Experimental Studies of Anaerobic Digestion of Organic Fraction of Municipal Solid Waste Using a Bioreactor with Integral Flow Features

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Abstract
Inadequate slurry flow dynamics have been reported to adversely affect biodigestion process resulting in poor bioreactor performance or outright failure in some cases. The incorporation of appropriate flow features in bioreactor design is expected to provide the basis of effective digestion of organic waste thus leading to high yield in biogas production. Consequently, a bioreactor with integral flow features was designed, fabricated and employed for the experimental studies of anaerobic digestion of organic fraction of municipal solid waste. The reactor comprises two identical cylindrical vessels connected to a central substrate dispensing unit and has a total void volume of 64.8l. Substrate flow features in this reactor were characterized by an upflow coupled with a crossflow and a dispersive downflow. The bioreactor was fed batch, operated at 37oC and with substrate recirculation effectuated at 450ml per minute by an electromagnetic metering pump. The feedstock was obtained by processing organic fraction of municipal solid waste into powdery form of 500μm particle size. The substrate was prepared as slurry from the powdery feedstock and the inoculum applied was lumen contents of a freshly slaughtered cow. The performance of the bioreactor was based on the following criteria: total biogas yield per kg of raw feedstock; the proportion of methane in the biogas; the chemical oxygen demand (COD) and total organic carbon (TOC) reductions. The experimental maximum biogas-yield obtained was 17.94l/kg measured at atmosphere pressure of 1.01 bars and temperature of 29oC. This value was quite close to the theoretical value (18.55l/kg) based on a modified Gompertz equation. The proportion of methane in the gas produced was 68%. The results for COD and TOC reduction efficiencies were 95.2% and 87.6% respectively. The resulting first order kinetic constant for COD reduction based on Fenton’s first order reaction model equation was 0.312. This indicates that the Hydraulic Retention Time (HRT) can be as low as 9 days for this twin vessel bio reactor with integral flow features.

Keywords: biodigester, bioreactor, anaerobic digestion, municipal wastes, biogas, methane, slurry, chemical oxygen demand (COD), total organic carbon (TOC)

INTRODUCTION
One of the single most important limitations to high quality biogas yield is the application of appropriate flow regimes in bioreactors. Agdag and Sponza (2005) reported that the methane content from bio waste can be increased by approximately 60% and the resultant residue applied directly as organic fertilizer. In the study by Hayes et al., (1980), a horizontal plug flow digester was reported to produce nearly 20% more biogas from manure as compared to a conventional mixed flow digester.

Borole et al., (2006) reported methane production in a 100l upflow bioreactor by anaerobic digestion of organic farm waste. The results showed a clear effect of mixing on digester operation. Without any mixing, the reactor performance deteriorated within 30-50 days, whereas with mixing, continuous production of biogas was observed. According to the theme of the 4th international symposium on Bioreactor and Bioprocess fluid dynamics (1977), most biological processes carried out in industries are influenced by the relationship between the biological entities of interest and the fluid dynamics regime imposed on them. Considering the aforementioned critical role of flow and mixing regimes, it can be alluded that poor performance of some domestically designed bioreactors in Nigeria may be attributed to inappropriate or non-existent slurry flow dynamics. It could be implied that its effects were not usually considered at the bioreactor design stage. Most biogas plants were designed and fabricated intuitively because the engineering data necessary are hardly available for the numerous agricultural and household...
organic waste used as substrate. Most Nigerian cities are densely populated with concomitant high turnover of household organic waste which often undergo unacceptable levels of decay before their relocation to dump sites. The adverse environmental and health issues of this practice cannot be overemphasized. The challenge has been how to convert these wastes to bio-fuels through efficient conversion technologies. This work was aimed at developing an experimental bioreactor with intrinsic features that would enhance biodegradation of the organic fraction of municipal solid waste. It is expected that the results obtained would aid in future designs of bioreactors and in achieving higher biogas yield from similar waste material.

LIMITATIONS OF THE STUDY
The experimental work was carried out on a laboratory scale in an anaerobic process at 370C. The scope of the study was limited to the use of organic substrate materials sorted from municipal solid waste obtained from the central market Owerri Imo State Nigeria. The total volumetric load of the reactor was 62.8liters of substrate slurry. Evaluation of process dynamics of the reactor was limited to the use parameters such as Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), Operating temperature, biogas yield, methane content and hydraulic retention time.

MATERIALS AND METHODS
Physico Chemical Parameters
The study was carried out in Projects Development Institute (PRODA), Enugu Nigeria. The following physico chemical parameters were determined in order to evaluate reactor performance: Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), Viscosity, Density and pH. The COD was determined in the laboratories of the Federal Ministry of Water Resources, Regional Quality Laboratory, Enugu, Nigeria using the Nigerian Industrial standards (NIS 554) 2007 which corresponds to AOAC 973.46 (1973). The TOC was measured using Thornton 550TOC model analyser. Density of the substrate was measured with density meter KEM, model DA-130N. Kinematic viscosity was measured with Gardner Viscometer A-T model and methane measurement was carried out using the Orsat gas analyzer.

