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MODELLING ENERGY RECOVERY FROM WASTEWATER TREATMENT BY ANAEROBIC DIGESTION

Odenigbo C¹ and Prof. Ademuluyi J.O²

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

²Department 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 $V_{CH4} = (0.40) |(S_o - S)(Q)(10^3 g / kg)^{-1} - 1.42 P_x|$ 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. The biogas yield obtained were used to power a micro gas turbine in order to determine electrical energy output from the system, a process that have now been commercialized for economic benefits. Equation 3.24 was derived and its consequent solution, equation 3.27 was used for that purpose. Figure 4.6 shows the energy output for experimental reactor 1. The result obtained shows a close fit between the turbine output and the model output. Precisely, a CORR value of 0.96 was obtained with a small error of estimate of 2.34 and 8.00 respectively for MAPE and RMSE. Similarly, figure 4.7 shows energy output for experimental reactor 2. In this, the coefficient of correlation was found to be 0.94 with MAPE and RMSE being 2.15 and 3.55 respectively. Figure 4.8 and 4.9 shows the energy output for model reactors 1 and 2 respectively. The CORR, MAPE and RMSE were 0.95, 3.78 and 5.51 respectively for model reactor 1 while a similar value of 0.97, 1.73 and 5.02 were recorded for model reactor 2 respectively. In all, a very good correlation values was obtained to show that energy generation from treatment plant can be modelled given the biogas yield data. It should be noted that turbine plant operational mechanism may vary

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slightly depending on their capacities; consequently, an updated recalibration of the model would be necessary.

KEYWORDS: Treatment, Sewage, Anaerobic reactor, Digestion, Energy

INTRODUCTION

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 8.2 million tons by 2010 (Lee et al., 2005). The EU produced 10 million tons of dry sludge in 2005 (Strunkmann 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 (Burke et al., 2003; Cusido et al., 2003). However, sludge treatments are expensive (Burke et al., 2003). In China, treatment and disposal of excess sludge account for 25-60% of the total expenses of a typical wastewater treatment plant (hang et al., 2009). Wastewater treatment plants represent a portion of the broader nexus between energy and water [Stillwell and others, 2009]. Collecting, treating, and discharging municipal wastewater to acceptable permit standards requires energy, mostly as electricity, but also as natural gas or other fuels. Nationwide, wastewater treatment represents 0.1 to 0.3% of total energy consumption and within local city and community government, water and wastewater treatment operations are often the largest consumer of energy [WEF, 1997]. Furthermore, energy for wastewater treatment is likely to increase in the future due to increasing population, stricter discharge requirements, and aging infrastructure. Possible future standards for removal of currently-unregulated contaminants, such as pharmaceuticals and personal care products, might require significant increases in energy consumption at wastewater treatment plants [Westerhoff and others, 2005; Zwiener and others, 2000]. Fortunately, most wastewater treatment facilities can significantly reduce their energy costs, by up to 30% or more, through energy efficiency measures and treatment process modifications [Means, 2004]. Through optimized aeration and improved pumping alone, wastewater treatment plants could save 547 to 1,057 million kWh annually, reducing overall energy use in the wastewater sector by 3 to 6% [Hoppock and others, 2008]. Wastewater treatment process modifications considered in this case study include anaerobic digestion with biogas utilization and biosolids incineration with electricity generation.

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 nutrient requirement and potential energy recovery from the produced biogas. Sewage sludge is stabilized during anaerobic digestion by converting most organic matter into biogas (Hwang et al, 2004). The conventional mesophilic anaerobic digestion process requires a long hydraulic retention time (≥ 20 days) and the operation efficiency is influenced by environmental changes. Although the thermophilic anaerobic process requires relatively less digestion time, it requires excessive heating (Zupancic and Ros, 2003). Biogas from digested sludge is now considered a bio-energy source. Our analysis provides a top-level estimate of energy savings within the wastewater sector in the United States via these two process modifications. We first

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examine potential energy recovery from anaerobic digestion with biogas utilization on a national scale. Since the state of Texas produces and consumes more electricity than any other state in the nation, we then use Texas as a testbed for analysis of energy recovery from biosolids incineration with electricity generation. These energy recovery strategies could help offset the electricity consumption of the wastewater sector and represent possible areas for sustainable energy policy implementation. Our analysis considers energy consumption and potential savings only; the economics of energy recovery from wastewater treatment, while highly relevant, is reserved for a separate analysis. Energy recovery at wastewater treatment plants represents an important policy lever for sustainability. However, to the best of our knowledge, no one has ever created a model of its potential. This work fills that gap.

