African Journal of Environment and Natural Science Research
Volume 2, Issue 1, 2019 (pp. 16-34)

www.abjournals.org

MODELLING BIOGAS RECOVERY FROM WASTEWATER TREATMENT BY ANAEROBIC DIGESTION

Odenigbo C[1] and Prof. Ademuluyi J.O[2]

[1]Department of Civil Engineering, Enugu State University of Science and Technology.

[2]Department of Civil Engineering, University of Nigeria Nsukka.

ABSTRACT: *In this study, attempt was made to model gas production process from an anaerobic digestion of sewage sludge in a treatment plant. Apart from the issue of environmental cleanup this process of sewage treatment offers, it has become a viable tool to solving energy problems that exist in many parts of the world. Nigeria has much wastewater and this constitutes environmental pollution when channelled to the freshwaters body. Some wastewater; domestic and industrial, has to be treated before channelling them into waterways and in doing this, biogas can be tapped from the system if anaerobic digesters are designed and incorporated into the treatment plants. In this study, this process of biogas production was modelled to ascertain the amount of energy that can be recovered from wastewater treatment plant, for economic usage in the operation of the treatment plant and municipal consumption. To achieve this objective, equation* $V_{CH4} = (0.40)\left[(S_O - S)(Q)(10^3 g/kg)^{-1} - 1.42P_x\right]$ *was derived and its application yielded a positive result. Results from two different experimental reactors, reactors 1 and 2 (see Table 4.2 above) were used in comparison with the model reactors to investigate performance of the model. Figure 4.1 shows the gas yield for the different reactors investigated. Statistical analysis of the overall results shows that model reactor 1 has a coefficient of correlation (CORR) of 0.95, this demonstrate a good fit with the experimental results obtained from reactor 1. However, a mean absolute percentage error (MAPE) and root mean square error (RMSE) of 2.15 and 7.49 respectively, was recorded during this process. These values indicate a significantly low error of estimates and shows that the model is reliable. Similarly, model reactor 2 gave a CORR of 0.96 with errors of estimate (MAPE) of 1.34 and RMSE OF 3.12. Meanwhile, it can be observed that both experimental reactor 1 and 2 have a slightly higher values of gas yield than their corresponding model reactors. This trend is rather good in relation to safety in gas production estimate using the model. An overestimating model would be misleading and give a false data when such is needed for energy generation design and operation.*

KEYWORDS: Biogas, Treatment, Wastewater, Anaerobic Reactor, Digestion.

INTRODUCTION

Wherever people live, there will be human and organic waste (waste water, seepage, food waste, restaurant grease, etc) with biogenic carbon that can be converted to energy, as well as nitrogen and phosphorus nutrients that can be recovered. Consistent recognition of these as renewable energy water resource recovery activities, create more clean energy jobs, and help reduce greenhouse gas emissions by reducing electricity demand from fossil – fuel – based

power plants. Wastewater utilities worldwide are involved in all areas of renewable energy, from traditional sources such as wind, solar, and hydropower, to energy derived from biomass (such as biogas), to research in emerging technologies. With the energy contained in wastewater and bio-solids greater than the energy required for treatment, water resource recovery facilities have the potential to be energy neutral or even net energy producers, and some plants have already achieved that status.

Reaching the goal of energy neutrality which requires a holistic energy management approach, incorporating conservation practices and generating renewable energy through the management of water resource recovery and its by- products. According to a United Nations report released in May 2011, renewable energy sources such as biomass could meet nearly 80% of the world's energy supplies by 2050 if governments implement policies that harness their potential.

Biogas and biogas systems are sources of electricity which are highly beneficial for environmental protection and development. Despite the fact that biogas systems are incapable of replacing fossil fuels yet which dominate the energy market, there are unlimited possibilities of their future use.

Biogas is a gas mixture of mainly methane and carbon dioxide (of which there is 25 – 40%, and small amounts of other gasses, such as hydrogen, nitrogen and sulphide. It develops in bacteria anaerobic decomposition of organic matter. This process is called anaerobic fermentation. The main holders of energy are methane and small amount of hydrogen, carbon dioxide and other gases are ballast. It is a colorless mixture of mainly methane and small amount of hydrogen which are the main energy carriers' other gases, such as nitrogen, ammonia and sulphide are only ballast. The heating value of biogas is between 18 and 25 mg/m^3. Anaerobic decomposition was discovered by an Italian physicist. A Volta who ran the first laboratory anaerobic fermentation in 1776, in the course of the 20^{th} Century anaerobic technologies were developed especially for anaerobic treatment of sewage sludge. The sewage treatment plant (STP) in Essen produced and supplied biogas to municipal gasworks as early as in 1922.

Biogas is used for production of electrical electricity heat and gaseous bio-fuel. Mostly, biogas is burnt in cogeneration units at STPS to produce electricity and heat on site.

Rapid industrialization and urbanization worldwide has resulted in global water pollution problems. Traditional wastewater treatment plants generate a tremendous quantity of sludge. In 2005, the United States generated 7.6 million tons of dry sludge; this production rate is predicted to increase to 8.2million tons by 2010. The EU produced 10 million tons of dry sludge in 2005 (Struntmann et al. 2006); China produced 1 million tons of dry sludge in the same year (Wang et al.2008), and the production is predicted to increase to 3.6 million tons in 2010 (Lee et al. 2006). Such dry sludge cannot be disposed before appropriate treatments. However, sludge treatments are expensive.

Anaerobic digestion is typically applied in sewage sludge treatment due to its advantages over aerobic systems, such as lower energy consumption, smaller amounts of solids generated, lower nutrients requirement and potential energy recovery from the produced biogas. Sewage sludge is stabilized during anaerobic digestion by converting most organic matter into biogas. The conventional mesophilic anaerobic digestion process requires a long

hydraulic retention time (Z 20days) and the operations efficiency is influenced by environmental changes. Although the thermophilic anaerobic process requires relatively less digestion time, it requires excessive heating (Zapancic and ROS 2003). Biogas from digested sludge is now considered a bio-energysource.

It has been known for almost one hundred years that bacteria could generate electricity, but only in the past few years has this capability become more than a laboratory novelty.