FEED STOCK PREPARATION
Organic fraction of Municipal Solid Waste (OFMSW) as presented in Table 1 was used in the preparation of feedstock. The OFMSW was obtained by careful segregation as represented in Fig1. Organic fraction comprising vegetable and plant wastes, food remains; straw and woody fibres were sorted and milled as shown in Fig 1. Fraction corresponding to 500 µm size were bagged according to standard procedure [AOAC 924-03 919240]. The substrate slurry was prepared by mixing 4.71kg of the powdery feedstock in 100l water. This gave a Chemical Oxygen Demand (COD) value of 120320mg/l. The Biological Oxygen Demand (BOD) was 780mg/l.

Table 1: Composition of Municipal Solid Waste obtained from Central Market Owerri, Imo State Nigeria

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<td>6</td>
<td>SUBSTANCES</td>
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(Source: Agulanna, 2012)

EXPERIMENTAL METHODS
This work was carried out with a twin vessel bioreactor with design features that permit a combination of flows comprising an upflow, cross flow and dispersive downflow sustained continuously by pump action in a central substrate dispenser and leading to significant performance of the reactor. Substrate slurry was forced up the dispenser vessel from its bottom by an electromagnetic metering pump at a discharge of 450ml/min. Under pump pressure, substrate slurry was forced to exit the dispenser through 4 horizontal 25mm diameter pipe outlets (2 for each twin vessel) into each of the twin vessels in a cross flow process. Subsequently, the weight of substrate coupled with continuous pump suction at the vessels bottom permit a down ward flow of substrate slurry into the twin vessels. Thereafter, a dispersive flow of substrate was induced by a distributor disc inside each reactor vessel base above the digestate bottom outlet. Digestate exiting from the twin vessels at the bottom was taken up by the pump in a continuous recycle loop. The outcome of these combined flows were to enhance mixing, provide the needed contact between microbes and substrate, reduce the resistance to mass transfer and minimize the buildup of inhibitory intermediate reactants and stabilize bioreactor environment as reported by Grady et al., (1999). The combined flow regime is intended to subvert the problem of granulation associated with anaerobic bioreactors especially the upflow types, as reported by Atiquullah et al., (1996).

INOCULUM
The inoculum selected was freshly slaughtered cow rumen contents. 800g of the fresh material was slurried into 2liters of water and sieved with 100µm sieve mesh. 800 ml of this filtrate was added to 100l of prepared substrate slurry and stirred in a mixing tank for 30minutes. The slurry was pumped to an
overhead feeder tank from where it was delivered to the twin vessel bioreactor by gravity.

**Bioreactor Experimental Set-Up**

Fig 2 represents the schematic diagram of the twin vessel bioreactor set-up. It consists of two identical cylindrical stainless steel vessels B2 and B3 of 28.4l each. The base of each vessel ends as an inverted frustum. The vessels share a central substrate dispensing unit D which has a void volume of 8l resulting to a total bioreactor void volume of 64.8l. Each of the twin vessels contains a basal disc which induces a dispersive downflow of substrate. Each of the twin vessels has the following set of accessories: pressure gauge, pressure relief valve, temperature probe, Thermostat, a substrate sampling port, electrical heating elements, seals and valves for control of flow of substrate and effluent. In addition the twin vessels share an electromagnetic metering pump. Valve X6 controls substrate inflow into the twin vessels while X7 controls outflow of effluent slurry. Valve G2 and G3 controls outflow of gaseous effluent. Substrate loading is by gravity through valve X6. On initial set up, the vessels were filled completely with substrate slurry until there is an overflow through valve G2 and G3. These valves were subsequently shut. The electromagnetic metering pump was de-aired in accordance to manufacture’s prescription. The bioreactor start up was performed by creating a head space of partial vacuum in each vessel. Substrate is continuously circulated during experimentation by the electromagnetic metering pump connected to the dispenser unit D. The pump discharged substrate into the dispenser at 450l/m. The dispenser in turn discharged substrate slurry through four pipes to the twin vessels. These connections ensured a recycle of substrate with an attendant cross flow into the twin vessels. Temperature in the vessels was maintained at 37oC by the thermostats.