The process can be divided into three stages that are performed by three different groups of microorganisms (See Figure 1.1). The first stage is called hydrolysis. During this stage cellulose, lipids, proteins, and other complex organic compounds are liquefied by the bacteria and converted into volatile organic acids through the processes of acidogenesis and acetogenesis. During acidogenesis organic molecules are converted to fatty acids, and during acetogenesis fatty acids are converted to acetic acid, carbon dioxide, and hydrogen. The bacteria that perform the first two steps are commonly known as acidogenic bacteria. The third stage is the biogas production stage. During this step methanogenic bacteria convert the acetic acid into methane, carbon dioxide, and small amounts of water vapor, hydrogen sulfide and ammonia (U.S. EPA, 2006). Maintaining methane production from an anaerobic digester is sensitive, and temperature and pH must be kept with a narrow range.

Figure 1.1



The composition of the biogas will vary depending on the facility. The efficiency of the process will be influenced by the temperature, as higher temperatures are more suitable for bacterial growth, and the retention time, which is the time that the process is allowed to take place. Not all of the soluble organic matter and organic acids will be converted into biogas; some will be unprocessed and become part of the effluent. The rest of the effluent will be a stabilized waste solution, meaning it will have a lower biological activity of organic matter (which can attract disease carrying organisms), a reduced mass of organic solids, and a reduction in the concentration of pathogenic bacteria (Parry, et al., 2004).

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Anaerobic digestion is a common part of organic waste management systems. It occurs when microorganisms break down organic material in an environment free of oxygen. The process produces biogas, which is made up of 50 to 70 percent methane, which can be used as a source of energy. Anaerobic digestion is used in concentrated animal feeding operations (CAFOs) as a way to treat livestock manure, in wastewater treatment plants (WWTPs) to treat sewage, and it occurs in all municipal solid waste (MSW) landfills as the organic waste breaks down.

WWTP of Tourh Centre – Qalyobia in Egypt has an average flow of 8000m³/day. The town of Tourh lies in middle of delta region and intensively surrounded by crops and farms. Being located in rural areas, concentrations of biodegradable components in the wastewater are higher than average concentrations in urban areas. Therefore, the energy recovered from the plant through the digester would be relatively high when compared to urban treatment plants of the same size. The plant uses activated sludge treatment process. In this process, wastewater flows continuously into an aeration tank where air is injected to mix the activated sludge with the wastewater and to supply the oxygen needed for the organisms to oxidize the organic compounds. The mixture of activated sludge and wastewater in the aeration tank is called mixed liquor. The mixed liquor flows from the aeration tank to a secondary clarifier where the activated sludge is settled out.

Most of the settled sludge is returned to the aeration tank, called return sludge, to maintain the high population of microbes that permits rapid breakdown of the organic compounds. The return sludge is diverted or wasted to the sludge handling system for treatment and disposal.

There are two main methods for sludge treatment; aerobic digestion and anaerobic digestion Aerobic digestion is a suspended – growth biological treatment process based on biological theories similar to those of the extended aeration modification of the activated sludge process. Anaerobic digestion (AD) plays an important role for its abilities to further transform organic matter into biogas (contains 65% - 70% methane by volume, 25% - 30% CO₂ and small amounts of N₂, H₂, H₂S, water vapor and other gases). The biogas or anaerobic digester gas (ADG), can be utilized to produce energy using combined heat power (CHP) technology. The plant uses the most common scenario in sludge treatment in Egypt where the thickened sludge is directly pumped to natural dewatering without involving the digestion process. Within here, the presence of anaerobic digester is assumed for sludge treatment. The production of digester gas has been estimated given the sludge daily mass, volume and concentration of biodegradable components in the raw sewage and sludge.

There is still a part of the WWTP electrical load demand which needs to be covered. Other RES (Solar and wind energy) are utilized. The software tool used for the micro-power system optimization HOMER allows modeling energy resources in the site together with the energy conversion systems and hence calculates optimum configuration and size of each component.

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

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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^{0} C water bath.

Two reactors were test reactors U1 ad 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.

Data were analyzed graphically and conclusions drawn. Microscopic examination was also carried out on the sludge for both ultrasonically treated and untreated sludge and observations were recorded. Generally conclusion was drawn on the effect of the ultrasound on the sludge and gas production.

