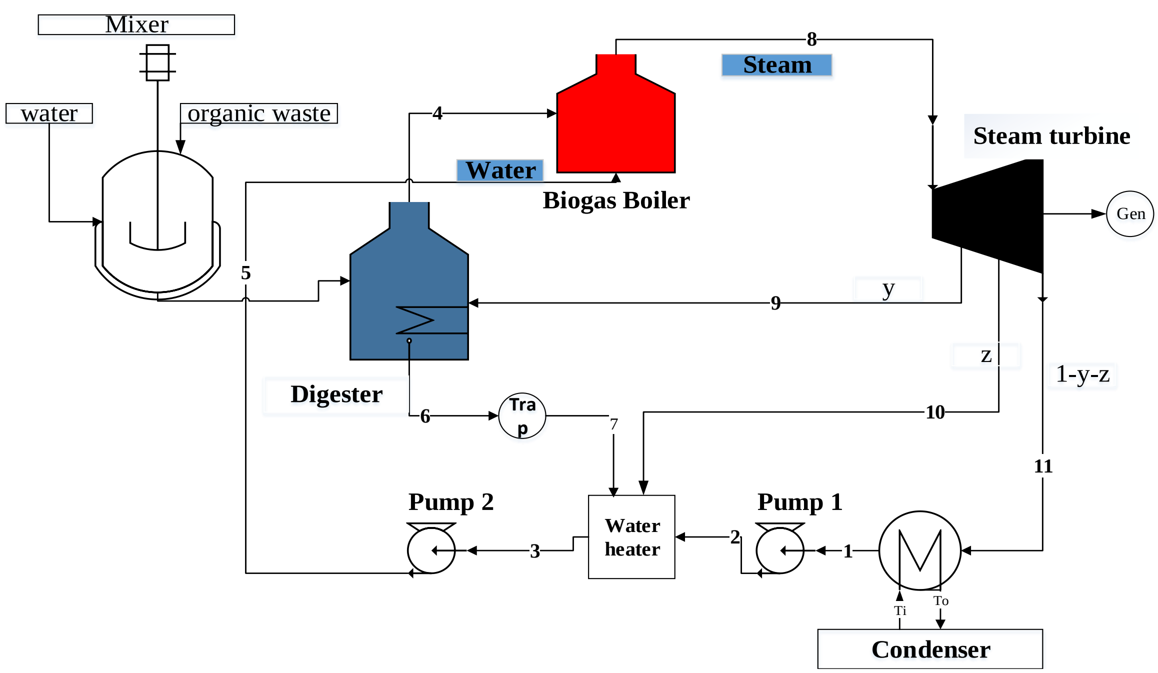

Fig. 2.3: Modeled Biogas Plant

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2.4.2 Simulation Methodology

Engineering equation solver software (EES) was used for the analysis to obtained variation of digester heat consumption with thermodynamic efficiency. The fluid and the operating conditions of the power cycle are first specified on the software. Thermodynamic expression and operating conditions of each unit process will be written on the software. Each process unit is connected to its preceding unit by equation relating them written in EES code. The code run and results displayed on result bar. Effect of heat consumed by the digester on thermal efficiency will be examined by varying the values of the desired parameter and running the code.

2.4.3 Thermodynamic Equations

The thermodynamic expressions for each unit process were written in EES code

Biogas Digester;

The energy requirement for the digester is evaluated by the amount of heat consumed for maintaining the digestion temperature which is given as;

$$Q_{digester} = \dot{m}_9([h_9]-[h_6]) \quad (2)$$

Biogas Boiler;

The heat generated by the combustion of the biogas in the boiler is given by;

$$Q_{in} = \dot{m}_{biogas} (LHV) (\eta_{comb}) \quad (3)$$

Energy balance across the biogas boiler is expressed as;

$$\dot{m}_{biogas} (LHV) (\eta_{comb}) = \dot{m}_{water} ([h_8]-[h_5]) \quad (4)$$

