Mesophilic Process Control and Optimization of Anaerobic Digestion of Domestic Food Waste

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ABSTRACT
Anaerobic digestion (AD) is a biological but engineered process in which micro-organisms break down the organic matter in wet biomass waste (sewage sludge, animal and food waste & slurry) in the absence of O_2, to produce biogas (CH_4, CO_2, H_2S & H_2) and digestate (a nutrient-rich bio-fertilizer). The aim is to understand the dynamics of AD by determining how pH and nutrient characteristics affects AD for process optimization. To achieve this, an AD laboratory-scale semi-continuous continuously stirred tank reactor (CSTR) fed at OLR;1.5gVS/L.d with food waste of 18% total solids, (TS) and 16.5% volatile solid (VS) were subjected to Mesophilic (35^0C) conditions and Hydraulic residence times (HRTs) of 28days at pH values of 6.0, 6.6, 7.2 and 7.8. Based on bio-kinetics of 1st order degradation, a statistical non- regression tool (R^2=0.95) was used to predict the biogas production (BGP). Results showed that at 35^0C and pH; 6, 6.6, 7.2 and 7.8, biogas production was 625.5ml/gVS, 696.5ml/gVS, 709ml /gVS and 685ml/gVS destroyed respectively indicating optimum performance at pH, 7.2. Again, to optimize the process, partial pressure of H_2 was reduced below10.132Pa and pH maintained by buffering with $KHCO_3$. CH_4 production was 62.5% (35^0C) at pH 7.2 and 48.5% (35^0C) at pH 6. The system efficiency of removal at pH 7.2 was 60% VS at 35^0C indicating the most destroyed nutrient character determining BGP. The CH_4 can be used to generate electricity by piping it to a combined-heat and power (CHP) engine while the heat produced can be used for space heating. Further research should be undertaken; for a different waste and in thermophilic condition and to develop an AD expert control system to enhance the process in future.

KEYWORDS: *Biogas production (BGP), Cumulative Biogas Production (CBGP), pH, Digestate, Biomass, Feedstock, Nutrient Character, Mesophilic, Volatile Solids*

1.0 INTRODUCTION

Anaerobic digestion is a natural process that has come a long way in treatment of waste. As at 1930 work has started in engineering the process of anaerobic activity with the first digester being built in India. The technology is being improved daily for optimum performance. With the rising demand for renewable energy (Biofuel), environmental protection and sustainable development, anaerobic digestion of biogas technology has attracted considerable attention in the modern world of science and technology. AD involves four distinct biological stages: Hydrolysis, acidogenesis, acetogenesis and methanogenesis which is a non-linear process very difficult to control, hence require expert operation to maintain performance. Therefore, a lot of research has been carried out to excavate reliable result for optimum performance. Bayr and Rintala (2012a) writes that a mesophilic maintained CSTR in a co-digestion of rendering and slaughterhouse wastes yielded $0.72m^3$ CH_4/kg VS destroyed with the hydraulic loading rate (OLR) of 1-1.5kg VS/m d. There are many parameters that play crucial role in the optimization process. In some systems, thermophilic temperature produces CH_4 in a short HRT. Bayr and Rintala (2012b) proved that AD of pulp and paper mill primary sludge (PS) in a thermophilic CSTR produced $0.19\text{-}0.24m^3$ CH_4/kg VS in an OLR of 1-1.4kg VS/m d in a HRT of 16-32days. Different biomass can function at different temperature depending on many factors such as the feedstock characteristics such as the available TS, VS and VFA for consumption. If the condition is arbitrarily changed, then the biomass will be affected. Yi et al, (2014) studied the performances of mesophilic anaerobic digestion of food waste with different total solids contents from 5% to 20% and discovered that better performances as a result of volatile solids reduction and methane yield were obtained in the reactors with higher total solids content. Reports also indicate that a mixture batch (mixed substrates) produces better performance than alone (single type of substrate) probes. Thus Cioabla, et al, (2012) observed that a mix substrate batch is able to produce larger quantities of biogas, with average value of 0.405 m /day, while the wheat bran batch had smaller average value of 0.323 m /day. Toxic shock loads or high OLR may be tolerated by an adapted community, whereas they could lead to process inhibition (Meyer and Edwards, 2014). For biomass to thrive, they must be acclimatised with their immediate conditions and their roles are defined (Demirel abd Scherer, 2008) hence the microbial activities in a successful AD is as a result of the co-operation and synthropy of hydrolysing, fermentative, acetogenic and methanogenic bacteria (de Bok et al, 2005). Biomass is also seriously affected by the nutrients in the feedstock. Vrieze and Boon, (2017) reports that in an AD performance recovery test of high-salinity wastewater, methane production decreased from $625\pm17\text{-}232 \pm 35$ mL CH_4/d for 20.4 ± 1.4g COD removed indicating a process disturbance which was recovered in a shift to waste activated sludge but not the microbial community composition. Also, pH effect is a result of the accumulation of amino acids, VFAs etc resulting in the fall in pH. Jayaraj et al, (2014) writes that at the pH of 7, the AD of a domestic waste resulted in the highest BGP after subjecting the substrate to different pH values. Wijekoon et al, (2011) has shown that an increase in OLR from 5-12kg COD/m^3 d increased VFA concentration and n-butyrate. However, OLR is a method of controlling pH (different from buffering) when amino acids and acetic acids accumulate with fall in pH. This study gives an insight into the effect of the variation of critical controlling factors; pH and feedstock characteristics and determine the process of optimization of the mesophilic AD.

