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Parametric Study of Biogas Production Using Continuous Stir Tank Reactor

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Abstract
In this study, a continuous stir tank reactor was modeled and tested for biogas production from municipal solid waste and also. The experimental and analytical studies of municipal solid waste were performed following the standard method. The Continuous stir tank reactor designed parameters were determined from preliminary kinetics studies of anaerobic digestion of municipal solid waste. The results showed that stirring the feedstock municipal solid waste improves its potential for biogas production. The conditions are a pH of 7.8, a retention time of 28 days, and an organic loading rate of 8kg with a maximum yield of 62.4mL of biogas yield.
Keywords: Bio-gas: Continuous Stir Tank Reactor: Municipal solid waste: Parametric Study

INTRODUCTION

A bioreactor refers to any manufactured or engineered device or system that supports a biologically active environment, (James et al, 2000). It is also a vessel in which a chemical digestion or degradation process is carried out, involving organisms or biochemically active substances derived from such organisms. Many factors affect the biodegradation of organic matter. These include, but not limited to, the microbial concentration, organic content of the substrate, operating temperature, pH, mode and degree of substrate agitation, mixing/flow regimes. (Rakib, et al, 2022), When these factors are under control as in bioreactors, degradation or digestion of organic matter, it can bring about beneficial effects and products. For example, under controlled conditions, biogas and waste organic fertilizer by-products can be produced by the biological breakdown of organic matter.
The poor performance of bioreactors may be attributed to inappropriate or non-existent slurry flow dynamics. It could be implied that its effects have never been considered at the bioreactor design stage. These attendant problems of bioreactor failure and poor performance calls for further research in order to understand more clearly some of the mitigating factors with a view to proffering solutions and developing high yield biogas plants. It is expected that the incorporation of appropriate flow regimes in the bioreactors will provide the basis for effective digestion of organic waste thereby avoiding putrefaction due to inadequate slurry mixing during digestion. Thus the operation of such bioreactors in any environment would not produce polluting effects.
However, (S. Achinas et al, 2020), reports that bioreactor operating and process conditions can well be established by experimental work but with an attendant delay in project launch. He identified fluid mechanic effects as one of the critical limiting factors in the design of large scale bioreactors. In furtherance of his study on prediction of flow characteristics in bioreactors, he employed computer simulations using Computational Fluid Dynamics (CFD) modelling. Also, (Ogunbiyi, 2001) have shown that fluid flow and mixing in bioreactors have significant effect on the overall performance of the systems. In their study of fluid mixing in a roller bottle bioreactor, they identified the problem of limited mixing, especially, in the axial direction and verified same computationally and experimentally. Such mixing limitations were readily overcome by introducing a small amplitude vertical rocking motion that disrupted both fluid symmetry and recirculation, leading to much faster and complete axial mixing which is a critical parameter in the performance of reactor.
Admittedly, one of the single most important limitations to high quality biogas yield is the application of appropriate flow regimes in bioreactors. Hence, purpose of this research what affects the production of biogas in a continuous stir tank.

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BIOGAS PRODUCTION

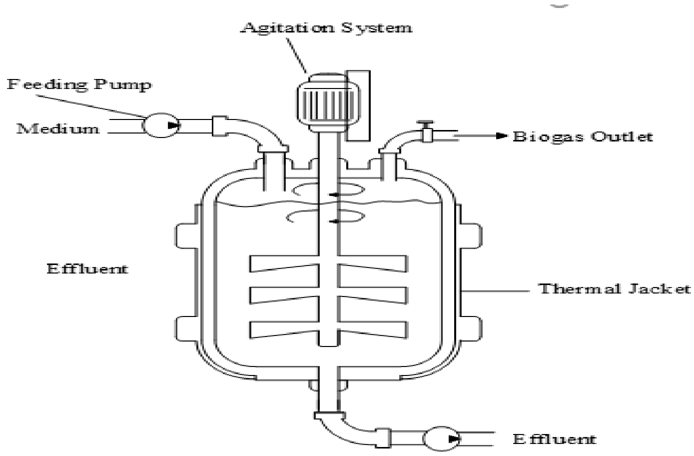

Figure 1: Continuous Stirred Tank Reactor (CSTR)