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^oC water bath. Fig.3.1 and Fig 3.2 show the experimental setup.

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





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. It also assures the presence of an active microbial community like the one in the full-scale process. The organic matter (i.e. volatile solids (VS) present in the digested sludge should not affect the biogas production in any considerable extent.

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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 note d that the waste activated sludge was unusually wet (total solids $(TS) \le 1\%$). 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 o 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):

$$T_R = \frac{v}{r}$$
 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 o 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.

Stable Reactors: Due to foaming and occasional overflows, three parameters were modified. 1. The retention time $(T_{1:})$, 2. The proportion between waste-activated sludge and digested sludge used for feeding and 3. The height of the propeller in the reactor. When an overflow took place, the reactor was opened and refilled with fresh digested sludge.

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The volume of the exchange sludge would traditionally be seen as the sum of waste activated sludge volume and the digested sludge volume fed to the reactor. However, one could argue that only the waste of the volume of the waste activated sludge should be used. Since the digested sludge in the substrate is partially the same as the sludge withdrawn from the reactor it can be viewed only as background material being replaced. Both points of view are valid since we want to know how much sludge in fact is replaced and how much waste s activated sludge – the material of interest. During the first part of the start-up period, retention times were looked upon from the view point of only the water activated sludge.

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)

The concentration of filterable chemical oxygen demand (FCOD) was used as direct measurement of cell lysis. FCOD is defined as the COD of the remaining filtrate after centrifugation and filtration of sludge. When cell walls are disintegrated due to ultrasonic cavitations, the material inside the cell is released into the reactor suspension. An increased FCOD after ultrasonic treatment of sludge is an indication of cell lysis. FCOD of waste activated sludge was analyzed five times, pre and post- ultrasonic treatment. 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 $1.2\mu m$. Two of the FCOD measurements were also accompanied by measurements of sludge temperature at different treatment lengths.

Sub – experiment 2: Microscopic Sludge Analysis

To see if filamentous bacteria were affected by ultrasonic treatment, samples of waste activate sludge with different treatment times were examined in a light microscope. Floc size and length of filaments were studied to see if the prevalence of filamentous bacteria differed between the reactors receiving ultrasonically treated sludge and the control reactor. Extended filament length, total filament abundance and floc firmness were studied and remarks made.

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.

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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 with a pH meter according to APHA (1997) standards. The reactor effluents were analyzed with a pH meter according to APHA (1997) standards.

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.

Gas Turbine

A gas turbine is a rotating engine that extracts energy from a flow of combustion gases that result from the ignition of compressed air and a fuel (either a gas or liquid, most commonly natural gas). It has an upstream compressor module coupled to a downstream turbine module, and a combustion chamber(s) module (with igniter[s]) in between. Energy is added to the gas stream in the combustor, where air is mixed with fuel and ignited. Combustion increases the temperature, velocity, and volume of the gas flow. This is directed through a nozzle over the turbine's blades, spinning the turbine and powering the compressor. Energy is extracted in the form of shaft power, compressed air, and thrust, in any combination, and used to power aircraft, trains, ships, generators, and even tanks.

Electric Power Generation per day of Gas Yield from Reactors.

A mini gas turbine generator set was employed for determination of the electrical energy output from which a model was developed for prediction purpose. An equal amount of gas yield per day was fed into the turbine in order to determine the equivalent amount of energy output. In the end, analysis was drawn between the model results for each reactors and the turbine output for each day of gas yield. Published by European Centre for Research Training and Development UK (www.eajournals.org)

MODEL DERIVATION

Suspended growth anaerobic contact reactor process

Determination of design SRT

Biomass Mass Balance

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

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

that is;

Accumulation = inflow – outflow + net growth
$$(3.1)$$

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

Where,

 $\frac{dX}{dt}$ = rate of change of biomass concentration in reaction, (gVSS/m³.d) V = reactor volume, (m³) influent flowrate, (m^3/d) Q = concentration of biomass in influent, (gVSS/m³) X_0 = O_w waste sludge flowrate, (m^3/d) = concentration of biomass in effluent, (gVSS/m³) Xe = concentration of biomass in return line from clarifier, (gVSS/m³) X_R = net rate of biomass production, (gVSS/m³.d) rg =but