Biogas production by anaerobic digestion (AD) of wastes is a combinational activity of diverse microbial populations. According to Heeg et al. (2014), the AD chain is initiated by bacteria that are responsible for the hydrolysis of high molecular weight organic substances. Subsequently, the mono-and oligomers produced are further degraded to volatilefatty acids (VFAs) (acidogens) and then to acetic acid, as well as CO_2 and H_2(acetogens). The final step (methanogenesis) is accomplished by acetoclastic and hydrogenotrophicArchaea,which convert acetic acid or CO_2/H_2 into methane.

The very first step of AD is very important as large organic molecules are not readilyabsorbable. In this step, several microbes secrete different enzymes which cleave the complex macromoiecules into simpler forms. Organisms that are active in a biotas process during the hydrolysis of polysaccharides include various bacterial groups such as *Bacteriodes, Clostridium,*and*Acetivibrio*(Cirne et al. 2007; Doi 2008; Heegetal.2011). Some of these organisms have several different enzymes combined into cellulosomes (large, stable, multi-enzyme complexes specialized in the adhesion to and degradation of cellulose that reside with protuberances visible on the cell surface) that are situated on the organism's cell wall (Liang et al. 2014).

The diversity of the microbial consortium involved in AD reaches its peak during thisstage. Most of the microbes involved in hydrolysis step are also involved in fermentation. Along with them, microbes belonging to the tie n era like*Enterobacterium, Acatobacterium*and *Eubacterium*also carry out the process of fermentation (Schnurer and Jarvis 2010). Through various fermentation reactions, the products from hydrolysis are converted mainly into various organic acids (acetic, propionic acid, butyric acid, succinic acid, lactic acid, etc.), alcohols, ammonia (from amino acids), carbon dioxide and hydrogen. Exactly which compounds are formed depends on the substrate and environmental process conditions, as well as on the microbes present (Schnurer and Jarvis 2010).

Acetogenesis: In this step, the fermented products are oxidized into simpler forms. According to (Heegetal.2014), this step in the AD process requires close cooperation between the microbes that carry out oxidation and the methanogens that are active in the next stage, which actually produce methane. Substrates for acetogenesis consist of various fatty acids, alcohols, some amino acids and aromatics (Heegetal. 2014). In addition to hydrogen gas, these compounds primarily form acetate and carbon dioxide (licet: et al.2014). *Syntrophomonas, Syntrophus, Clostridium,* and *Syntrobacter*ia examples of genera in which there are numerous organisms that can perform acetogenesis in synthrophy with an organism that uses hydrogen gas (Mclnerney et al, 2008).

African Journal of Environment and Natural Science Research
Volume 2, Issue 1, 2019 (pp. 16-34)
www.abjournals.org

MATERIALS AND METHOD

Review of experimental procedure

Fresh waste activated sludge and partly digested sludge sample were collected from Wupa Abuja sewage treatment plant from the six aerobic reactors respectively before treatment and were divided into four portions. Four experimental reactors were designed, and numbered. They were numbered U_1, U_2 and C_1, C_2. A measured proportion of the sludge was fed into each reactor. All the four reactors were covered with black plastic to prevent light from entering the digester and the digester was placed in a 37^0C water bath.

Two reactors were test reactors U1 and U2 receiving waste activated sludge (WAS) treated with ultrasound. The other two reactors C1 and C2 were control reactors receiving untreated sludge. The reactors were operated in a semi-continuous made with feeding once a day, six times per week.

Biogas was produced in reactor without ultrasound treatment and also in the reactor incorporated with ultrasound sonicator probe with sonication of 420W. Gas was collected over acidified water to avoid CO2 absorption. The volume of waste displaced measured the volumes of gas produced. The gas was tapped, pressurized and stored. The physiochemical parameters of the sludge like, TS, VS, FCOD, and PH was determined using ALPHA (1997 & 1998) Standards. Most parameters were expressed in percentage.

Digestion Experiment

Four reactors comprised the set up. Each reactor had two openings one small for feeding and withdrawal of sludge and one large plugged with stopper. The stopper was equipped with two entrances one for a propeller axis and one for a gas outlet tube. On the tube, there was a three-way valve for gas sampling. All four reactors were covered with black plastic to prevent light from entering the reactor and placed in a 37^0C water bath.

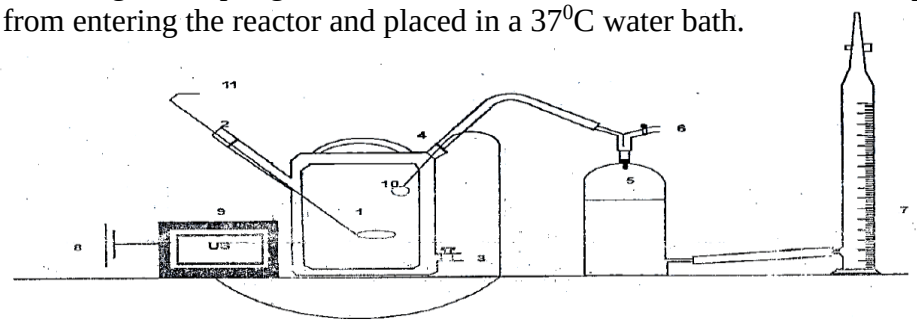

Figure 1. Illustration of the biogas reactor with ultrasound. 1.Digester (V = 5 L) capacity, 2.Feed inlet and effluent outlet, 3.Sludge outlet, 4.Gas opening, 5.Water displacement jar, 6.Gas outlet 7.Measuring jar, 8.Power source, 9.Ultrasound Machine, 10.Ultrasound sonicator probe, 11.Stirrer/ propeller

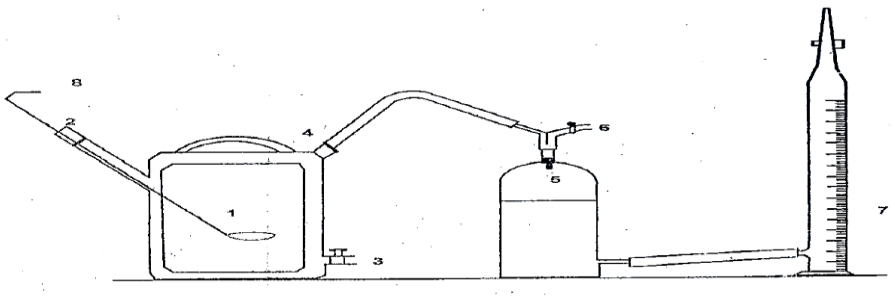

Figure 2. Illustration of the biogas control experiment set up. 1. Digester (V = 5 L) capacity, 2.Feed inlet and effluent outlet, 3.Sludge outlet, 4.Gas opening. 5.Water displacement jar, 6.Gas outlet 7.Measuring jar, 8.Stirrer/ propeller

Fig.3.1 and Fig 3.2 Show the Experimental Setup.