Continuous stir tank reactor (CSTR) can be considered a closed tank reactor, usually of cylindrical configuration, with a stirring mechanism such as an impeller as shown in fig. 1 above. (Nathenial et al, 2019), in the study of boiling stirred tank reactors used multiple impeller configurations which consist of six flat blade disk turbines and six-concave blade disk turbines. (Ondiba, et al, 2017), reported that various mixing forms such as axial, radial or mixed flows can be produced by impellers. (Oyinola, 2001), reported that agitation in CSTR increases the rate of mass and heat transfer operations and provides the required degree of mixing of the reactor contents. Insufficient agitation leads to limitations in the transfer operations and appearance of regions of insufficient nutrient content or inadequate temperature or pH. As a result, the overall productivity of the reactor declines. CSTR is usually baffled in order to improve mixing. (Sinnott, 2005), reported some applications of the CSTR in waste water treatment. In his study of diary waste water treatment, the chemical oxygen demand COD removal efficiency was 60% and methane composition in the generated biogas was in the range of 22.5-76.9%.

Some other successful studies have been carried out for the treatment of palm oil mill effluent POME using CSTR, (Marylee et al, 2018). In the study, CSTR registered 90% reduction in COD, with a hydraulic retention time HRT of 6days and 64% methane in the produced biogas.

Biogas is derived from the microbial degradation of organic waste stored in the absence of air; a process called anaerobic digestion and variously defined as “a biological decomposition of organic waste done in the absence of air (Agbede ete al, 2019). This is why (Shahzad et al, 2020) says anaerobic digestion is “a bioreactor in which organic matter is progressively degraded in the absence of oxygen by a process known as methanogenesis”. (Juan et al, 2014), (Bailet et al, 1986). (Spyridon et al, 2018) Explains that recently anaerobic digestion is also being applied to the treatment of municipal solid waste (MSW) and thus offers a more holistic definition when he says that anaerobic digestion is “the use of microbial organisms in the absence of oxygen, for the stabilization of organic materials by conversion to methane and inorganic products, including carbon dioxide”.

A myriad of factors affect the performance of bioreactors. A careful study and control of these factors is imperative for efficient operation of bioreactors. Some of the major factors commonly reported in literature include the following: pH (Oluka, 2001) and (Olaoye, 2001) reported that methanogenesis decreased when pH for microbial growth is between 6.8 and 7.2. pH lower than 4 or higher than 9.5 are not tolerable. Temperature is an important factor in bioreactor processing of organic materials. Microbial activities thrive in the mesophillic i.e. 30-50^{0}C or in the thermophilic i.e. 50-60^{0}C temperature ranges. (Aguwamba, 2001) and (Eze, 2004) said failure to control temperature increase can result to biomass washout and therefore bioreactor failure. Carbon/Nitrogen Ratio (C:N Ratio) C:N ratio measures the relative amounts of carbon and nitrogen in the substrate. In the absence of carbon, bacteria tend to die and deficiency of Nitrogen leaves them no means of rebuilding new cell structure, Organic Loading Rate (Olr) for same substrate composition and volume, the measure of chemical oxygen demand (COD) reduction by bioreactors denote the efficiency and extent of the organic material degradation process. Some studies have shown that higher OLR will reduce COD removal efficiency in waste water treatment system, (S. Achinas et al, 2020). Flow/Mixing Requirements is a very important factor in bioreactor performance. Mixing provides the needed contact between microbes and substrate, reduces resistance to mass transfer, minimizes the build-up of inhibitory intermediate reactants and stabilizes bioreactor environment, (Ondiba, et al, 2017).