 $\mathbf{r.} = -\mathbf{Y}\mathbf{r}_{\mathrm{su}} - \mathbf{k}_{\mathrm{d}}\mathbf{X} \tag{3.3}$

where

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

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

$$r_{su}$$
 = rate of substrate utilization, (gbsCOD/m³.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 (X₀ = 0), equation (4.2) can be simplified to yield;

$$(\mathbf{Q} - \mathbf{Q}_{w})\mathbf{X}_{e} + \mathbf{Q}_{w}\mathbf{X}_{R} = \mathbf{r}_{g}\mathbf{V}$$

$$(3.4)$$

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

$$\frac{(Q - Q_w)X_e - Q_w X_R}{VX} = -Y \frac{r_{su}}{X} - K_d$$
(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.

$$SRT = \frac{VX}{(Q - Q_w)X_e - Q_wX_R}$$
(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. (4.5) can be written as

$$\frac{1}{SRT} = -Y\frac{r_{su}}{X} - K_d \tag{3.7}$$

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

$$\frac{1}{SRT} = -\mu \tag{3.8}$$

but

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

Where

S = growth limiting substrate concentration in solution, (g/m³) 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

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$$\frac{1}{SRT} = \frac{YKS}{K_s + S} - K_d \tag{3.10}$$

but

$$\mu_{\rm m} = KY \tag{3.11}$$

Where,

 $\mu_{\rm m}$ = maximum specific bacterial growth rate, (g new cells/gcells.d)

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

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

Determination of sludge production

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

$$P_{X,TSS} = \frac{QY(S_o - S)}{[1 + (k_d)SRT](0.85)} + \frac{f_d(k_d)QY(S_o - S)SRT}{[1 + (k_d)SRT](0.85)} + Q \text{ (nondegradable TSS)}$$
(3.13)

Where,

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

Determination of reactor volume and hydraulic detention time, $\boldsymbol{\tau}$

The volume is determined using the equation;

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

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X_{TSS} = MLSS biomass concentration

For hydraulic detention time, $\boldsymbol{\tau}$

$$\tau = \frac{V}{Q} \tag{3.16}$$

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

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

Simply put,

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

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

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

Where

 $V_{CH4} =$ Volume of methane produced at standard condition (O^OC and 1 atm), (m³/d)

0.35 = theoretical conversion factor for the amount of methane produced, m³, from the conversion of 1kg of bCOD at O^OC. See below.

 $Q = flowrate, m^3/d$

 $S_0 = bCOD$ 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)

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<u>Published by European Centre for Research Training and Development UK (www.eajournals.org)</u> The COD of methane is the amount of oxygen needed to oxidize methane to carbon dioxide and water.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{3.19}$$

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;

$$PV = nRT (3.20)$$

$$V = \frac{nRT}{P}$$
(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)
Т	=	temperature, k (273.15 + $^{\mathrm{O}}\mathrm{C}$)
Р	=	absolute pressure, atm

Thus, at standard condition ($O^{O}C$ and 1 atm), the volume occupied by one mole of CH₄ is obtained using eqn. (3.21).

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

V = 22.414L

So the CH₄ equivalent of COD converted under anaerobic conditions is; $(22.414L)/(64g COD/mole CH_4) = 0.35L CH_4/g COD$.

Thus, at 35^oC, the volume occupied by one mole of CH₄ is

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

V = 25.29L

So the CH₄ equivalent of COD converted under anaerobic conditions at 35° C is; (25.29L)/(64g COD/mole CH₄) = 0.40L CH₄/g COD.

It implies that the volume of methane produced per day at $35^{\circ}C$ (conversion factor at $35^{\circ}C = 0.40$) is computed using eqn. (3.18) modified, since volume occupied by gas is temperature dependent, hence,

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

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

$$P_{X} = \frac{YQ(S_{o} - S) \times (10^{3} g / kg)^{-1}}{1 + k_{d} (SRT)}$$
(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 .

Electricity generation from biogas

Producing electricity from biogas is still relatively rare in most developing countries; however, conversion of biogas to electricity has become a standard technology.

Conversion to electricity

The conversion of biogas to electric power by a generator set is much more practical. In contrast to natural gas, biogas is characterised by a high knock resistance and hence can be used in combustion motors with high compression rates. The following model was used to describe the process effectively.

$$\frac{d^2I}{dv^2} - 3\frac{dI}{dv} + 2I = v^2$$
(3.24)

Where

I = Amount of electricity generated (in kwh)

V = volume of methane gas (i.e. V_{CH4})

The plant mechanism shows that at V = 0, I = 0.75kwh and $\frac{dI}{dv}$ = 2.5.