1.1 Benefits of AD

There are millions of tonnes of food waste generated each year. If only 50-60% of these wastes are degraded by AD, then there is hope for a cost-effective and efficiently eco-friendly way of waste management and recycling. For Africa, this is a potential avenue to tackle the power crisis bedeviling the continent. A host of communities can utilize the methane gotten from biogas to power their homes and use many things to better their lives. It can also create jobs for the people. AD can be an avenue for the reduction of the emission of greenhouse gas effect by fossil fuel replacement, reducing energy footprint of waste plants, almost elimination of CH_4 gas emission from landfills, use of eco-friendly fertilizers instead of industrial chemical fertilizers, as cooking gas and space heating. Biogas produced from anaerobic digesters can be connected to a Combined Heat and Power (CHP) engine to generate renewable energy.

2.0 METHODOLOGY

2.10 Feedstock/Substrate

Food waste used for this experiment was sourced from the Abuja hostel of University of Port Harcourt, Rivers State, Nigeria. The food waste was prepared by first removing non-digestible solids. The wet biomass was obtained by masticating and subsequent crushing of the food waste by an electric crusher which was thoroughly mixed and carefully stored at 5^0C.

2.20 Characterization of the feedstock/substrate

The analytical method was performed based on the standard method for wastewater/sludge test (APHA, 2012). The total solids (TS) (APHA - 2540B) of the food waste was determined as 18% while the volatile solids (VS)(APHA - 2540D) was 16.4% (APHA, 2012) and COD, 15% which is in concurrence with Municipal solid Waste (MSW) or Food wastewater (Peces et al, 2014). NH_4^+ produced by the release of NH_3(as a result of the accumulation of amino acids) was buffered by the addition of $KHCO_3$ to form NH_4HCO_3 to produce a desired pH of 6, 6.6,7.2 and 7.8 (Gerardi, 2003, and APHA - 2320 B, 2005) measured with a pH meter. The substrate and the digestate were characterized before and at the end of the AD respectively. This is to determine the removal/destruction (of VS) efficiency of the digester. Inoculum was obtained from poultry excreta at the feed: inoculums ratio (7:1)