Steam Cycle Equations;

The steam cycle efficiency integrated with the biogas digester is expressed as the ratio of net work produced by the steam cycle plus heat consumption of the digester and the heat of combustion produced in the biogas boiler [9].

$$\eta_{th} = \frac{Wnet + Qdig}{Q_{comb}} \quad (5)$$

Where:

$$W_{net} = W_{st} - W_{pumps}$$

$$W_{st} = [h_8] - (y[h_9] + z[h_{10}] + (1-y-z)[h_{11}]) \quad (6)$$

$$W_{pumps} = \dot{m}_3 ([h_5] - [h_3]) + \dot{m}_1 ([h_2] - [h_1]) \quad (7)$$

Condenser Equation;

For the condenser, the heat balance is expressed as:

$$\dot{m}_{condenser} Cp_{water} (T_{out} - T_{in}) = \dot{m}_{11}([h_{11}] - [h_1]) \quad (8)$$

III. Results and Discussion

3.1 Livestock Manure Digestion Results

The experimental stage of the study was conducted using six different setups. The substrates used are as follows; Cow dung + Poultry manure (S1), Cow dung + Sheep manure (S2), Slaughterhouse waste + Poultry manure (S3), Sheep dung + Poultry manure (S4), Poultry manure + Whey (S5) and Vegetable waste + Cow (S6).
The total solid content, COD and pH of the mixtures were analyzed by the method prescribed in the methodology section.

3.1.1 Total Solid Content Analysis

The total solids for Cow dung + poultry manure (S1) mixture was calculated to be 48% as shown below.

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A = weight of dried sample + dish (g) = 42.55g

B = weight of dish = 35.50g

C = weight of wet sample + dish = 45.50g

$$\% \text{ Total solids} = \frac{(A-B)}{(C-B)} \times 100$$

$$= \frac{(40.30-35.50)}{(45.50-35.50)} \times 100$$

= 48 %

The same evaluation was done for S2, S3, S4, S5 and S6. The total solids were found to be 46%, 42%, 56%, 76% and 47% respectively.

Sheep dung + poultry (S4) manure mixture has the highest total solids because the samples were almost dried at the time of collection. Cow dung was fresh at the time of collection so it has more than 50% of liquid content, but after mixing with poultry and sheep manure in half with half ratio the moisture content decreases.

Table 3.1: Pre digestion test results

	S1	S2	S3	S4	S5	S6
Total solids (%)	48	46	42	56	76	47
pH (slurry)	7.08	8.45	7.15	8.00	7.03	7.46
COD (mg/l)	30700	31100	28700	24700	29000	27200

The total solid content is quite good for biogas production as its represent the both organic and inorganic portion of the sample. The initial pH of the six experiments shows alkalinity which is the preferred concentration for biogas production. However, the pH value of 8.45 for S2 is slightly close to 8.50 value which is considered as unwanted pH value for anaerobic digestion because it is high enough to retard acidiogenesis process and subsequently stops the biogas formation [10].

The higher the COD value of a sample the higher the biogas production expected. For all the experiment involved here COD is greater than 15000mg/l which is the minimum value for liquid manures according to many researchers [11].

The initial COD of the diluted samples of the chicken and whey are within the expected COD range for liquid manures, the higher the chemical oxygen demand the greater biogas production potentials the substrate will have at standard digestion condition [12].

3.1.2 Biogas Yield

The biogas yield of each experimental setup was evaluated using this relation;

$$\text{Biogas yield} = \frac{amount\ of\ biogas\ produce\ \ (ml)}{amount\ of\ total\ solids\ of substrate\ used\ \ (g)}$$

16 grams each of cow and poultry manure were weighed on a measuring scale. The two samples were mixed together to form 32grams of substrate before diluted with 368ml distilled water to achieve 8% total solid dilution. There by making 400ml of slurry as the experimental working volume.

