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Comparative Study on Biogas Yields of Plug Flow and Batch Reactors fed with Rice Straw at Mesophilic Temperature

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Abstract

The present energy crisis has stimulated various research activities to evaluate energy potentials of renewable energy sources. Improper disposal of rice straw constitutes nuisance to our environment especially in most rice producing states of Nigeria. To this end, the biogas potential of rice straw was evaluated in Plug Flow Reactor (PFR) and Batch Reactor (BR) operated at mesophilic temperature (37^oC). A 140-litre capacity PFR was filled with 105 litres previously digested sludge as inoculum. The loading of the rice straw into the reactor was commenced at a low L_R of 0.5 goTS/l.d and was increased weekly by 0.5 goTS/l.d until a L_R of 4.5 goTS/l.d was attained. For the batch reactor, 10.15 g of rice straw was loaded into each of the two digestion vessels. Two additional vessels were filled with inoculum as control. For the PFR, the biogas produced was collected using gas bags and then measured with a multi-chamber rotor gas meter. The gas analyzes was done with an Infrared Gas Detector. The scale wet gas collectors were used for the batch reactor and the gas measurement done with the gas analyzer (Model GA 2000). It was established that the biogas yields increased with increase in L_R (PFR). The highest biogas yields of 0.20 l/goS and 0.167 l/goS were recorded in PFR and BR, respectively. In all, continuous feeding using PFR (at optimum L_R) has been established to be better than batch feeding using BR at mesophilic temperature.

Keywords: Renewable energy; rice straw; Biogas; Loading rate; Plug flow reactor

1. Introduction

Organic wastes constitute nuisance to our environment and should be gotten rid of. One of the ways to do this is bioconversion to biogas through anaerobic digestion. Also, one of the major problems being faced by most African countries is energy. Conventional sources of energy appear to be inadequate in meeting the energy needs of the continent especially because of the environmental problem associated with its usage. Combating energy problem confronting most African countries requires a shift into alternative sources of energy. However, there are several challenges that are associated with the conventional energy sources. These challenges include negative health effect of discharges from fossil fuel into the atmosphere, unstable fuel prices and its non-renewability. Biogas, an environmentally friendly gas is produced through anaerobic digestion. It has been forecast that 20% of energy that will be consumed in the year 2020 will come from renewable energy sources [EurObserver, 2010].

According to Jekayinfa and Scholz (2009), crop residues are available in abundance. These residues are mostly burnt in the rural area since they are not compact enough to be used as fuel. However, they could be harnessed for energy production. Anaerobic digestion makes possible the use of agricultural residues for the benefit of mankind. Agricultural residues which could be converted to biogas are sugarcane bagasse, husks from jatropha, maize stalks and cobs, rice straw, wheat straw, water hyacinth, press cake and so on. The use of agricultural crop residues for biogas production will benefit our environment in the form of reduced nitrogen leaching from arable land and improved efficiency in the use of plant nutrients [Borjesson and Berglund, 2003, SJV, 2004].

Various biomass sources have been used by researchers for the production of biogas. Some of these common sources are agricultural crops and or their residues [Adebayo et al., 2018; Santi *et al*, 2015; Adebayo *et al.*, 2015a], livestock residues [Zhang et al., 2014, Adebayo et al., 2015b], organic waste [Linke and Schelle, 2000], sewage sludge [Caporgno, 2015], municipal solid waste [Pognani, 2009, Macias-Corral, 2008]. The main constituent of biogas is methane, with a significant proportion of carbon dioxide, and smaller quantities of other gases such as nitrogen and hydrogen [Keefe and Chynoweth, 2000]. Temperature, organic loading rate, $\boldsymbol{L_R}$, feedstock properties, pH, Hydraulic Retention time, HRT, type of digesters among others are some of the factors that affect anaerobic digestion [Adebayo *et al.*, 2015c]. To this end, laboratory scale plug flow and batch reactors were used for the evaluation of biogas potential of rice straw at mesophilic temperature (37^oC).