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The breakdown of carbohydrates, nitrogenous compounds and fats can simply be expressed using chemical formula as follows:

$C_6H_{12}O_6 + 2H_2O \qquad 2C_2H_4O_2 + 2CO_2 + 4H_2$ (1)

From the acetic acid and hydrogen products of the above reaction, methane would be produced thus.

$2C_2H_4O_2 \qquad 2CH_4 + 2CO_2$ (2)

$4H_2 + CO_2 \qquad CH_4 + 2H_2O$ (3)

When these expressions are combined, the generalized equation for the anaerobic digestion process is obtained as follows

WASTE DEFINED

Generally, waste is regarded as a useless material that is unwanted and therefore discarded. This explains that waste is "anything or anyone rejected as useless, worthless, or in excess of what is required". Hence municipal solid waste (MSW) is defined as "all waste collected by private and public authorities from domestic, commercial and some industrial (non-hazardous) sources" (Spyridon et al, 2018) and (Agbede ete al, 2019) say MSW comprises small and moderately sized solid waste items from houses, businesses, and institutions. Management of Municipal Solid Waste like many other cities in Nigeria (Ekenta, 2001), large volumes of refuse are generated on a daily basis in Port Harcourt and also improperly discarded by residents. Energy Potential of Municipal Solid Waste (Oyinola, 2001) cites the 1997 appraisal report of the Urban Development Bank of Nigeria Plc; and states that the estimated average per capita waste generation for the country is 0.45kg/day, and that for Port Harcourt metropolis is 0.33kg/day.

MATERIALS AND METHOD

The municipal solid waste (MSW) was collected from the entire waste bins located at various strategic points in Enugu East metropolis and the chemical reagents were purchased from certified vendors in Enugu state. The laboratory work and reactor experimentation was done in Energy Research Center Nsukka, in the University of Nigeria Nsukka. One (1) container-waste-load of total volume 0.098m^3 was collected from each waste receptacle, for designated 10 sites randomly selected throughout the Enugu East metropolis, given a total of ten (10) container-waste-loads of total volume 0.98m^3. When the wastes were collected with the bin, they were weighed in their composite form as-discarded, and then the same mass of waste was compacted with manual compactor until the change in volume became constant. The measured wastes were then sorted into individual components on the bases of their organic and inorganic character. After the sorting, both the organic and inorganic components were measured by volume and weight, both 'as-discarded' and 'as-compacted'. The results were used in the determination of the 'as-discarded' and 'as-compacted' densities, and the "ratio of the 'as-compacted' density (ρ_c) to the 'as-discarded' density (ρ_d)) is the compaction ratio (r) (Nathenial et al, 2019), which was employed in the design of the digester for the waste.

$$r = \frac{\rho_c}{\rho_d} \qquad (4)$$

About 5.00g of sample was weighed and dried in an oven at a regulated temperature of 105^{0}C. The drying sample was constantly reweighed every 10 mins interval until a constant weight was obtained. The crucible and its content was retrieved and cooled in desiccators. The difference in weight was recorded and the moisture content calculated as using equ. 5 below

$$\%\,Moisture = \frac{wt\ of\ wet\ \ sample - wt\ of\ oven\ dry\ \ sample}{wt\ of\ oven\ dry\ shell\ sample} \times \frac{100}{1} \qquad (5)$$

The volatile matter content was obtained by heating 10g of moisture free sample in a muffle furnace at 900°C for one hour. Heating in the absence of air at high temperature removes the volatile matter only, its percentage was obtained using equ. 6 below.

$$\%\,Volatile\ matter\ = \frac{weight\ loss}{weight\ of\ moisture\ free\ sample} \times \frac{100}{1} \qquad (6)$$

The crude fibre content was determined using equation 7 and the result was shown in Table 1

$$\%\,Crude\,fiber = \frac{Loss\,in\,weight\,on\,ignition\,(W_2 - W_1) - (W_3 - W_1)}{Weight\,of\,shell\,sample} \times \frac{100}{1} \quad (7)$$