**Biogas Collection**

Fig 3: schematic diagram of biogas collector (Source: Agulanna, 2012)
Fig 3 represents the schematic drawing of the biogas collector. Gas collection is by the principle of water displacement. However, Iyagba et al., (2009) prescribe the use of acidified brine solution to prevent dissolution of biogas in water. Thus, saturated acidified brine solution coloured with a blue commercial dye, in order to assist visibility of liquid levels, is the working fluid for the device. The gas collector is set up by introducing the acidified saturated brine solution into the gas collector pipe S3, through the solution inlet S4. Biogas is subsequently collected by connecting the device through valve G5 to the gas outlet of the twin vessels. Gas issuing from the bioreactor twin vessels under pressure enters through opened valve G5 of the gas collection device. Brine solution equivalent in volume flows out of the gas collector through valve G7 of the device. The rate of production of gas can be measured by the amount of brine collected.

Acclimatization of Internal Bioreactor Environment
In order to prepare the internal bioreactor environment for anaerobic digestion, the reactor was fed full-with a solution of 2 liters liquid soap in 62.8l of distilled water. The soap solution filled the entire void space of the reactor vessels. The system was run for 10 hours continuously to allow dissolution of unwanted oils or chemicals in the bioreactor. Subsequently the system was flushed and then filled with 64.8l of distilled water for another run of 10 hours. Finally the system was once again fed full with actual substrate slurry and run for another 2 days. In this way the bioreactor was freed of substances that could impair its performance. Actual experiment with the twin vessel reactor commenced afterwards.

Data Reduction Method
At the outset of experiment, the twin vessel bioreactor was initially filled with substrate slurry. A void space has to be creased in order to facilitate release of evolved biogas. This process was carried out by running the electromagnetic pump and allowing a measured one liter substrate slurry out from each of the twin vessels. Thus a one liter head space was created in each of the twin vessels, thereby reducing the substrate working volume in the twin vessel bioreactor from 64.8l to 62.8l. The experiment was carried out in duplicates and the bioreactor operated anaerobically under mesophilic temperature of 370c and data averages on measures of gas volume generated recorded six hourly.

Kinetics of the Biogas Production and Cod Reduction
It is common practice to evaluate biogas yield kinetics from organic wastes in bioreactors using empirical relationships. Napharatana et al., (2007) and Yusuf et al., (2011) recommended the application of modified Gompertz equation as given in equation 1

\[ B_t = B_{max} \exp \left[ -\exp \left( \frac{B_t}{B_{max}} - e^{k_1(t - t_0)} \right) \right] \] (1)

Where the cumulative biogas production at any time, \( B_{max} \) is the biogas potential, \( R_b \) is the biogas production rate and \( \lambda \) is the lag time for biogas production and \( t \) is the period of biogas production.

Many other researchers have applied eqn 1 in their work. Lo et al., (2011) utilized this modified equation for modelling biogas production from organic fraction of municipal solid waste (OFMSW), while Budiyono et al., (2010) applied the equation in the study of biogas yield from cattle manure. This equation was usually applied on the assumption that biogas production rate in batch condition correspond to specific growth rate of methanogenic bacteria in the bioreactor, Zwietering et al., [1990], Lay et al., [1998] and Momirlan and Veziroglu, (1999). This modified Gompertz equation will be applied to the experimental study.

Furthermore, Ghosh et al., (2011), recommended a model for biodegradation based on chemical oxygen demand (COD) reduction by Fenton’s reaction in first order kinetics. This model is expressed by eqn 2;

\[ \frac{\text{COD}(t)}{\text{COD}(0)} = \exp (-kt) \] (2)

Where \( k \) is a constant for first order kinetics Equation (2) can be rearranged to obtain

\[ \frac{\text{COD}(t)}{\text{COD}(0)} = \exp (-kt) \] (3)

Taking the logarithm of both sides of eqn 3 gives

\[ \ln \left( \frac{\text{COD}(t)}{\text{COD}(0)} \right) = -kt \]

Or

\[ \ln \left[ \text{COD}(t) \right] = \ln \left[ \text{COD}(0) \right] - k \]

Eqn (4) is analogous to the straight line equation

\[ Y = M_x + C \] in which \(-k\) represents the slope while \( \ln \left[ \text{COD}(0) \right] \) represents the intercept on the \( \ln \left[ \text{COD}(t) \right] \) axis.

This Fenton’s reaction model, in first order kinetics, expressed by eqn 2 will be applied to the experimental results in order to determine the constant \( k \) which is a measure of biodegradation.