Inoculum: The inoculums consisted of a mixture (1:1) of digested sludge from the six reactors of Abuja sewage treatment plant. The sludge was taken fresh from the Wupa Abuja aerobic reactors and subsequently poured into the reactors designed for the experiment. Afterwards, the experimental reactors were immediately sealed and placed in the water bath and allowed to degs under siring for 24hrs.

Substrate: The substrate was partly waste activated sludge (WAS) and partly digested sludge (DS). Even though the full-scale aerobic digestion chambers at Abuja were run on a mixture of primary sludge and waste activated sludge, primary sludge was excluded in this experiment. Primary sludge varies heavily in both composition and quality and would have meant an unnecessary source of variation in gas production. Digested sludge as a part of the substance ensures that the digestion process is not affected by lack of nutrients, which in the full-scale process are found in the primary sludge.

Start-up Period: The reactors were inoculated on 22-09-2009 and the first feeding took place the following day (day 1). At the beginning of the start-up period T_R was 16(22.9) days and the proportion of waste activated sludge in the substrate was 70% (see fig.1). All reactors were fed with untreated sludge. On day 6, T_R was slightly increased to 17.8 (25.4) to better agree with the full-scale process.

In the second week, it was noted that the waste activated sludge was unusually wet (total solids (TS)≤1%). The sludge was in fact lacking addition of polymer; explaining the low TS. After a couple of days, polymer usage was resumed in the sludge thickening processing and at the beginning of the third week; the sludge had TS of 4%. On day 15, TR was decreased to 14.5(16) days and the proportion of waste activated sludge were increased to 90% in an effort to get a higher gas production. It was also noted that the stirring propellers were not all on the same height as they were adjusted accordingly (lowered). At day 19, all the propellers were raised to a new height of 1/3 of the sludge height. On day, 21 the test reactors started receiving material. The treatment time was 45s (after which 55% of the sludge had been treated at least once). On day 33, the ultrasonic treatment time was increased to 2 min and 4s (corresponding o three retention times) in the ultrasonic treatment equipment or 91% of the sludge being treated at least once). Since there were still problems with foaming, the volume of digested sludge in the substrate was increased to make sure a sufficient amount of (active) microorganisms was present. TR was lowered to 10 (16) days and the proportion of waste activated sludge were decreased to 62.5%. This was a suitable combination of T_R and sludge proportions, which were maintained further. On day 61, all the reactors gas measuring apparatus was measuring gas at a sufficient resolution and the experimental period then began.

The retention time (T_R) is defined as the ratio between the total volume (V) and the volume of exchanged sludge per day (r):

$$T_R = \frac{v}{r} \qquad 3.1$$

Experimental Run: T_R was 10(6) and the proportion of waste activated sludge was 62.5% at the second day of the 16-day experimental period, and the ultrasonic treatment time was increased to 6 min, raising the possibility of getting a difference in gas production more easily to measure. The test reactors received treated sludge for twelve days. During the last three days, all reactors received untreated sludge.

The sludge was treated with ultrasound for 53 min, in intervals of 3 min with 1.5 min brakes in between, to prevent overheating of the sonicator. Thus, the effective treatment time was 36 min. the treatment began 17 min after the can had been filled but space was allowed, as the can was not completely filled. An effective treatment time of 36 min means that approximately 75% of the sludge was treated at least once. The trial went on for 50hrs and data of gas measurements were collected during the three periods. Gas production as the only parameter measured.

Method Validation: During a start-up period of 61 days mainly two problems were dealt with the stability of the reactors and accuracy in gas-production measurements.

Accuracy in Gas-Production Measurements

To increase the accuracy of measurements, two approaches were used: physical modification of the gas meters and increased gas production from increase of the organic loading.

Sub-Experiment 1: Filterable Chemical Oxygen Demand (FCOD)

An analysis of the total COD was made twice. Treatment lengths ranged from 40 s to 10 min. after 1200 rpm of the sludge in a centrifuge, the supernatant layer was filtered through a medium grade filter paper with pore size 1.2μm. Two of the FCOD measurements were also accompanied by measurements of sludge temperature at different treatment lengths.

Sampling and Analysis: Gas production was measured by water displacement method, the burette was already calibrated and error of parallax was avoided while taking readings on the burette. Gas flow was calculated using stopwatch, and volume of gas produced was found to be at the rate of 3.5 mL/min. prior feeding (i.e. six times a week) readings on the burette and stop watch were taken at same time and recorded and later subtracted from the previous reading. Syringes and needles (Micro lance)^{TM} were used for gas and sludge sampling.

- **Methane** was sampled once a week from the reactor.
- **COD** was analyzed using the APHA (1997) Standard methods. Samples were heated in a thermostatically controlled oven.

FCOD samples were centrifuged at 1200 rpm and the supernatant layer was filtered through a medium grade filter paper with apore width of 1.2 μm. FCOD samples were diluted five or ten times. Samples analyzed for total COD were diluted 500 times.

Temperature of the ultrasonically treated water activate sludge was measured with a standard liquid in-glass thermometer. TS were analyzed according to APHA (1997) Standards. The reactor effluents were analyzed twice a week. Collective samples of the waste activated sludge were analyzed weekly. VS were analyzed according to APHA (1997) Standards. The reactor effluents were analyzed twice a week. Collected samples of the water activated sludge were analyzed weekly. pH was analyzed with a pH meter according to APHA (1997) standards. The reactor effluents were analyzed twice a week.