The solution to equation (3.24) follow thus;

Complementary function (C.F) is given as; $m^2 - 2m + 2 = 0$

:.
$$(m-1)(m-2) = 0, m = 1 \text{ or } 2$$

$$\Rightarrow$$
 I = Ae^v + Be^{2v}

Particular integral (P.I) is given as

 $I = CV^2 + DV + E$

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 $:. \quad \frac{dI}{dv} = 2 \text{ CV} + \text{D} \text{ and } \frac{d^2 I}{dv^2} = 2\text{C}$ $2\text{C} - 3(2\text{CV} + \text{D}) + 2(\text{CV}^2 + \text{DV} + \text{E}) = \text{V}^2$ $2\text{CV}^2 + (2\text{D} - 6\text{C})\text{V} + (2\text{C} - 3\text{D} + 2\text{E}) = \text{V}^2$ $2\text{C} = 1, \qquad \text{C} = \frac{1}{2}$ $2\text{D} - 6\text{C} = 0 :. \quad \text{D} = 3\text{C} = \frac{3}{2}$ 2C - 3D + 2E = 0 $:. \qquad 2\text{E} = 3\text{D} - 2\text{C} = \frac{9}{2} - 1 = \frac{7}{2} \qquad :.\text{E} = \frac{7}{4}$ $:. \qquad \text{P.I is } I = \frac{V^2}{2} + \frac{3V}{2} + \frac{7}{4} = \frac{1}{4} \left(2V^2 + 6V + 7\right)$

General solution:

$$I = Ae^{V} + Be^{2V} + \frac{1}{4} \left(2V^{2} + 6V + 7 \right)$$
(3.25)

Substituting the conditions;

V = 0, I = 0.75 in eqn. (3.25), yields
0.75 = A + B +
$$\frac{7}{4}$$

 \Rightarrow A + B = -1 (i)

by differentiating equation (4.25), we obtain:

$$\frac{dI}{dV} = Ae^{V} + 2Be^{2V} + \frac{1}{2}(2V^{2} + 3)$$
(3.26)

again, at V = 0, $\frac{dI}{dV}$ = 2.5, substitute in equation (3.26)

$$2.5 = A + 2B + \frac{3}{2}$$

:. $A + 2B = 1$ (ii)

Solving equations (i) and (ii) simultaneously gives:

A = -3 and B = 2Substitute these values in eqn. (3.25) to give;
I =
$$2e^{2V} - 3e^{V} + 0.25(2V^{2} + 6V + 7)$$
 (3.27)

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.

DAY	Experimental	Experimental	Model	Model
	REACTOR 1	REACTOR 2	REACTOR 1	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

Table 4.2: Gas yield (ML/gVS) for each day for the reactors

			-	-
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

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Biogas production model

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 3.22 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.

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Fig. 4.1: The graph of variation of gas yield with days for the experimental and modeled reactors.

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

Table 4.3: Gas yield for experimental reactor 1 and model reactor 1



Fig. 4.2: Gas yield for experimental reactor 1 and model reactor1 at selected peak yield.

	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		

 Table 4.4: Gas yield for experimental reactor 2 and model reactor 2

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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.

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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.

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		

Table 4.6: TS (%) and VS (%) of experimental reactor 2 during digestion experiment

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Fig. 5.5: 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.

4.5: Electric Power Generation per day of Gas Yield from Reactors.

Table 4.7: electrical energy generated from daily gas yield from experimental reactor 1

	Experimental Reactor 1			
Day	Gas yield(ML/gVS)	Turbine Output (kwh)	Model Output (kwh)	
1	256	1.65	1.63	
2	256	1.65	1.63	
3	281	1.78	1.75	
4	281	1.78	1.75	
5	290	1.82	1.79	
6	295	1.84	1.81	
7	325	1.97	1.97	
8	314	1.83	1.92	
9	285	1.77	1.77	
10	304	1.87	1.86	
11	295	1.81	1.81	
12	322	1.99	1.95	
13	325	1.98	1.97	
14	322	1.97	1.95	
15	311	1.92	1.9	
16	311	1.9	1.9	