2.30 Experimental Procedure

Digesters consist of four (4) identical 2.5L conical bottom laboratory-scale semi-continuously fed continuously stirred tank reactors (CSTRs) at mesophilic temperatures of 35^0C. These vessels are akin to the egg-shaped anaerobic digesters in terms of mixing and suspension of grit. The mouths of the vessels were modified with rigid lid opened in four places; Influent tube, Effluent tube, Mixer Shaft, and Gas Line outlet. Its lid is modified to accept a threaded thermometer mounted to measure the temperature. Thermo scientific Orion Benchtop pH Meter (Star A211 pH meter) was used to measure the pH at the end of every feeding cycle. The temperatures of the digesters are maintained using external circulating water bath attached to a 14mm vinyl tube water jacket around the digester. The four vessels were labeled D_1-D_4 and maintained at 35^0C and pH values of 6, 6.6, 7.2, and 7.8. The sludge was buffered by the addition of $KHCO_3$ to form NH_4HCO_3 and maintained at a desired pH of 6, 6.6, 7.2 or 7.8. The vessels have mechanical stirrers for proper mixing of the substrates. Each vessel was fed semi-continuously with 2L wet biomass from day 1 through a syringe-like apparatus under an air tight anaerobic condition with solid feed of 7% and OLR; 1.5gVS/Ld on daily basis (once-a-day draw off and feeding). The HRT is 28 days. The primary sludge was heated gently before introduction into the reactors which were purged with nitrogen gas for 5min at 35^0C to provide anaerobic conditions. Biogas produced passes through a respirometer (ANR-100) system and was read by a computer system. The biogas quality was analysed by chromatographic method on a Shimadzu Gas Chromatograph (Model GC-2014) with

a thermal conductivity detector (TCD-14). The TCD-2014 unit consists of packed column measurement design which employs semi-diffusion process. Helium was used as the carrier gas. Headspace hydrogen gas concentrations were analysed using a Reduction Gas Detector (Trace Analytical RGA5).
The Volatile acids (VS), Volatile fatty acids (VFA), alkalinity (mg/L $CaCO_3$) were analysed twice a week. VS and VFA was analysed on a Shimadzu Gas Chromatograph (Model GC-2014) with a Flame Ionization Detector (FID-2014)

2.40 Kinetic Prediction
The degradation of the wet biomass was assumed to obey a 1st order decay rate. A nonlinear statistical regression analysis of first order reaction equations were performed using MATLAB software to assist in interpretation of the Cumulative Biogas Production (CBGP) with confidence level of regression, $R^2 = 0.95$.
First order decay rate, $G = G_0\,(1-e^{-kt})$
Where G = CBGP at time t-days. G_0 = Biogas potential of the substrate. K= rate constant. MATLAB Software was used to determine G_0, K and predicted CBGP.

2.5 Precaution
Temperature fluctuations have greater effect on the methanogens than the operating temperature according to previous studies. So, the temperature fluctuations was kept at 2-3 ^{0}C

3.0 RESULT AND DISCUSSION
3.10 pH variation
During the experiment, significant observations were made. The most outstanding was the variation in the volume of **BGP/gVS destroyed** and Cumulative Biogas Production (**CBGP)**.