Design of Anaerobic Suspended GROWTH PRocesses

Anaerobic suspended growth processes may be designed in a manner similar to completely mixed aerobic activated sludge processes, because the hydraulic regime and biomass conc. extraction can be reasonably defined. The design procedure is outlined below:

1. Select an SRT to achieve a given effluent concentration and percent COD removal
2. Determine the daily solids production and mass of solids in the system to maintain the designed SRT
3. Select the expected solids concentration in the reactor and determine the reactor volume.
4. Determine the gas production rate
5. Determine the amount of excess sludge wasted and the nutrient needs
6. Check the volumetric organic loading rate
7. Determine alkalinity needs.

BIOGAS PRODUCTION MODEL DERIVATION

Determination of Design SRT

Biomass Mass Balance

$$\begin{pmatrix} Rate\ of\ accumulation\ of \\ micro-organism\ within \\ the\ system\ boudnary \end{pmatrix} = \begin{pmatrix} Rate\ of\ \ flow\ of \\ micro-organism\ in\ to \\ the\ system\ boudnary \end{pmatrix}$$

$$- \begin{pmatrix} Rate\ of\ \ flow\ of \\ micro-organism\ out\ of \\ the\ system\ boudnary \end{pmatrix} + \begin{pmatrix} net\ growth\ of \\ micro-organism\ within \\ the\ system\ boudnary \end{pmatrix}$$

that is;

Accumulation = inflow – outflow + net growth (3.1)

$$\frac{dX}{dt}V = QX_0 - [(Q - Q_w)X_e - Q_wX_R] + r_gV \quad (3.2)$$

Where,

$\frac{dX}{dt}$ = rate of change of biomass concentration in reaction, (gVSS/m^3.d)

V = reactor volume, (m^3)

Q = influent flowrate, (m^3/d)

X_0 = concentration of biomass in influent, (gVSS/m^3)

Q_w = waste sludge flowrate, (m^3/d)

X_e = concentration of biomass in effluent, (gVSS/m^3)

X_R = concentration of biomass in return line from clarifier, (gVSS/m^3)

r_g = net rate of biomass production, (gVSS/m^3.d)

but

$$r. = -Yr_{su} - k_dX \quad (3.3)$$

where

Y = synthesis yield coefficient, (gVSS/g bsCOD)

k_d = endogenous decay coefficient, (gVSS/gVSS.d)

r_{su} = rate of substrate utilization, (gbsCOD/m^3.d)

X = biomass concentration (g/m^3)

Assuming a steady state conditions $\left(\frac{dx}{dt} = 0\right)$ and neglecting influent biomass concentration, that is ($X_0 = 0$), equation (4.2) can be simplified to yield;

$$(Q - Q_w)X_e + Q_wX_R = r_gV \quad (3.4)$$

by combining eqn (4.3) and (4.4), the result becomes;

$$\frac{(Q - Q_w)X_e - Q_wX_R}{VX} = -Y\frac{r_{su}}{X} - K_d \quad (3.5)$$

The inverse of the term on the left-hand side of eqn. (4.5) is defined as the average solids retention time' (SRT) as given below.

$$SRT = \frac{VX}{(Q - Q_w)X_e - Q_wX_R} \quad (3.6)$$

By definition, the SRT is the solids in the system divided by the mass of solids removed per day. Using the above definition of SRT, eqn. (3.5) can be written as

$$\frac{1}{SRT} = -Y\frac{r_{su}}{X} - K_d \quad (3.7)$$

The term 1/SRT is also related to μ, the specific biomass growth rate as given below:

$$\frac{1}{SRT} = -\mu \quad (3.8)$$

but

$$r_{su} = -\frac{KXS}{K_S + S} \quad (3.9)$$

Where

K = maximum specific substrate utilization rate, (g substrate/g microorganisms. d)

S = growth limiting substrate concentration in solution, (g/m^3) half-velocity constant, or

Ks = substrate concentration at one-half the maximum specific substrate utilization rate, (g/m^3).

Substituting eqn. (4.9) into eqn. (4.7) yields

$$\frac{1}{SRT} = \frac{YKS}{K_S + S} - K_d \quad (3.10)$$

but

$$\mu_m = KY \quad (4.11)$$

Where,

μ_m = maximum specific bacterial growth rate, (g new cells/gcells.d)

Substituting eqn. (4.11) into eqn. (4.10) gives

$$SRT = \left(\frac{\mu_m S}{K_S + S} - K_d\right) \quad (3.12)$$

Determination of sludge production

To determine solids production, the following equation can be used:

$$P_{X,TSS} = \frac{QY(S_O - S)}{[1 + (k_d)SRT](0.85)} + \frac{f_d(k_d)QY(S_O - S)SRT}{[1 + (k_d)SRT](0.85)}$$

+ Q (nondegradable TSS) (3.13)

Where,

$P_{X,TSS}$ = net waste activated sludge produced each day, (Kg TSS/d)

S_O = influent substrate concentration, (mg/L)

S = effluent substrate concentration, (mg/L)

f_d = constant, based on cell debris/biomass decay

$(S_O - S)$ = COD degraded = influent COD – nondegradable TSS COD – effluent soluble degradable COD (3.14)

Other coefficients are obtained from table of design parameters for completely mixed suspended growth reactors.

Determination of reactor volume and hydraulic detention time, τ

The volume is determined using the equation;

$$\text{Volume} = \frac{(P_{X,TSS})(SRT)}{X_{TSS}} \quad (3.15)$$

Where

X_{TSS} = MLSS biomass concentration

For hydraulic detention time, τ

$$\tau = \frac{V}{Q} \quad (3.16)$$

Where

V = reactor volume

Q = wastewater flowrate

Determination of gas production rate

Prediction of methane gas production:

A steady-state mass balance for COD was prepared to determine the amount of the influent COD converted to methane

$$O = \begin{pmatrix} Influent \\ COD \end{pmatrix} - \begin{pmatrix} portion\ of \\ \text{inf}\ luent\ COD \\ in\ effluent \end{pmatrix} - \begin{pmatrix} \text{inf}\ luent\ COD \\ converted\ to \\ cell\ tissue \end{pmatrix} - \begin{pmatrix} \text{inf}\ luent\ COD \\ converted\ to \\ methane \end{pmatrix}$$

Simply put,

$$COD_{in} = COD_{eff} + COD_{vss} + COD_{methane} \quad (3.17)$$

The quantity of methane gas can then be calculated from the relationship;

$$V_{CH4} = (0.35)\left[(S_O - S)(Q)(10^3 g/kg)^{-1} - 1.42P_x\right] \quad (3.18)$$

Where

V_{CH4} = Volume of methane produced at standard condition (O^OC and 1 atm), (m^3/d)

0.35 = theoretical conversion factor for the amount of methane produced, m^3, from the conversion of 1kg of bCOD at O^OC. See below.