The amount of substrate used is 32g, considering the amount of total solids of the mixture;

32 * 0.48 = 15.36g

Amount of total solids of substrate used is 15.36g

For Cow dung + poultry manure (S1) mixture, the total amount of biogas produced is 362.5ml which is equivalent to 362.5cm^3.

$$\text{Biogas yield} = \frac{362.5}{15.36}$$

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$= 23.6 cm^3/g$

$= 0.0236\ m^3/kg$

Total amount of biogas produced for S2, S3, S4, S5 and S6 are 340ml, 355ml, 418ml, 385ml and 288ml respectively. The same biogas yield computation was performed for S2, S3, S4, S5 and S6 and was found to be $0.0231 m^3/kg$, $0.0264 m^3/kg$, $0.0234 m^3/kg$, $0.0266 m^3/kg$ and $0.0191 m^3/kg$ respectively.

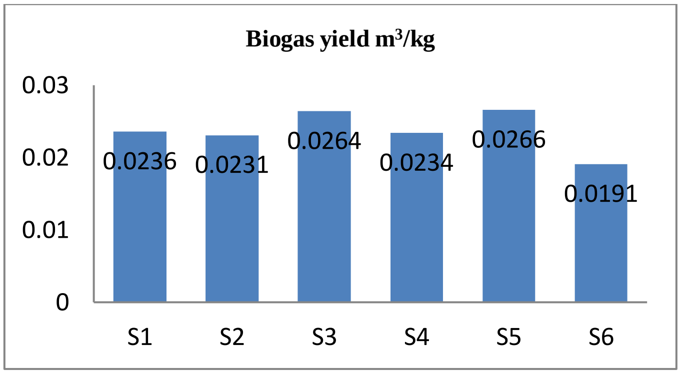

Fig.3.1: Biogas yield

The biogas yields obtained are slightly above the minimum reported value for co-digestion of manure slurry which is 0.015 to $0.040 m^3/kg$ [13]. This is due to the nature of the experimental setup used because biogas production is only ascertained if certain amount of water is displaced. There is a possibility of gas accumulating within the system which cannot be measured. Also, daily pH measurement by withdrawing 5ml sample, measuring its pH and injecting back is destabilizing the system by introducing air inside. The biogas yield for S3 and S5 are a little bit higher than that of S1, S2, S4 and S6 due to the better buffering capacity poultry manure.