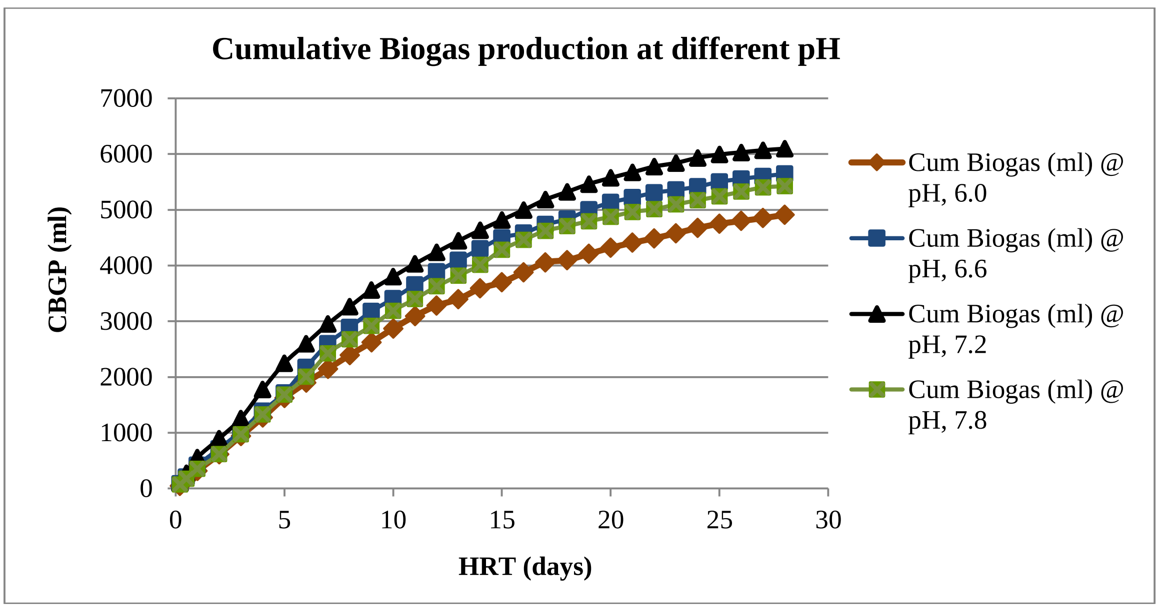

Fig1.0: *CBGP at mesophilic condition and different pH*

The 28 days CBGP was 4910, 5690, 6095 and 5425ml for pH values of 6, 6.6, 7.2 and 7.8 indicating a very high gas production for pH 7.2 and 6.6. Importantly, the BGP Potentials at the investigated pH values of 6.0, 6.6, 7.2 and 7.8 were 629.5ml/gVS destroyed, 696.5ml/gVS destroyed, 709ml/gVS destroyed and 685ml/gVS destroyed respectively. It can be said that at pH 7.2 (709ml/gVS), the system performance was optimum because it produced the highest BGP/gVS destroyed followed by 696.5ml/gVS destroyed for pH, 6.6. The lowest BGP potential was 629.5ml/gVS destroyed for pH 6.0 which is acidic because of the accumulation of VFA (Westerholm et al, 2012). At 7.2, it could be explained that since methanogenic archaea (CH_4-producing bacteria) are very sensitive to pH and temperature, 7.2 must have offered the most favorable condition for their action as against the acidogens which thrive very well in acidic condition. Fig 1.0 and 2.0 show the curve and chart of the mesophilic CBGP and Biogas potentials at pH values of 6, 6.6, 7.2, and 7.8.

Investigation into the Daily Biogas Production (DBGP) showed that, BGP was high initially but declined as the days go by. Fig 2.0 shows that the pH 7.2 had the highest daily biogas production of 519ml on the 4th day, against 350, 461and 420ml at 6, 6.6.and 7.8 on the 5th, 6th and 7th day respectively apparently showing that the optimized pH condition is 7.2. This implies that the rate of biogas production was fastest at pH 7.2 at the early stage of the process. The energies of the microbial community are high and the consumptive nutrients were available at the beginning which resulted to fast degradation process. As the process proceeds, later the CBGP began to decline because of the exhaustion of microbial energies.