Q = flowrate, m^3/d

S_O = bCOD in influent, (mg/L)

S = bCOD in effluent, (mg/L)

bCOD = biodegradable COD

P_X = net mass of cell tissue produced per day, (kg/d)

The COD of methane is the amount of oxygen needed to oxidize methane to carbon dioxide and water.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (3.19)$$

From the above, the COD per mole of methane is 2(32g O_2/mole) = 64g O_2/mole CH_4. The volume of methane per mole at standard conditions (O^OC and 1 atm) is determined using universal gas law. That is;

$$PV = nRT \quad (3.20)$$

$$V = \frac{nRT}{P} \quad (3.21)$$

Where,

V = volume occupied by the gas, L

n = moles of gas, mole

R = universal gas law constant, (0.082057 atm.L/mole.k)

T = temperature, k (273.15 + ^OC)

P = absolute pressure, atm

Thus, at standard condition (O^OC and 1 atm), the volume occupied by one mole of CH_4 is obtained using eqn. (4.21).

$$V = \frac{(1mole)(0.082057atm.L/mole.K)[273.15+0)]K}{1.0atm}$$

V = 22.414L

So the CH_4 equivalent of COD converted under anaerobic conditions is; (22.414L)/(64g COD/mole CH_4) = 0.35L CH_4/g COD.

Thus, at 35^{O}C, the volume occupied by one mole of CH_4 is

$$V = \frac{(1mole)(0.082057atm.L/mole.K)[273.15+35)]K}{1.0atm}$$

V = 25.29L

So the CH_4 equivalent of COD converted under anaerobic conditions at 35^{O}C is; (25.29L)/(64g COD/mole CH_4) = 0.40L CH_4/g COD.

It implies that the volume of methane produced per day at 35^{O}C (conversion factor at 35^{O}C = 0.40) is computed using eqn. (4.18) modified, since volume occupied by gas is temperature dependent, hence,

$$V_{CH4} = (0.40)\left[(S_O - S)(Q)(10^3 g/kg)^{-1} - 1.42P_x\right] \quad (3.22)$$

The mass of biological solids synthesized daily, P_X can be estimated using.

$$P_X = \frac{YQ(S_O - S)\times(10^3 g/kg)^{-1}}{1+k_d\,(SRT)} \quad (3.23)$$

Where

Y = yield coefficient, (gVSS/g bCOD)

K_d= endogenous coefficient, (d^{-1}) (typical values range from 0.02 to 0.04)

Other terms as defined previously. For a complete – mix digester, the SRT is the same as the hydraulic retention time, τ.

RESULT AND DISCUSSION

Digestion Experimental Results

The digested sludge from the digestion chambers one and two, comprising the inoculums, had total solids (TS), volatile solids (VS) and P^H according to table 4.1.

Table 4.1: Total Solids (TS), Volatile Solids (VS) and $P^H$of the two Sludge Making up the Inoculum

Digestion chamber	TS (%)	VS (%)	PH
1	3.3	62	7.4
2	1.1	63	7.5

During the experiment period, the TS and Vs of the waste activated sludge were in the range of 2.8-3.8% and 74-74% with mean value of 3.5% and 76%, respectively. These TS and Vs values gave a mean organic load of 1.7g VSL/d for the experimental period.

Biogas Yield

Fig. 4.1, fig 4.2 and fig 4.3, show the biogas yield over the experimental period during day 1-7 there was a general increase in gas production and the increase appeared to be stronger for the modeled reactors. For day 7-12, the difference in gas yield did not increase further. During day 14-16, when the reactors received untreated sludge, the difference in gas yield decreases constantly, an indication that gas yield result from sludge treatment. The gas yield for each day for the reactors is shown in table 4.2 below.

Table 4.2: Gas Yield (ML/gVS) for Each Day for the Reactors

DAY	Experimental REACTOR 1	Experimental REACTOR 2	Model REACTOR 1	Model REACTOR 2
1	256	270	248	266
2	256	279	252	277
3	281	289	280	281
4	281	289	281	284
5	290	298	283	299
6	295	298	296	299
7	325	300	312	300
8	314	282	314	280
9	285	285	275	287
10	304	257	300	248
11	295	257	296	249
12	322	285	323	288
13	325	295	327	290
14	322	314	318	309
15	311	309	309	304
16	311	285	306	272

Biogas Production Model

Results from two different experimental reactors, reactors 1 and 2 (see Table 4.2 above) were used in comparison with the model reactors to investigate performance of the model. Figure 4.1 shows the gas yield for the different reactors investigated. Statistical analysis of the overall results shows that model reactor 1 has a coefficient of correlation (CORR) of 0.95, this demonstrate a good fit with the experimental results obtained from reactor 1. However, a mean absolute percentage error (MAPE) and root mean square error (RMSE) of 2.15 and 7.49 respectively, was recorded during this process. These values indicate a significantly low error of estimates and shows that the model is reliable.

Similarly, model reactor 2 gave a CORR of 0.96 with errors of estimate (MAPE) of 1.34 and RMSE OF 3.12. Meanwhile, it can be observed that both experimental reactor 1 and 2 have a slightly higher values of gas yield than their corresponding model reactors. This trend is rather good in relation to safety in gas production estimate using the model. An overestimating model would be misleading and give a false data when such is needed for energy generation design and operation.