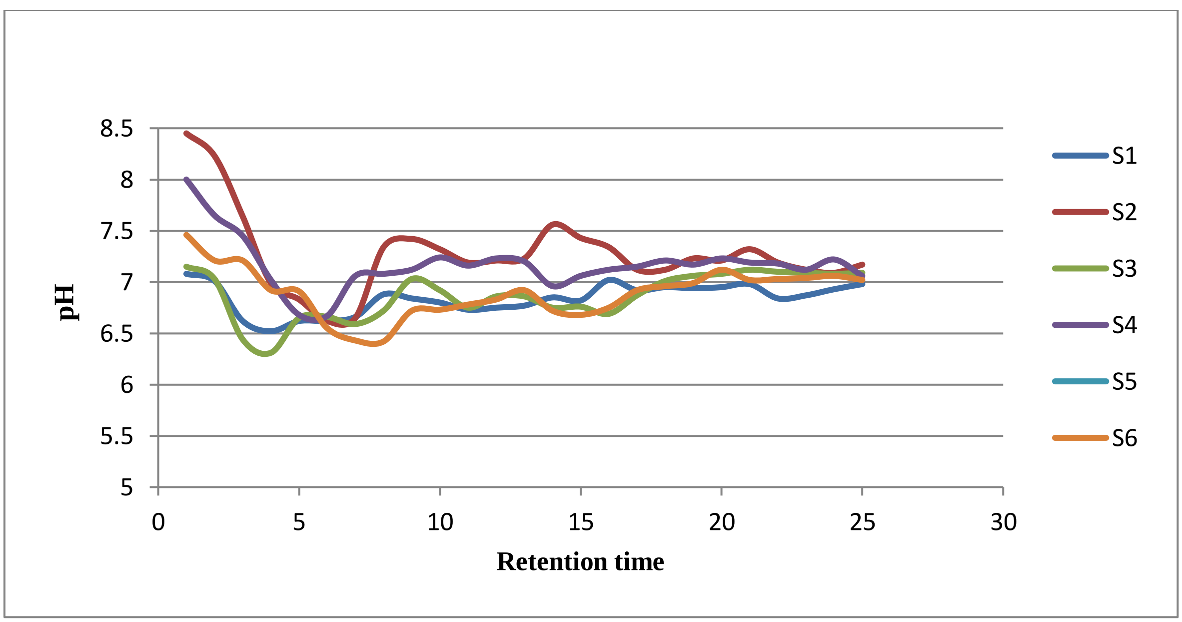

Fig. 3.2: Daily pH measurement

All experiments showed alkaline concentration at start, which is the most preferred pH for starting anaerobic digestion process. Stable pH was observed along the retention time after biogas production starts, except for S6 which shows slight acidity for three days.

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As shown on figure 3.3 no biogas was produce in the first four days this is due to the time required for the bacteria to generate and adapt to the system condition before they can produce biogas.

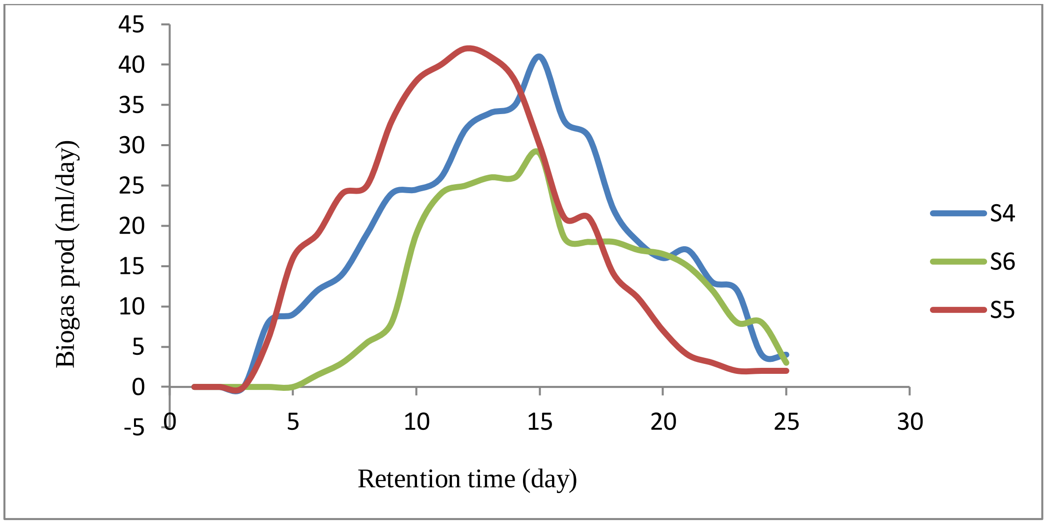

Fig. 3.3: Daily Biogas Production for S4, S5 and S6

The biogas production for S1 and S2 starts on the fifth day and seventh day for S3 this is due to the slow degradability of the slaughterhouse waste and vegetable waste. All the experiment showed increase in biogas production until they reach their peak production values at around day 15 to 17. Decrease in biogas production was observed as the retention time increases from the peak point. In all the experiment involved here 90% of the biogas was produced at retention time of less than 21 days.