4.6 Energy generation model

The second part of this study focused on the energy generation from the anaerobic treatment of the sewage sludge. The biogas yield obtained in the previous section were used to power a mini gas turbine in order to determine electrical energy output from the system, a process that have now been commercialized for economic benefits. Equation 3.24 was derived and its consequent solution, equation 3.27 was used for that purpose. Figure 4.6 shows the energy output for experimental reactor 1. The result obtained shows a close fit between the turbine output and the model output. Precisely, a CORR value of 0.96 was obtained with a small error of estimate of 2.34 and 8.00 respectively for MAPE and RMSE. Similarly, figure 4.7 shows energy output for experimental reactor 2. In this, the coefficient of correlation was found to be 0.94 with MAPE and RMSE being 2.15 and 3.55 respectively. Figure 4.8 and 4.9 shows the energy output for model reactors 1 and 2 respectively. The CORR, MAPE and RMSE were 0.95, 3.78 and 5.51 respectively for model reactor 1 while a similar value of 0.97, 1.73 and 5.02 were recorded for model reactor 2 respectively. In all, a very good correlation values was

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obtained to show that energy generation from treatment plant can be modelled given the biogas yield data. It should be noted that turbine plant operational mechanism may vary slightly depending on their capacities; consequently, an updated recalibration of the model would be necessary.



Fig. 5.6: Graph of energy output for experimental reactor 1

	Experimental Reactor 2			
Day	Gas yield (mL/gVS)	Turbine Output (kwh)	Model Output (kwh)	
1	270	1.72	1.69	
2	279	1.77	1.74	
3	289	1.81	1.78	
4	289	1.82	1.78	
5	298	1.83	1.83	
6	298	1.83	1.83	
7	300	1.87	1.84	
8	282	1.79	1.75	
9	285	1.8	1.77	
10	257	1.7	1.67	
11	257	1.69	1.64	
12	285	1.77	1.77	
13	295	1.85	1.81	
14	314	1.95	1.92	
15	309	1.89	1.89	
16	285	1.79	1.77	

Table 4.8: electrical energy generated from daily gas yield from experimental reactor 2





Fig. 5.7: Graph of energy output for experimental reactor 2



Fig. 4.8: Graph of energy output for model reactor 1

		Model Reactor 1	
Day	Gas yield	Turbine	Model
	(ml/gVS)	Output (kwh)	Output (kwh)
	_		
1	248	1.62	1.59
2	252	1.65	1.62
3	280	1.74	1.74
4	281	1.78	1.75
5	283	1.79	1.76
6	296	1.86	1.82
7	312	1.95	1.91
8	314	1.96	1.92
9	275	1.71	1.71
10	300	1.84	1.84
11	296	1.83	1.82
12	323	1.99	1.96
13	327	2.02	1.98
14	318	1.98	1.94
15	309	1.91	1.89
16	306	1.88	1.87

Table 4.9: electrical energy generated from daily gas yield from model reactor 1

Table 4.10: electrical energy generated from daily gas yield from model reactor 2

	Model Reactor 2		
Day	Gas yield (ML/gVS)	Turbine Output (kwh)	Model Output (kwh)
1	266	1.7	1.67
2	277	1.74	1.73
3	281	1.74	1.75
4	284	1.78	1.76
5	299	1.85	1.83

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6	299	1.85	1.85	
7	300	1.88	1.84	
8	280	1.77	1.74	
9	287	1.78	1.78	
10	248	1.6	1.59	
11	249	1.6	1.6	
12	288	1.82	1.78	
13	290	1.84	1.79	
14	309	1.92	1.89	
15	304	1.87	1.86	
16	270	1.73	1.7	



Fig. 4.9: Graph of energy output for model reactor 2

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 resources 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. Furthermore, the other part of this study focuses on modeling the energy output from the treatment process. In this, the model gave a well fitted prediction with an average correlation of 0.96. energy recovery from the treatment of wastewater has become a potent tool in proffering solution to the energy crises facing many

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developing countries and in turn reduce the over dependency on petroleum as the major source of energy.

Recommendation

1. The model developed in this study shows a high level of accuracy and is recommended for use in the design and operation of treatment plants as well as energy generation processes.

2. Further investigation is required to validate the models developed in this study for commercialization.

3. Further study is recommended to ascertain that the methane content of the biogas produced is not affected by treatment.

4. Other methods of sewage sludge treatment is required to investigate biogas yield since the model developed in this study only considered the anaerobic method.

5. Digestion experiments on a thicker sludge, say TS of 5 - 7% is required to further ascertain the rate of production of biogas.

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