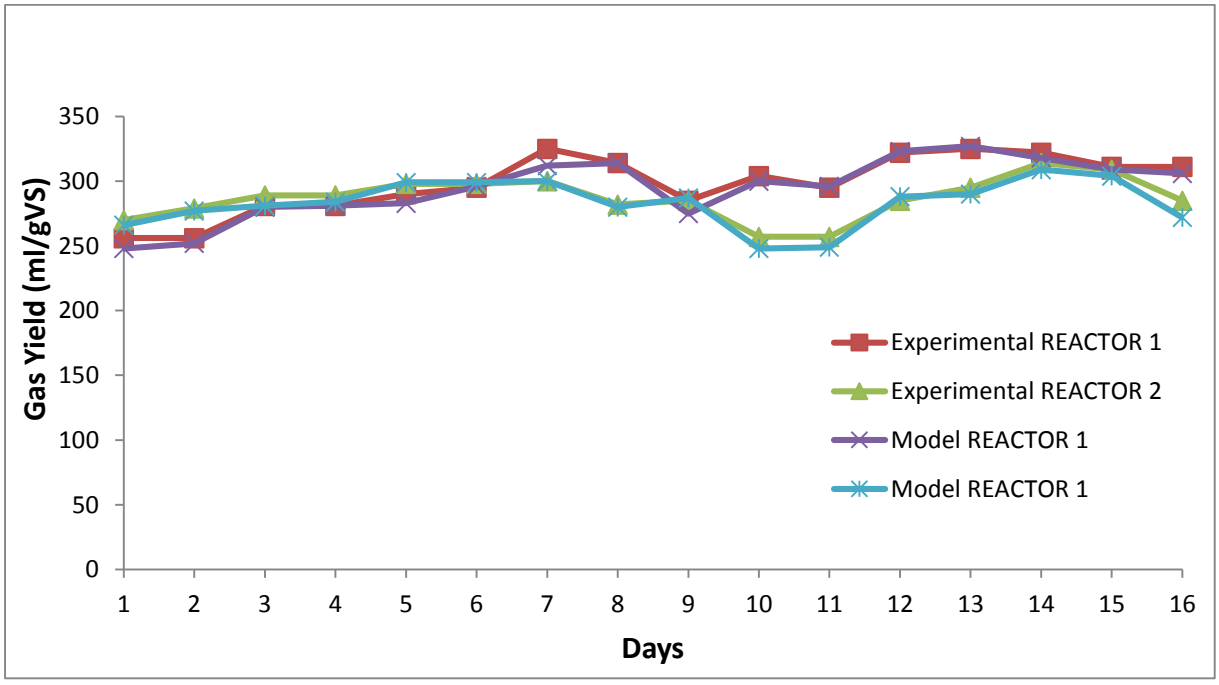

Fig. 4.1: The Graph of Variation of Gas Yield with Days for the Experimental and Modeled Reactors

Table 4.3: Gas Yield for Experimental Reactor 1 and Model Reactor 1

Day	Gas Yield (ml/gVS)	
	Experimental Reactor 1	Model Reactor 1
7	333	312
8	314	314
9	285	275
10	304	300
11	295	296
12	322	323

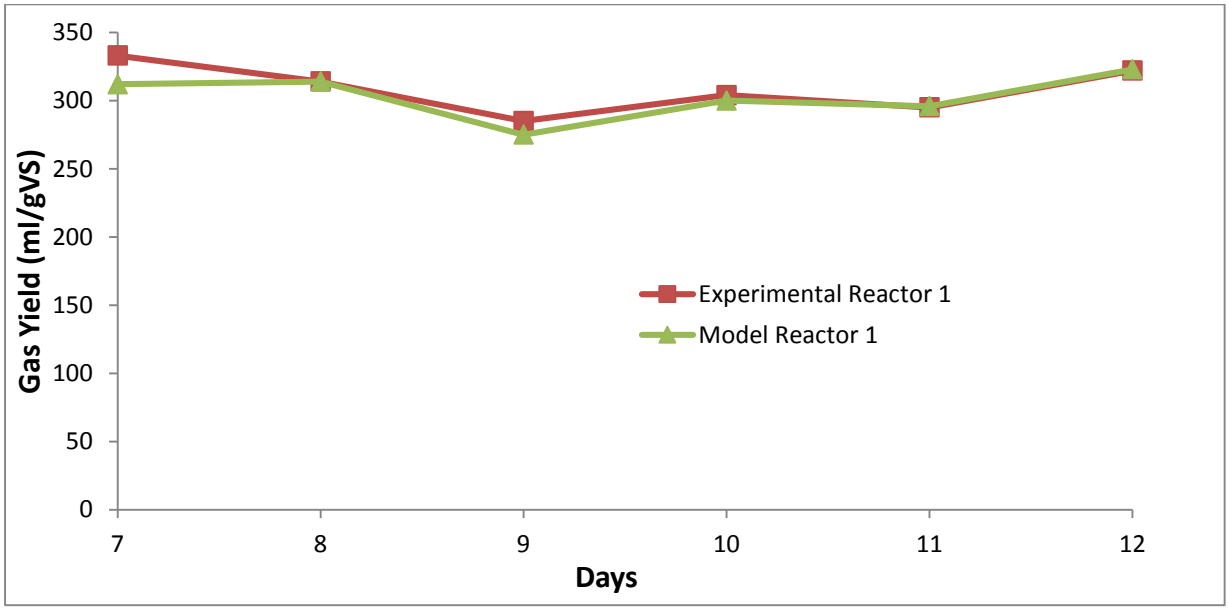

Fig. 5.2: Gas Yield for Experimental Reactor 1 and Model Reactor 1 at Selected Peak Yield.