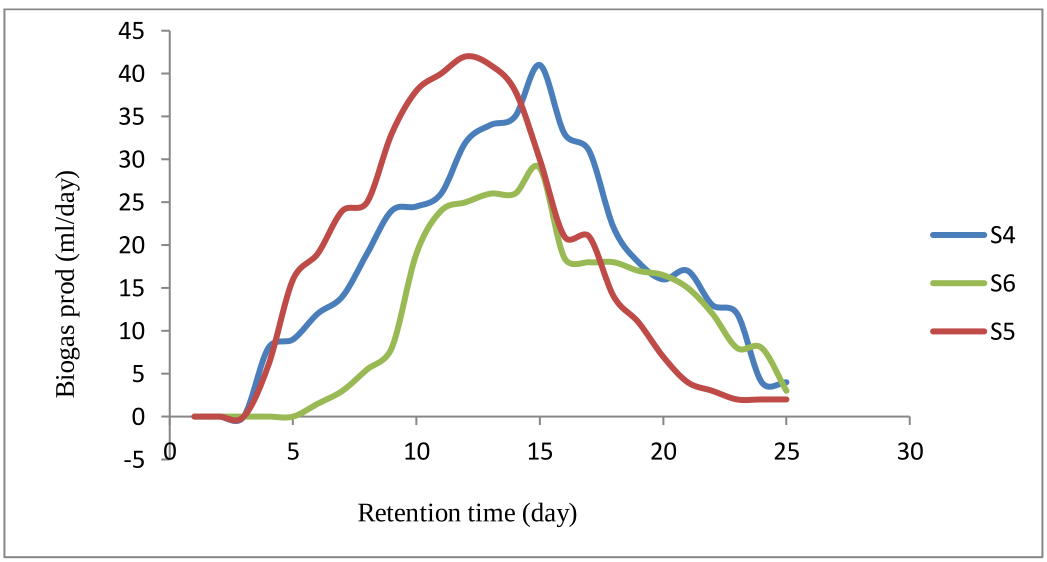

Fig. 3.4: Daily Biogas Production for S4, S5 and S6

The process was stopped at retention time of 25 days because the amount of gas produced is very low indicating the anaerobic digestion process is almost finished. In all the experiment involved here 90% of the biogas was produced at retention time of less than 21 days.

Figure 3.4 shows the biogas production with respect to retention time for S4, S5 and S6. Biogas production starts on the fourth day and increases as the retention time is increased this is as a result of increase in population of the desired microorganisms with time. At standard digestion condition, increase in microbial population in the digester will results to more utilization of the substrate with an equal generation of biogas. S6 shows lower production than the rest because of the slight acidity of the system for two days. The experiments were stopped at the retention time of 25 days due to little biogas production observed.

The biogas yield obtained for S3 is low as compared to results from literature this is because the slaughterhouse waste collected contains only intestine and no any pretreatment process was employed to increase the degradability of the slaughterhouse waste [14].

3.2 Simulation Results

The thermodynamic equations are written in EES code, the system involve 73 equations and variables. No syntax error was found after the run was completed in two seconds.