2. Materials and Methods

2.1 Materials

The following materials and equipment used were used in this research; the plug flow reactor (digester), thermostatic cabinet for batch experiment, water tank, rice straw and inoculum. The PFR was fitted with pump which helps to agitate the substrate in it. The rice straw used for this experiment originated from Cuba, having been brought to the Leibniz-Institute for Agricultural Engineering, Potsdam in Germany for research. It was mechanically pre-treated to aid degradation. This was done by reducing the size using a standard size reducing machine. The size was reduced to between 2 to 5mm.

2.2 Chemical and thermal Properties of the Substrate

The following chemical and thermal properties of rice straw were determined in the laboratory; the Total Solid (% TS), Organic Total Solid (% oTS), Ammonium Nitogen (NH_4-N g/kgFM), N_{kjel}, g/kgFM, Phosphorus, P (mg/kg TS60°), Potassium, K (%TS), Crude Fibre (%TS), pH and Conductivity (mS/cm) using standard methods [APHA, 1992, VDI, 2006].

2.3 Methods

2.3.1 Plug Flow Reactor

A plug-flow digester previously designed and fabricated comprises of a horizontal tank with water jacket through which heated water from the heater flows to maintain a constant mesophilic temperature (37^{o}C) in the fermenter (Figure 1).

The reactor was fed on continuous basis (daily) and this allows the substrate to move slowly in the form of a ‘plug’ through the tank towards the effluent reservoirs. The 140 litres capacity PFR was filled with 105 litres of pre-cultivated adapted sludge as inoculum leaving 25% of its volume as headspace for gas production. The digester was fed from one end and the digestate which can flow over the ram incorporated inside the reactor is then emptied using the hole provided through the top cover of the reactor. The temperature of the digester was maintained at the mesophilic value of 37^{o}C by circulating the heated water through its jacket. The feeding of the reactor with rice straw (calculated using equation 1) was started at a low OLR of 1.0 g oTS l^{-1} d^{-1}. The L_R was raised by 0.5 g oTS l^{-1} d^{-1} every 7 day (weekly) as recommended for crop residues (VDI, 4630). The biogas produced was collected in a gas bag (LINDE), the volume measured with a multi-chamber rotor gas meter (RITTER) and analyzed twice weekly using an Infrared Gas Detector (PRONOVA). The loading of the reactor was monitored with respect to the biogas yields and was stopped at L_R of 4.5 goTS/l.d.

$$M_s = \frac{L_R \times R_V}{C_s} \qquad (1)$$

Where:

M_s = Mass of substrate, (g)
L_R = Loading Rate (organic), (goTS/l.day)
R_v = Reactor volume, (litres)
C_s = substrate concentration, (%)

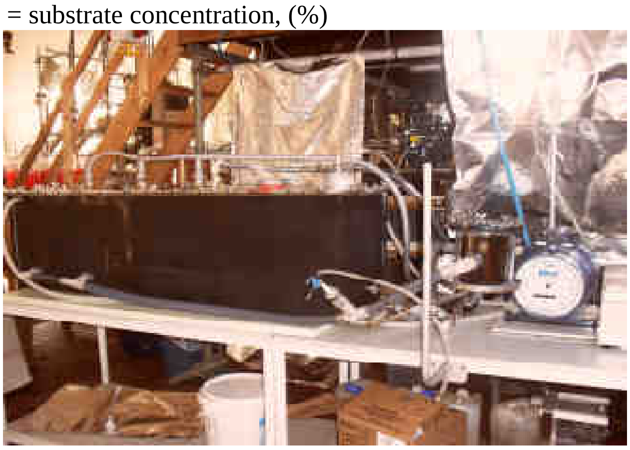

Figure 1: Plug Flow Reactor Set up

2.3.2 Batch Reactor

The substrate (rice straw) was kept in the refrigerator at temperature +3°C. German standard procedure was used in determining the amount of substrate fed into the digestion bottles (equation 2).

$$\frac{oTS_{substrate}}{oTS_{seeding\ sludge}} \leq 0.5 \qquad 2$$

Where:

$oTS_{substrate}$ = organic total solid of the substrate and;
$oTS_{seeding\ sludge}$ = organic total solid of the seeding sludge (the inoculum)