RESULTS AND ANALYSIS
Six hourly recordings of biogas generation were carried out and the results are presented in Table 2. Daily measurements of chemical oxygen demand (COD), used for determination of treatment efficiency in anaerobic digesters, Agamuthu (1999) were carried out. The results including computed values of COD reduction efficiencies are presented in Table 3. Also, TOC measurements and computed reduction efficiencies are presented in Table 4.
Table 2: Biogas Yield

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<td>BIOGAS PRODUCTION (ML)</td>
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(Source: Agulanna, 2012)

Table 3: Chemical oxygen demand removal

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(Source: Agulanna, 2012)

Table 4: Daily TOC and Cumulative Biogas yield

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</table>

(Source: Agulanna, 2012)
The experimental maximum cumulative biogas production was 52.915 l. In terms of kg of raw feedstock, the maximum cumulative gas production was 17.941 kg. The COD and TOC reduction efficiencies were 95.2% and 87.6% respectively. Analysis of experimental results was carried out using MATLAB R12 programme. The plot of cumulative biogas production as a function of time is shown in Fig 4. The resulting theoretical kinetic model equation is expressed by equation 5.

\[ B_t = \left[-0.081e^{-4.952t} + 0.4572t - 4.952t\right] \times 10^3 \tag{5} \]

Further evaluation of the experimental biogas yield was carried out for the reaction using the modified Gompertz equation. The constants B, Rb and \( \phi \) were determined using the non-linear regression approach with the aid of MATLAB R12 software programme and the resulting kinetic parameters are presented as follows:

- Biogas production potential, \( B = 54727.456 \text{ml} = 1855 \text{ml/kg feedstock.} \)
- Maximum biogas production rate = 8991.721 ml/day
- Lag phase, \( \phi = 1/3 \) days = 8 hours.

The model equation based on the modified Gompertz model is obtained as

\[ B_t = 54727.456 \exp \left\{-0.1643\exp(1)(1/6 - ts) + 1\right\} \tag{6} \]

This model equation was observed to adequately describe biogas production for the bioreactor and has a goodness of fit (R2 values) of 0.97.

\[ y = 103(-0.0010x^2 + 0.4972x - 4.9528) \]

Furthermore, the first order equation for COD reduction based on Fenton’s first order reaction was used to assess the rate of COD reduction in the bioreactor. The resulting model equation and first order kinetic constant K was determined by applying EXCEL 2007 ANALYSIS TOOL software programme. Fig 6 represents the graph with a goodness of fit (R2 values) equal to 0.934. The model equation obtained is expressed by:

\[ y = 0.312 x + 12.29 \]

where \( y \) is \( \ln\text{COD (ts)} \) and \( x \) is time (ts) in days.

The kinetic constant, \( k = 0.312 \).

In addition, TOC as a function of time was also plotted using MATLAB R12 program (see Fig 8). The resulting kinetic model equation for TOC reduction is expressed as

\[ y = -4e+002x^3 + 7.1e+003x^2 - 4.1e+004x + 1e+005 \tag{7} \]

Finally the combined plot of TOC and biogas yield, Figure 8 shows the correlation between TOC reduction and biogas yield. These results express complementary information to the performance of the bioreactor.
A general estimate for the caloric value (Ca) of biogas is equal to 20MJ/M3, Surha and Kandpal (1990).

Thus, the energy value of the produced biogas is

$$Q = 52.915 \times 10^{-2} \times 20 \times 10^6 = 1058300\text{joules}$$

The ratio of energy value of biogas to power input in bioreactor is given by

$$\frac{1058300}{33.82} = 31292\text{joules/watt}$$.

This nominal ratio of 31292J energy value per unit power input is for the experimental scale production. This ratio is expected to improve for higher nutrient substrate applications. For larger industrial plants, the factor of economy of scale would most probably bring about an increase in this ratio with attendant higher economic benefit. Although, this ratio does not include other operational power requirements of substrate preparation and transfer into feeder tank, it presents an attractive economically viable option for large scale processing of organic municipal waste into biofuel.

CONCLUSION AND RECOMMENDATION

The bioreactor operated in nine days hydraulic retention time at mesophilic temperature of 370c. COD and TOC reduction efficiencies were quite appreciable at 95.5% and 87.6% respectively. Experimental maximum biogas yield of the bioreactor was 17.94l per kilogram of raw feedstock material. This value is consistent with the theoretical maximum biogas yield of 18.55l/kg based on a modified Gompertz equation.

The first order kinetic constant for COD reduction based on Fenton’s first order reaction was 0.312. Furthermore, the estimated biogas energy yield per unit nominal operational power input is 31292J/w. These results show that the twin vessel bioreactor with integral flow features, as described, demonstrated high performance in biogas yield and digestion efficiency. The methane content of the biogas was 68%. Considering that anaerobic digestion is exothermic, a country like Nigeria, where the temperature range of 20-40 0C is attainable throughout the year, provides a suitable environment for mesophilic digestion with no external heat requirement, (Anyawu, 2002). Therefore, it is recommended that a scale up of this twin vessel reactor be sponsored by the Nigerian government to enable the demonstration of an industrial ability to efficiently convert organic waste to biogas, thereby attracting entrepreneurial interest for this work.

REFERENCE


FIG 1: Process/Product chart for the preparation of OFMSW to powdery form
(Source: Agulanna, 2012)