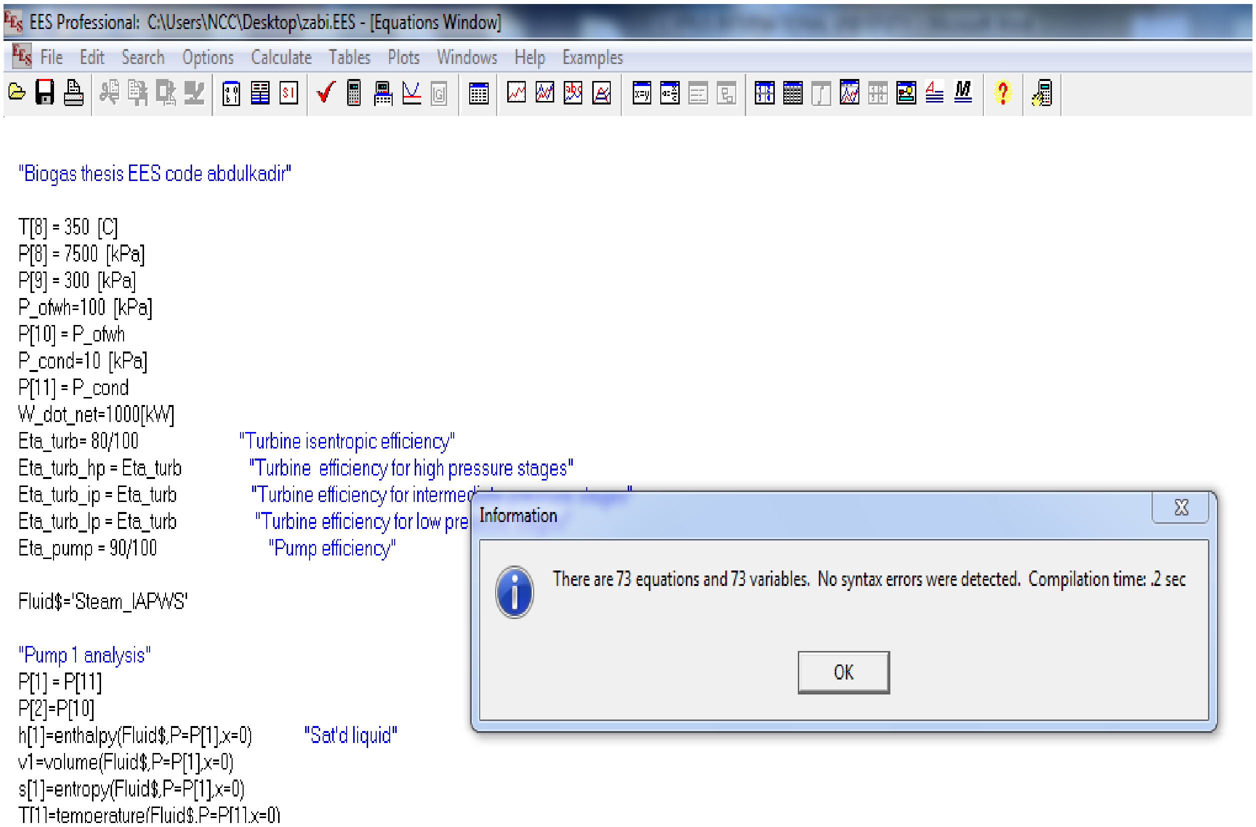

Fig. 3.5: Equation window

Figure 3.5 shows the result obtained after specifying the operating conditions as shown in appendix 1.4. efficiency of 42.55% was obtained assuming 200 kJ/kg digester heat consumption, this efficiency is higher than steam power cycle efficency alone without the integration with the biogas digester which was found to be 36.56%.