Batch experiments were carried out in lab-scale vessels with two replicates as described by Linke and Schelle (Linke and Schelle, 2000). A constant temperature of 37°C was maintained through a thermostatic cabinet heater (Figure 2). Anaerobically digested material from a preceding batch experiment was used as inoculum for this study. The chemical and thermal properties of the rice straw and inoculum were determined. Vessels (1 litre capacity each) were filled with 800g of the stabilized inoculum. The substrates fed into the digestion bottles was calculated using equation (2). The calculated amounts of the substrates (10.15g), using equation (3) was added to 800g inoculums to ensure compliance of the oDM feedstock to ODM inoculum ratio being less or equal 0.5 as it is recommended in VDI 4630 (equations 2 and 3). Two digestion bottles were also filled with 800g of inoculums to serve as control. Scaled wet gas meters were used to collect the biogas produced for 34 days when the experiment was terminated according to VDI 4630 (daily biogas rate is equivalent to only 1% of the total volume of biogas produced up to that time). The volume of the gas produced was measured daily. Besides, other gas components, methane (CH_4) and carbon dioxide (CO_2) contents were determined about six times during the batch fermentation test using a gas analyser GA 2000. The test was conducted in two replicates. Plate 1 shows the set-up of the batch experiment conducted at mesophilic temperature (37°C).

Quantitative evaluation of the results gained in batch anaerobic digestion tests included the following steps: standardizing the volume of biogas to normal litres (1_N); (dry gas, t_o=273 K, P_o=1013hPa) and correcting the methane and carbon dioxide contents to 100% (headspace correction, VDI 4630). Readings were analysed using Microsoft Excel spread sheet.

Equation (2) can be modified to read

$$p_i = \frac{m_i . c_i}{m_s c_s} \qquad 3$$

Where

p_i= mass ratio=2 ; m_i= amount of inoculum, g
c_i=Concentration of inoculum, oDM in % Fresh mass
m_s= amount of substrate,g
c_s= Concentration of substrate, oDM in % fresh mass

Plate 1: Experimental set up for batch digestion

3. Results and Discussion

Table 1 shows the results of the laboratory analysis of rice straw. Figure 2 presents the relationship between the yields (biogas and methane) and the L_R. The biogas yields of rice straw at L_R of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 goTS/l.d were 0.20, 0.11, 0.15, 0.14, 0.16 ,0.17, 0.16, 0.16 and 0.18 l/goS respectively with the corresponding methane (CH_4) yields of 0.0865, 0.058, 0.080, 0.076, 0.070, 0.087, 0.075, 0.085 and 0.071 L CH_4/goS respectively.

The highest biogas yields of 0.20 l/goS was recorded at the OLR of 0.5 goTS/l.d. The biogas and methane yields from L_R of 1.0 to 4.5 goTS/l.d appeared relatively constant indicating that it is not advisable to continue to increase the L_R. The reactor can be run at the L_R of 0.5 goTS/l.d. The will safe materials and at the same time give satisfactory yields. The yields recorded after the optimum point (L_R of 0.5 goTS/l.d) were no longer commensurate with the feed input and hence reducing the digestion efficiency of the reactor. Figure 3 presents some relatively constant yields with increase in L_R after L_R of 0.5 goTS/l.d.

For the batch reactor the average Organic Dry Matter (ODM) biogas and methane yields of 0.167 l_N/goDM (oS) and 0.116 CH_4 l/goDM (oS), respectively (Figures 4, 5 and 6). Comparing this with the yields from PFR, the biogas yield at L_R of 0.5goTS/l.d was a higher than what was obtained from the batch reactor. It is also worthy of note that the batch reactor was loaded once, and the yields measured with time. The PFR on the other hand was daily loaded with seven feeds per week. In all, continuous feeding used in PFR produced higher yields than batch feeding used in BR. This agrees with previous research (Osita *et al.*, 2014).