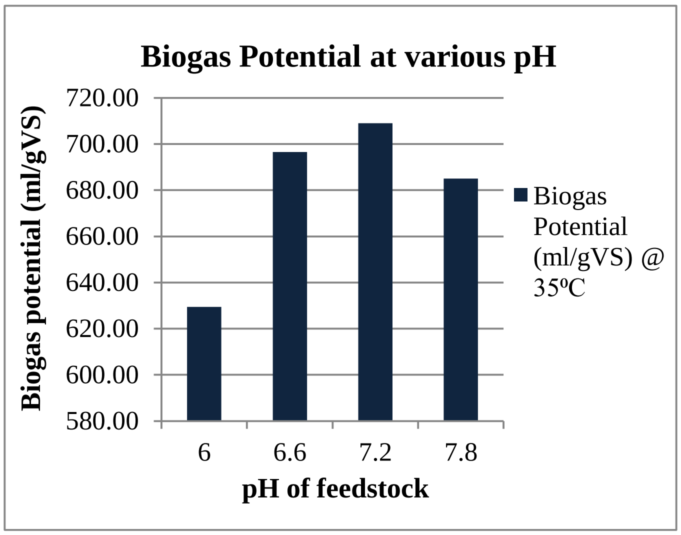

Fig 2.0: *Maximum Biogas Potentials*

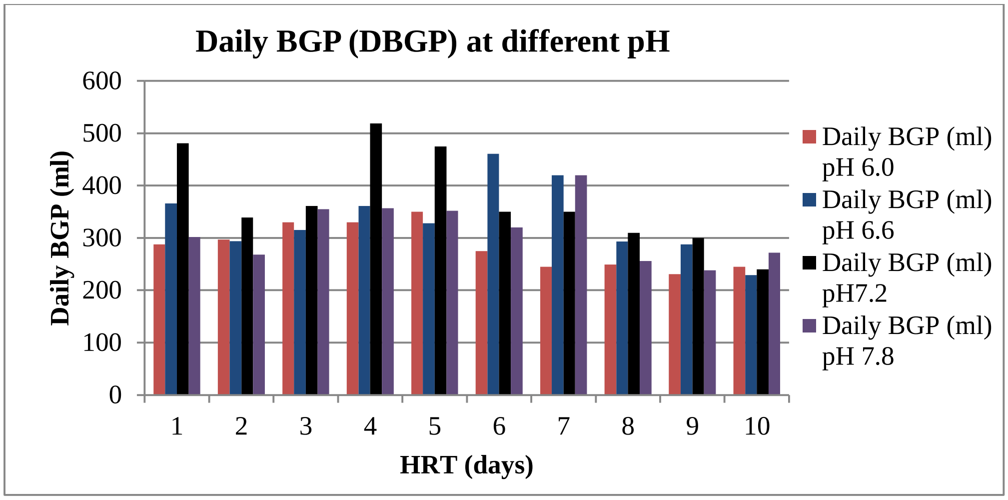

Fig 3.0 Daily Biogas Production for the 1st ten days

Table 1.0: Mesophilic degradation constants

pH	Degradation constant K (35^0C)
6	0.0610
6.6	0.0625
7.2	0.0680
7.8	0.0620

Table 1.0 show that the highest degradation constant is 0.680 at pH 7.2. This implies that the highest degradation rate is at pH 7.2 followed by 0.0625, 0.062 and 0.0610 for pH 6.6, 7.8 and 6.0 respectively. At pH 6.0, the lowest degradation rate was recorded.

3.3 Methane production

The gas chromatography carried out (*Fig 4.0)* shows that the highest % CH_4 was produced at pH 7.2 and least at pH 6.0. This condition can be said to be the most favourable condition for methanogens (aceticlastic and Lithotrophic) to thrive in the production of biogas. This result in *Fig 4.0* is agreeable to De Graaf and Fendler, (2010) and Anonymous, (2010).

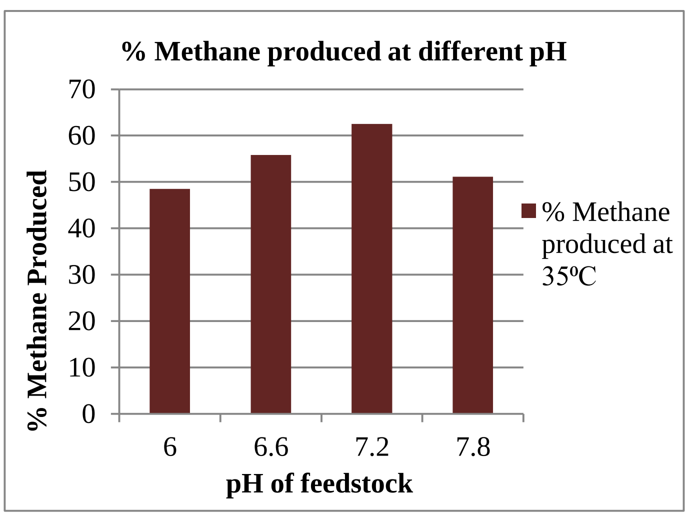

Fig 4.0: % methane produced in mesophilic condition

3.4 Digestate

The substrate and digestate characteristics recorded in table 2.0 and 3.0 showed that the highest removal efficiency of TS, VS and COD are 58%, 60% and 54% respectively at pH 7.2 apparently showing that the VS is very crucial and has a significant effect on BGP in AD process (Metcalf and Eddy, 2003).

The implication of this result is that in this system, 58% of TS, 60% of VS and 54% of COD were consumed for BGP.