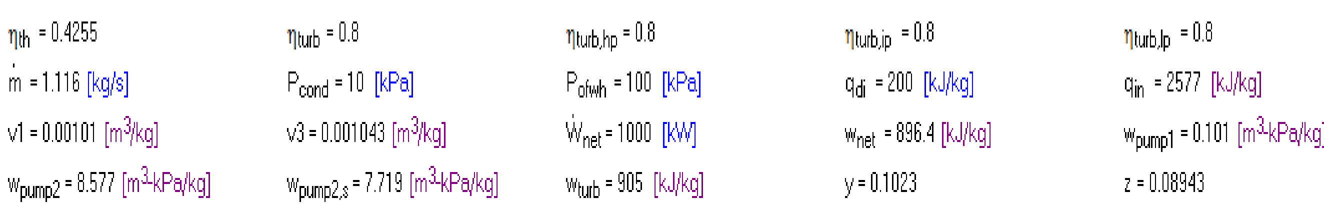

Fig.3.6: Results window screen shot efficiency

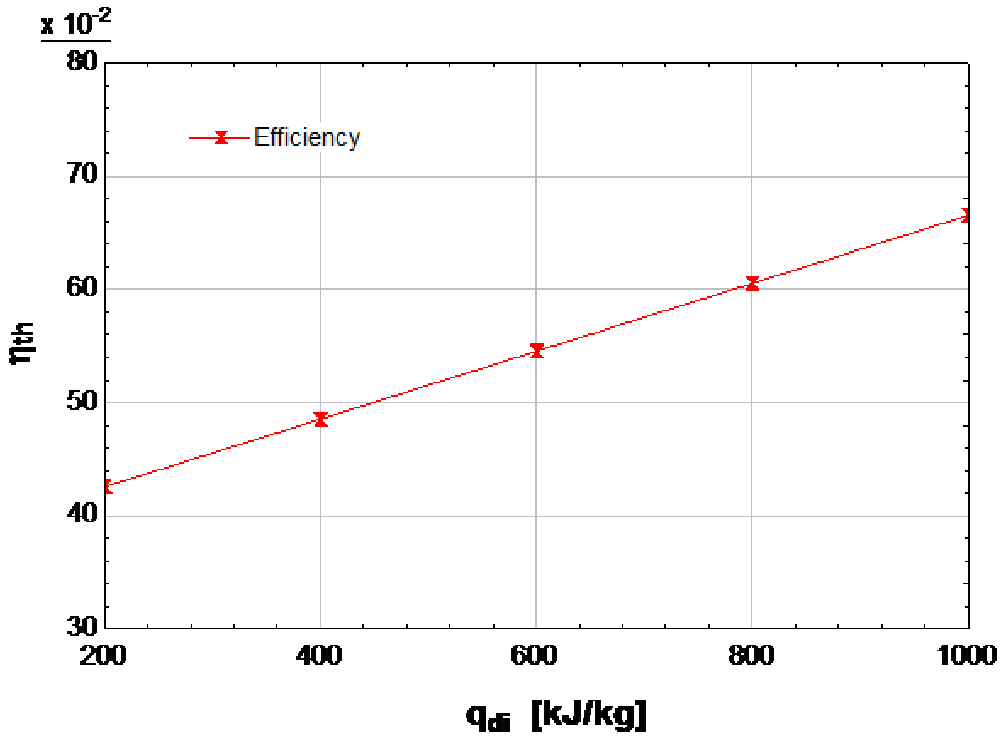

Fig. 3.7: Effect of digester heat consumption on efficiency

The themal efficiency of the system increases as the digester heat consumption increases this is due to the utilisation of heat from the steam turbine for the digestion process and preheating of feed water.

IV. Conclusions

This study involves the evaluation of the potentials of biogas generation from anaerobic co-digestion of biomass feedstock and to conduct energy analysis of a modeled biogas plant using EES software. The experimental stage consists of six set of experiments (S1, S2, S3, S4, S5 and S6). The biogas yields

obtained for the co-digestion of Cow dung + Poultry manure (S1), Cow dung + Sheep manure (S2), Slaughterhouse waste + Poultry manure (S3), Sheep dung + Poultry manure (S4), Poultry manure + Whey (S5) and Vegetable waste + Cow (S6) are 0.0231m^3/kg, 0.0264m^3/kg, 0.0234m^3/kg, 0.0266 m^3/kg and 0.0191m^3/kg respectively. These biogas yields are in accordance with yield of 0.015 to 0.040m^3/kg for manure slurry [16]. However, the biogas yield obtained here are slightly above the minimum reported gas yield for co-digestion of organic substrates [17]. This is due to the nature of the experimental setup used, biogas production is only ascertained if certain amount of water is displaced. There is possibility of gas accumulating within the system which cannot be measured. Also, daily pH measurement by withdrawing 5ml sample, measuring its pH and injecting back is destabilizing the system by introducing air inside. These problems leads to the lower biogas yield which is supposed to be close to maximum because of the co-digestion of substrate employed. It can be concluded that livestock manure, vegetable waste and slaughterhouse waste has a great potential for biogas production by utilizing anaerobic co-digestion process, which is a better digestion process than the single feedstock digestion. Also, from the simulation carried out, it can be seen that the efficiency of the modeled biogas plant is 42.55%, integration of the digestion process to the steam cycle provides better heat utilization. Thus, the efficiency of the integrated system is higher than that of normal steam cycle [18].

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