Table 1: Chemical and thermal Properties of Rice straw and inoculum

Parameters	Rice straw	Inoculum
Total Solid, TS (%)	74.68	2.13
Organic Total solid, oTS (%TS)	73.15	48.25
Organic Total solid (%FM)	54.63	1.03
TS (60°-105°C)	97.12	-
NH_4-N (g/kgFM)	0.19	0.31
N_{kjel}, g/kgFM	1.51	0.85
Pmg/kg TS60°	584.8	306.6
K %TS	1.18	15.50
Crude Fibre(%TS)	33.33	4.43
pH	5.22	8.16
Conductivity (mS/cm)	0.185	11.56
Fat (%TS)	0.39	-
Ethanol (g/l)	0.04	<0.04
Propanol	<0.04	<0.04
Total Acetic Acid	0.84	0.33
N (%)	0.397	
Carbon (%)	44.99	-

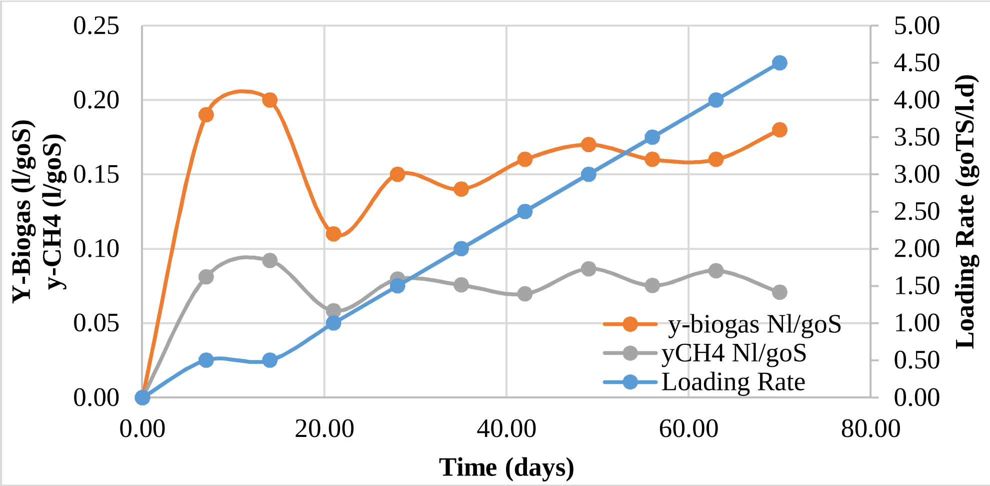

Figure 2: Plots of y-biogas, y-CH_4 and L_R against Time (PFR)

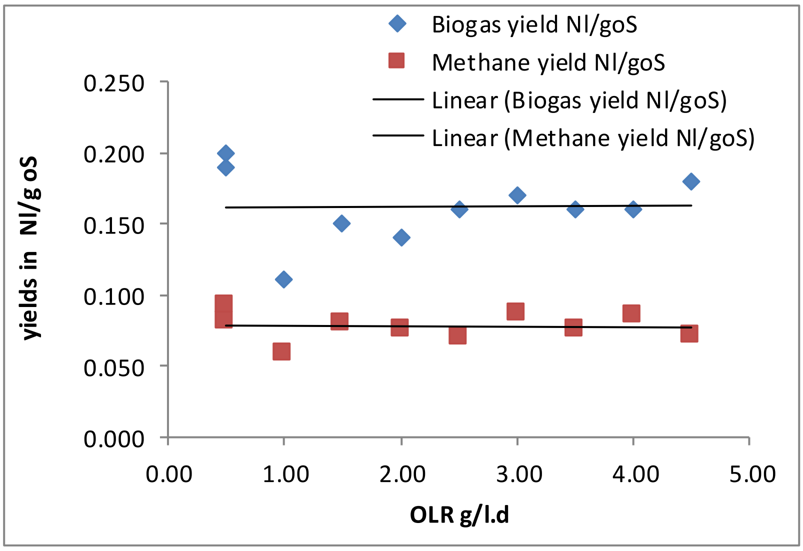

Figure 3: Plot of yields against Loading Rate (PFR)