The VS had the highest removal efficiency and this was recorded at pH 7.2 indicating an optimized pH of 7.2. Again, as the removal efficiency increases for a substrate parameter, more of it is degraded resulting in BGP at the optimized pH of 7.2. Furthermore this shows that system performance can be measured by the mass of VS destroyed or consumed from the system for BGP. The least removal efficiency of TS, VS and COD are 44%, 54.2% and 40% respectively were recorded at pH 6.0 and apparently showing that the system was not fully optimized which implies that as the pH becomes acidic there is accumulation of VFA and n-butyrate (Wijekoon et al, 2011) which inhibits the process. The nutrient content of the substrate determines the substrate characteristic. From the substrate characteristics, the TS was 18% while the VS was 16.4%, so a substantial part of the TS is VS, hence the high system performance. Therefore, it is the mass of VS destroyed from the substrate in the system that gives better indication of system performance.

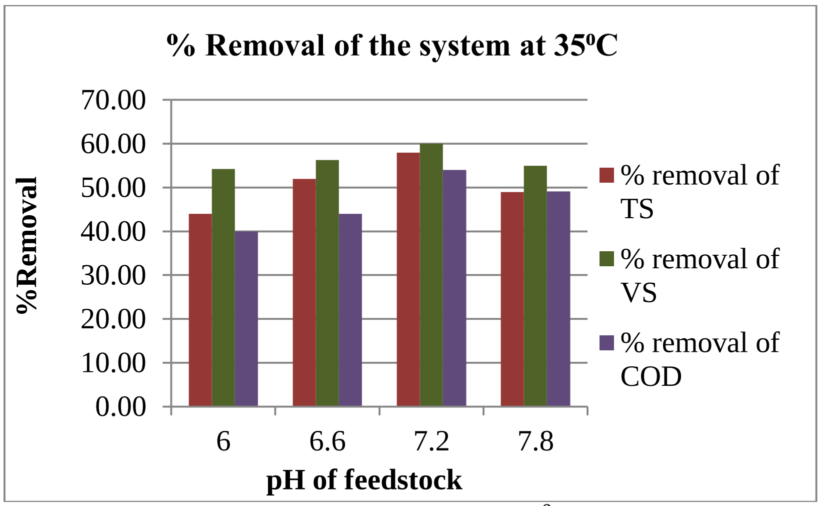

Fig 5.0: % Removal of the system at 35^{0}C

Table 2.0: Substrate characteristics

Characteristics of the substrate		
TS (g/L)	**VS (g/L)**	**COD (g/L)**
16	14.4	10.1

Table 3.0: *Digestate characteristics*

	Characteristics of the digestate (35ºC)		
pH	**TS (g/L)**	**VS (g/L)**	**COD (g/L)**
6	8.96	6.60	6.06
6.6	7.68	6.30	5.66
7.2	6.72	5.80	4.65

7.8	8.16	6.48	5.15

4.0 CONCLUSION

From the results obtained in this study, it is hereby concluded that mesophilic (35ºC) systems can be used under controlled pH and OLR to completely degrade food waste and generate biogas. Comparing the Biogas potentials (ml/gVS), CBGPs and % Removal (removal efficiency) of the system at various pH values, pH 7.2 is the optimum pH for mesophilic system.

The higher the degradation constant the more the substrate is consumed and the higher the BGP.

When the pH was 6.0 and 7.8, there was process slow down resulting in low BGP. The next favourable pH was 6.6 following the pH 7.2. Hence, pH plays a vital role in the optimization of the AD process.

This paper also concludes that the rate of biogas production in the system is faster at the initial stage than at the later part.

Importantly, the substantial part of TS contains the VS from the substrate content hence the high VS destruction laying credence to the finding that the mass of VS destroyed from the substrate in the system gives a better indication of system performance.

5.0 RECOMMENDATION

Further studies on the feasibility of mesophilic and thermophilic conditions are recommended for another type of waste. AD is a non-linear process which is difficult to control automatically and therefore has been relied on expert operators to maintain the performance and stability of AD sites. Further research should be undertaken to develop an AD expert control system which will enhance the process in future to reduce cost of human expert operation.

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