Table 5.4: Gas Yield for Experimental Reactor 2 and Model Reactor 2

	Gas Yield (ML/gVS)	
Day	**Experimental**	**Model**
	Reactor 2	**Reactor 2**
7	300	300
8	282	280
9	265	287
10	257	248
11	257	249
12	275	288
13	292	290
14	314	309
15	309	304
16	285	272

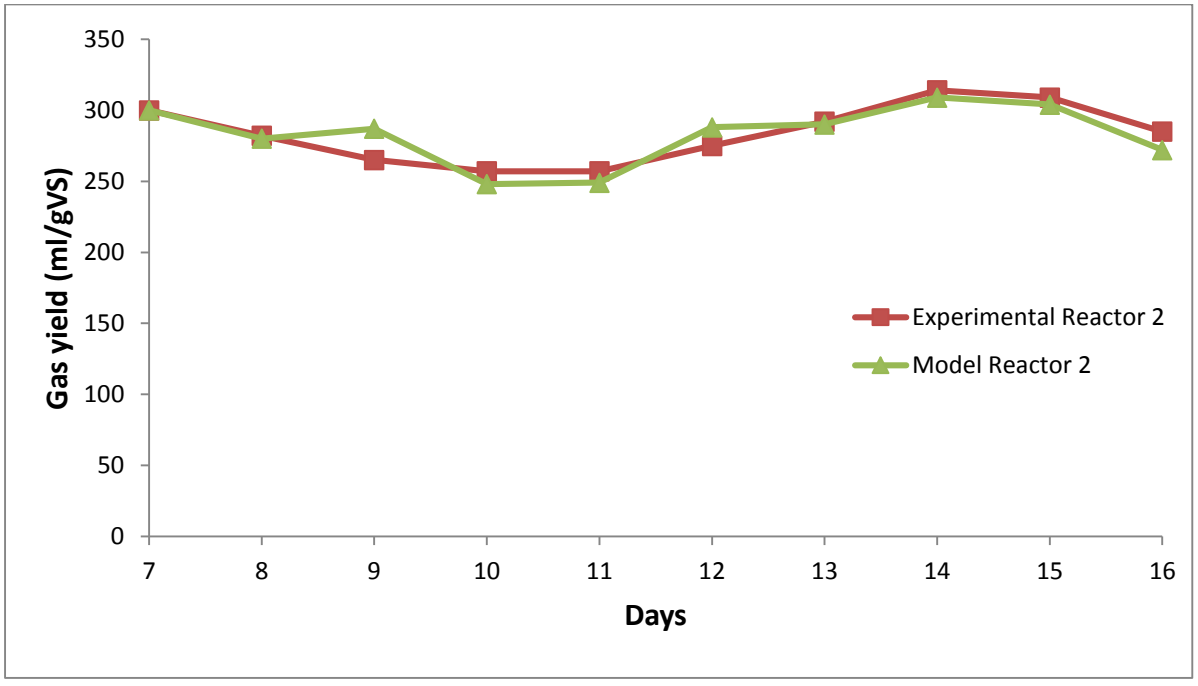

Fig. 4.3: Gas Yield for Experimental Reactor 2 and Model Reactor 2 for Selected Peak Yield.

Accuracy in Gas-Production Measurements

The gas yield for the experimental reactors, a mean of 293mL/gVS for day 7-12 was in the lower range of the reference values cites by brown et al (2003) and lower than the value presented in the report on Wupa Abuja Sewage Sludge. Still, the values are in the same range, confirming that the gas measurement was correct.

The methane content: The methane content (58.5%) of the biogas was stable throughout the reactors.

pH value: The pH was neutral throughout the experiment for both experimental reactor 1 (pH of 7.3-7.7) and reactor 2 (pH of 7.4 - 7.6). Neutral pH values correspond well with the low, <100mg1L, concentration of organic acids. From the neutral pH and the low concentration of organic acids, it can be concluded that the reactors were not overloaded.

TS: TS of the reactor effluents was fairly constant (at about 2.5%) over the experiment and equal among the reactors.There was a minor general decrease of VS in the reactor effluent, which shows that there was no buildup of undisintegrated organic material in the reactors.

However, to be able to draw further conclusion from the decrease in VS a longer experiment is required. Graphs of TS and VS of the reactor effluents are shown in fig. 4.4 and 4.5 below.

Table 4.5: TS (%) and VS (%) for Reactor Effluent of Experimental Reactor 1

Day	TS(%)	VS(%)
1	2.4	64
4	2.6	64
8	2.6	64
11	2.4	64
15	2.5	64

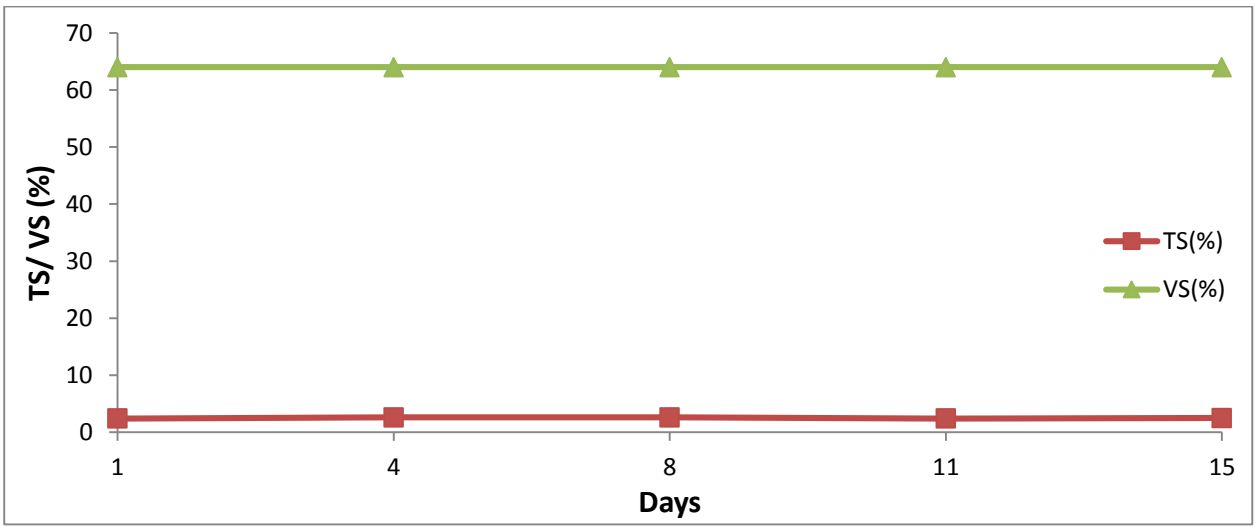

Fig. 4.4: Graph of TS and VS for Reactor Effluent of Experimental Reactor 1.