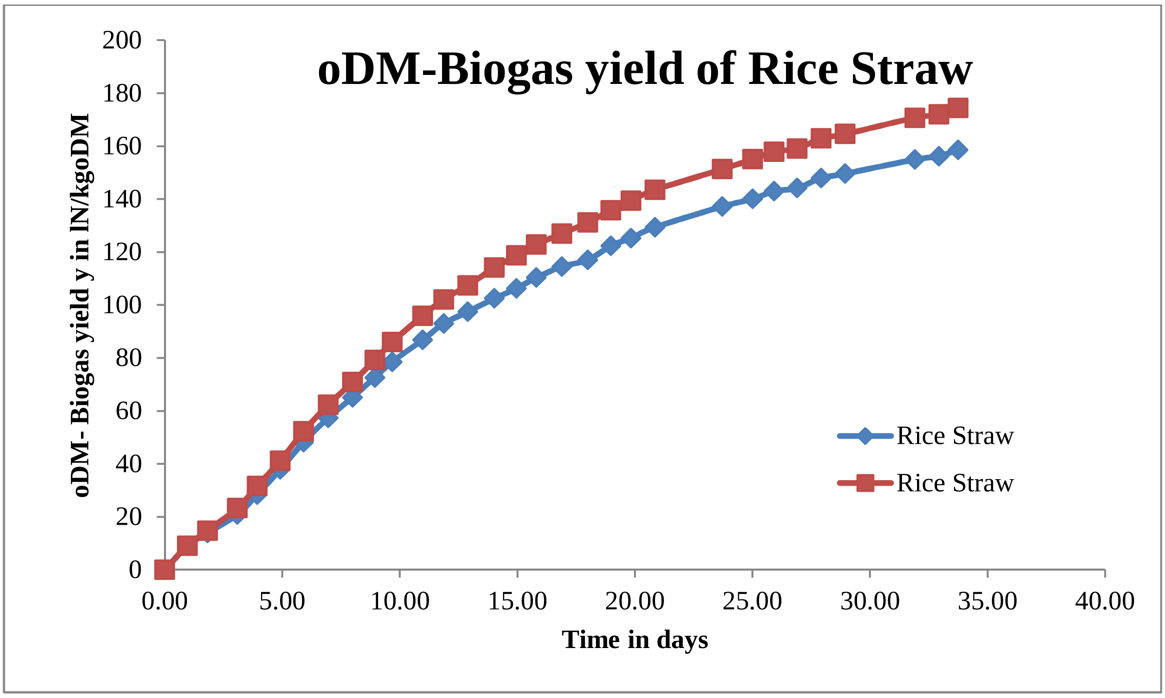

Figure 4: oDM Biogas yield (BR)