The sample was exhaustively extracted of its lipid for 3hrs by heating the flask on an electric hot plate at a temperature of 50ºC. After 3hrs, the extranctant (petroleum ether) was distilled off while the flask and its content were cooled in a desiccators before reweighing. (AOAC, 1995)
The percentage lipid was calculated using equ. 8

$$\%\,Lipid(or\,fat) = \frac{weight\,of\,lipid}{weight\,of\,sample} \times \frac{100}{1} \quad (8)$$

A clean empty specific gravity bottle was weighed on an electronic balance and the mass (W_1) noted. It was then filled with the sample at the required temperature and its mass (W_2) and volume noted. The mass of sample (W_s) was the difference between W_2 and W_1. The density, ρ, was calculated using the equation:

$$Density = \frac{Mass}{Volume} \quad (9)$$

The bottle was washed, dried and filled with equal volume of water at the required temperature and the mass (W_3) was noted. The mass of water (W_w) was the difference between W_3 and W_1. The specific gravity of the sample was determined using the equation:

$$Specific\,gravity = \frac{Weight\,of\,sample}{Weight\,of\,equal\,volume\,of\,water} \quad (10)$$

That is:

$$Specific\,gravity = \frac{W_2 - W_1}{W_3 - W_1} \quad (11)$$

The energy content of the waste was determined using the equation for the estimation of the energy content of MSW, presented by (Spyridon et al, 2018) as:

$$EC = 0.051[F + 3.6(CP)] + 0.352(PLR) \quad (12)$$

Where: Ec - Energy content of MSW, MJ/kg
F - % of food by weight
CP - % of cardboard and paper by weight
PLR - % of plastic and rubber by weight
Reactor Experimentation was done at energy Research Center Nsukka laboratory. Five batch-wise anaerobic digesters each of 5 liters volume were set up for this experiment. The schematic of the experimental design layout is as shown in Fig 2 below:

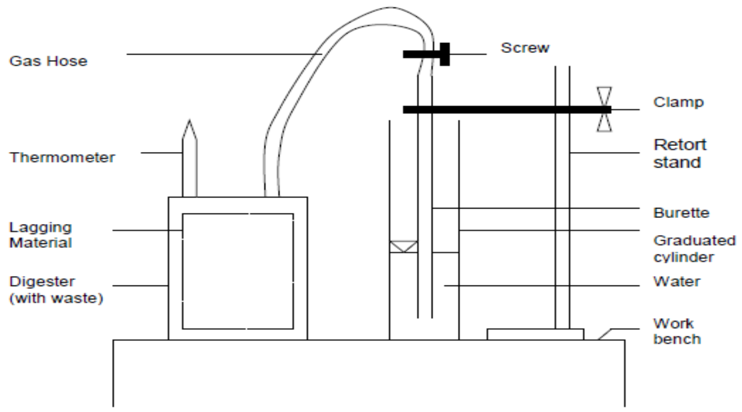

Figure 2: Schematic of Reactor Experimentation Design Layout (Igoni et al, 2007)

MODELS FOR THE CSTR DESIGN

The development of models for the CSTR is strictly based on the requirements of a high rate, low solids processing where there is "continuous mixing and continuous or intermittent sludge feeding and sludge withdrawal, and the contents are in a homogenous state (Richardson, 2004) (Igoni et al, 2007)states that the volume of a CSTR is defined as the product of the rate of flow of the medium and the hydraulic retention time.
This is stated mathematically as:

$$V_c = Q\theta_h \qquad (13)$$

Where;
Vc = overall volume of the continuous digester, m^3
Q = influent sludge flow rate, m^3/day
θ_h = hydraulic retention time, days.

But hydraulic retention time, θ_h is equal to;

$$\theta_h = \frac{\alpha}{(1-\alpha)}\left[\frac{K_s + [S]}{K[X]}\right] \qquad (14)$$

Substituting equation 13 into equation 14 we have;

$$V_c = Q\left\{\frac{\alpha}{(1-\alpha)}\left[\frac{K_s + [S]}{K[X]}\right]\right\} \qquad (15)$$

The diameter and height of the tank is related to the tank volume by the following equation;

$$V_c = A_c \times H_c \qquad (16)$$

Where
A_c = cross-sectional area of the tank, and
H_c = height of the tank.