Table 4.6: TS (%) and VS (%) of Experimental Reactor 2 During Digestion Experiment

	Experimental Reactor 2	
Day	**TS (%)**	**VS (%)**
1	2.5	64
4	2.6	65
8	2.6	64
11	2.5	64
15	2.6	64

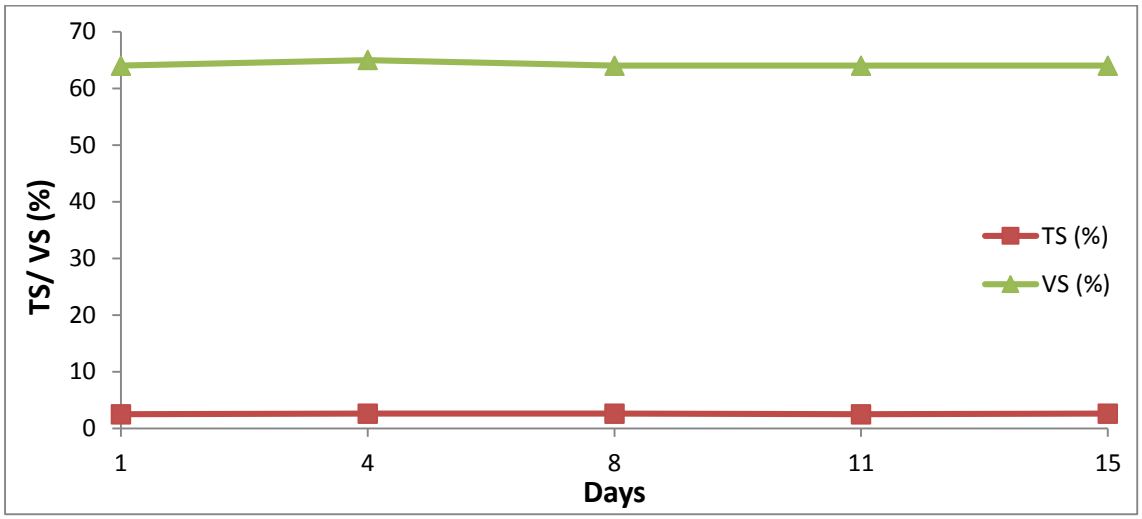

Fig. 4.5: Graph of TS and VS of Experimental Reactor 2.

VS Reduction: In fig 4.4 and fig 4.5, there was no difference in VS reduction between the reactors. VS reduction for reactors 1 and 2 was 31% and 33% respectively. The increase in gas production of 12.8%, in this case corresponds to approximately 0.1g more VS being degraded per day.Thus, no detectable difference in VS reduction was expected, since an increase of 0.1g Vs being degraded is rather difficult to measure. This experiment, with its high organic matter, was designed primarily for the study of gas production. For a better study of VS reduction, a large experiment is needed and preferably with a longer detention time.

CONCLUSION AND RECOMMENDATIONS

Conclusion

The treatment of sewage sludge by anaerobic process in plant is not only necessary in order to protect the environment from pollution and degradation but also for the purpose of energy recovery. Tapped biogas from anaerobic digesters incorporated into the treatment plants can

become a useful resource in improving energy generation as shown in this study. The biogas yield from the experimental reactors was modeled, and the results obtained suggest a good correlation with an average value of 0.95.

Recommendations

1. Further investigation is required to validate the models developed in this study for commercialization.
2. Further study is recommended to ascertain that the methane content of the biogas produced is not affected by treatment.
3. Other methods of sewage sludge treatment are required to investigate biogas yield since the model developed in this study only considered the anaerobic method.
4. Digestion experiments on a thicker sludge, say TS of 5 – 7% is required to further ascertain the rate of production of biogas.

REFERENCES

[1] Alpha. (1989). Standard Methods for the Examination of Water and Wastewater, 17th Edition, American Public Health Association, Washington, DC.

[2] Cirne DG, Lehtomaki A. Bjornsson L, Blackhall LL. Hydrolysis and microbial community analysis in two-stage anaerobic digestion of energy crops. J Appl Microbial. 2007;103:516-527. Doi:10.1111/j.1365-2672.2006.03270.x. [PubMed] [Cross Ref]

[3] Heeg K, Pohl M, Mumme J, Klocke M, Nettmann E. Microbial communities involved in biogas production from wheat straw as the sole substrate within a two-phase solid-state anaerobic digestion. Syst Appl Microbial. 2014;37:590-600. doi: 10.1016/j.syapm.2014.10.002. [PubMed] [Cross Ref]

[4] Lee DH, Behera Sk, Kim J, Park Hs. Methane production potential of leachate generated from Korean food waste recycling facilities: a lab scale study. Waste Manag. 2009;29:876-882.doi:10.1016/j.wasman.2008.06.033. [PubMed] [Cross Ref]

[5] Liang Y-L, Zhang Z, Wu M, Wu Y, Feng J-X. isolation, screening and identification of cellulolytic bacteria from natural reserves in the subtropical region of China and optimization of cellulose production by Paenibacillus terrae ME27-1. BioMed Res Int.2014 [PMC free article] [PubMed]

[6] Mclnerney MJ, Struchtemeyer CG, Sieber J. Mouttaki H, Stams AJ, Schink B, Rohlin L, Gunsalus RP. Physiology, ecology, phylogeny and genomics of microorganisms capable of syntrophic metabolism. Ann NY Acad Sci. 2008; 1125:58-72. Doi:10.1196/annals.1419.005. [PubMed] [Cross Ref]

[7] Schnurer A, Jarvis A (2010) Microbiological handbook for biogas plants. Swedish Waste Management U2009:03, Swedish Gas Centre Report 207, pp 1-74

[8] U.S. Environmental Protection Agency (EPA). 2011. Combined Heat and Power Partnership. Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field. October. Available at: http://www.epa.gov/chp/markets/wastewater.html verified 08/09/2012.

[9] Volta, Alessandro (1777) *Lettere del Signor Don Alessandro Volta ... Sull' Aria Inflammable Nativa Delle Paludi* [Letters of Signor Don Alessandro Volta ... on the flammable native air of the marshes], Milan, Italy: Giuseppe Marelli.