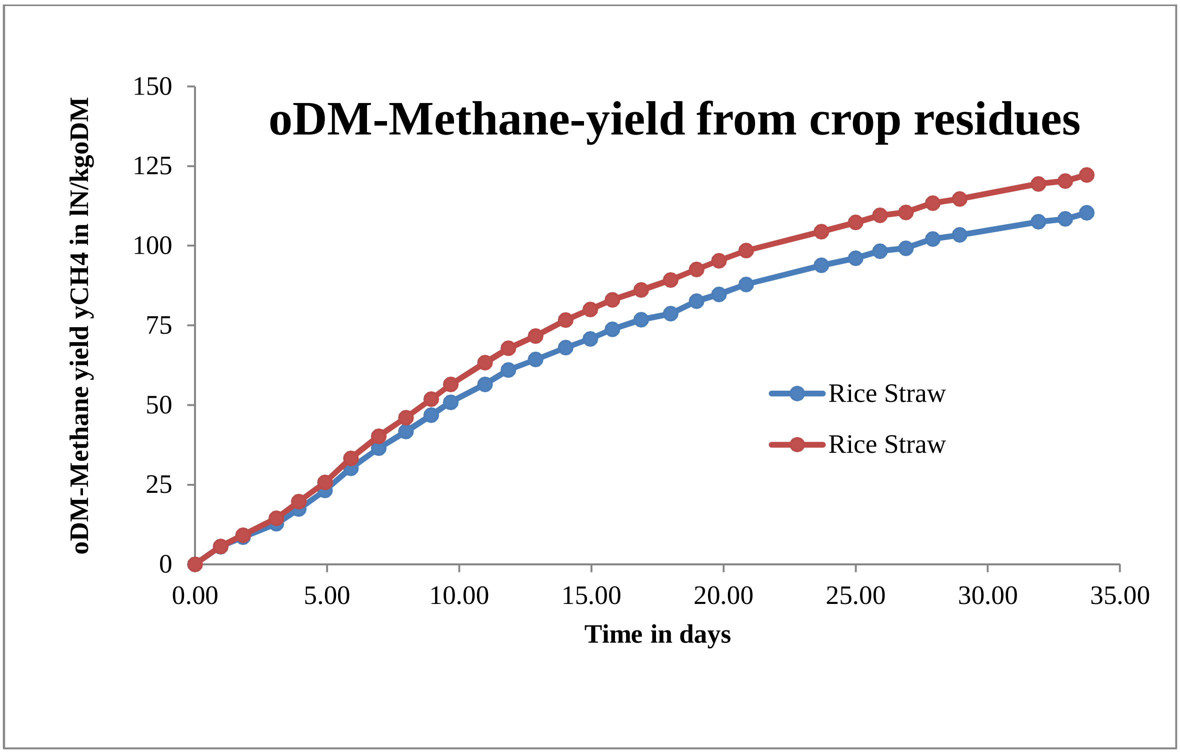

Figure 5: oDM Methane yield (BR)

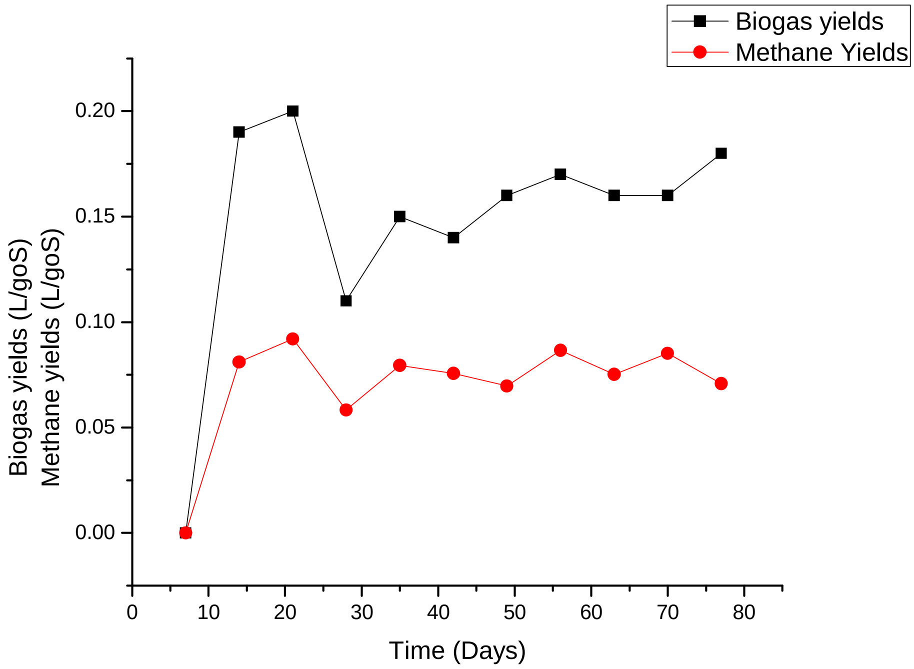

Figure 6: Biogas and Methane yields of rice straw using a batch reactor

4. Conclusions

From the results obtained, the following conclusions could be drawn:

- An OLR of 0.5 goTS/l.d gave the highest biogas yields and thus can be recommended as the L_R for running the PFR. Also, the highest biogas yield of 0.167 l_N/goDM (oS) was obtained when the batch reactor was used at mesophilic temperature.
- Continuous feeding using PFR (at optimum L_R) has been established to be better than batch feeding using BR at mesophilic temperature.
- Rice straw can be harnessed to produce biogas using a batch reactor for short term operation and PFR for long term operation.

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