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Therefore, adapting the established relation between the digester tank diameter and height as being in the ratio of 2:1 according to (Igoni et al, 2007), so that $D_c = 2H_c$ or $H_c = {}^{D_c}/_2$, then equation 16 becomes

$$H_c = \sqrt[3]{\frac{2}{\pi}\left[Q\left\{\frac{\alpha}{(1-\alpha)}\left[\frac{K_s + [S]}{K[X]}\right]\right\}\right]} \qquad (17)$$

RESULTS AND DISCUSSION

The thermo-physical properties of the municipal solid waste (MSW) used in biogas generation in this work is shown in Table 1

Table 1: Proximate analysis of the Municipal Solid Waste (MSW)

S/N	**Properties**	**Values (%)**
1	Ash content (%)	3.4
2	Crude fat (%)	0.70
3	Moisture content (%)	83.56
4	Crude fibre (%)	8.0
5	Carbon content (%)	7.0
6	Protein content (%)	5.68
7	Nitrogen (%)	0.014
8	Phosphorus (%)	0.72
9	pH	6.9
10	Energy value (KJkg)	14,734.50

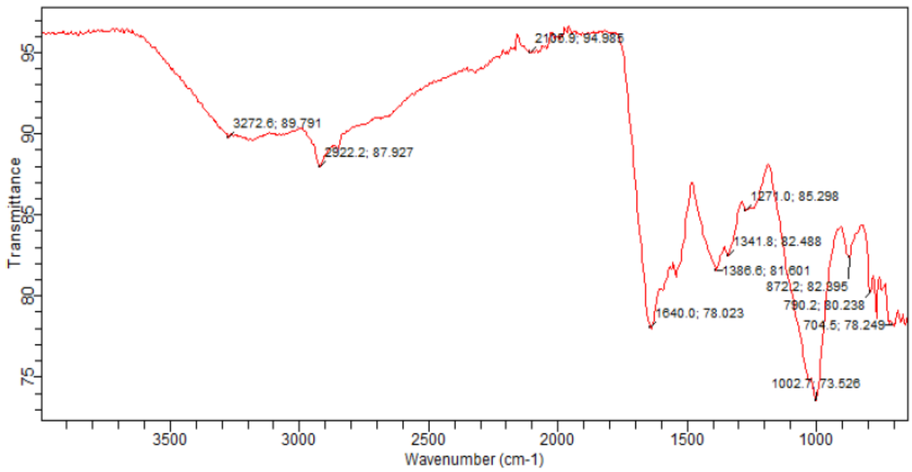

Figure 3: FTIR Spectra of Municipal Solid Waste

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FOURIER TRANSFORMED INFRA-RED SPECTROSCOPY (FTIR) ANALYSIS OF THE MSW.

Fourier transformed infrared (FTIR) spectra of the feedstocks (MSW) was analyzed with the range 1000-3500cm^{-1} wave number using Potassium bromate (KBr) as a background material in the analysis, are presented in Fig. 3 and Table 2. it was observed that the major functional groups present in substrates are; (O-H, N-H, C-H, COOH, C-O and Si-O) which are very useful in anaerobic digestion of biomass; N-H and Si-O groups are also important anaerobic digestion and application of digestate as fertilizer. The presence of methyl and methylene functional groups in the spectra suggested that the substrates will be very good as biogas substrates.

Table 2: Result of FTIR Analysis of Municipal Solid Waste

Wave number (cm-1)	Functional Groups	Description
3695-3620	O-H	Axial deformation in kaolinite
3500-3100	O-H	Stretching vibration link by hydrogen bond and N-H
2918-2500	C-H	Asymmetric axial deformation in methyl and methylene
1670-1620	COOH	Asymmetric axial deformation in anion carboxylate
1400-1500	COOH	Symmetric axial deformation in carboxylate anion
1080-1050	C-O	Axial deformation in polysachride
1030-1020	Si-O	Axial deformation in kaolinite or O-H
1010-1000	NIL	
900-690	C-H	Out plane folding in aromatics
540-500	Si-O	Angular deformation kaolinite or gibbsite
470-400	Si-O	Angular deformation in koalinite or gibbsite

Table 3: Result of X-Ray Fluorescence (XRF) Analysis of Municipal Solid Waste

	Municipal Solid Waste	(MSW)
S/N	Elements	Concentration (wt %)
1	Na_2O	5.363
2	MgO	0.764
3	Al_2O_3	3.680
4	SiO_2	52.764
5	P_2O_5	12.383
6	SO_3	4.631
7	Cl	2.227
8	K_2O	4.057
9	CaO	9.816
10	TiO_2	0.338
11	Cr_2O_3	0.011
12	Mn_2O_3	0.223
13	Fe_2O_3	3.654
14	ZnO	0.056
15	SrO	0.033

It was observed from Table 3, that P content found in MSW is (14.52wt %) whereas, the K, Mg, S, Cl, Ca and Zn contents are higher. The Al, Na and Si contents are higher in MSW is enough to support anaerobic micro-organism growth. The traces of heavy metals contents such as Cr, Mn, Fe, and Ti found in the MSW are within the acceptable range.

EFFECT OF PH ON BIOGAS PRODUCTION

The pH of the substrate was adjusted to the required value (6.8-7.6) by adding 1 N sodium bicarbonate solution. Fig. 4 showed the daily biogas production over 30 days retention period for the substrate with different pH respectively. Fig 4 shows that the biogas gas production was higher within the period of 6-15 days, and decreasing gradually as the day passes beyond 15days. The maximum gas yield of 5.6L was obtained for pH 7 on the 15th day,

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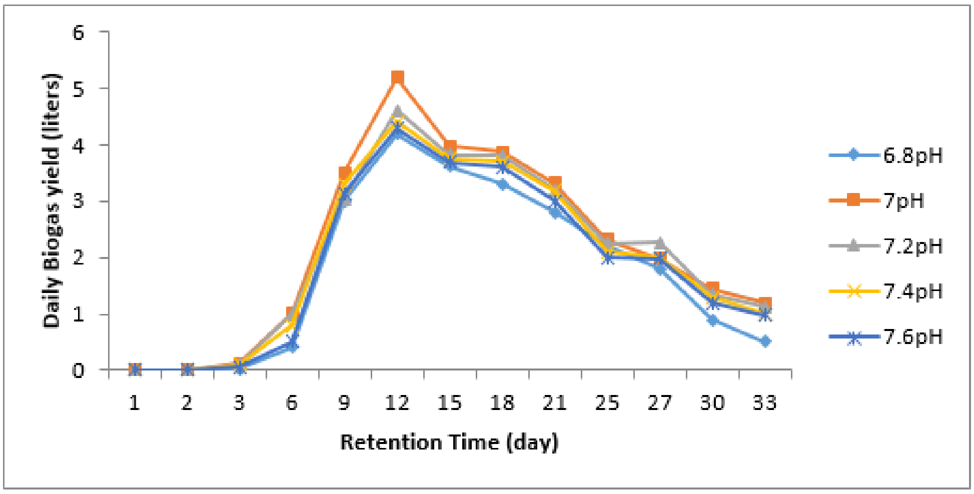

Figure 4: Effect of pH on biogas yield from municipal solid waste

EFFECT OF ORGANIC LOADING RATE

The biogas yield for various loading rates is presented in Fig.5. The highest biogas yield observed was 5.4L biogas for 10kg loading rate for the 25L digester used to perform the experiment. As the loading rate was increased, a gradual decrease in the biogas production was observed. The overloading was marked by the fall in pH and gas yield and increase of carbon dioxide content in the biogas.

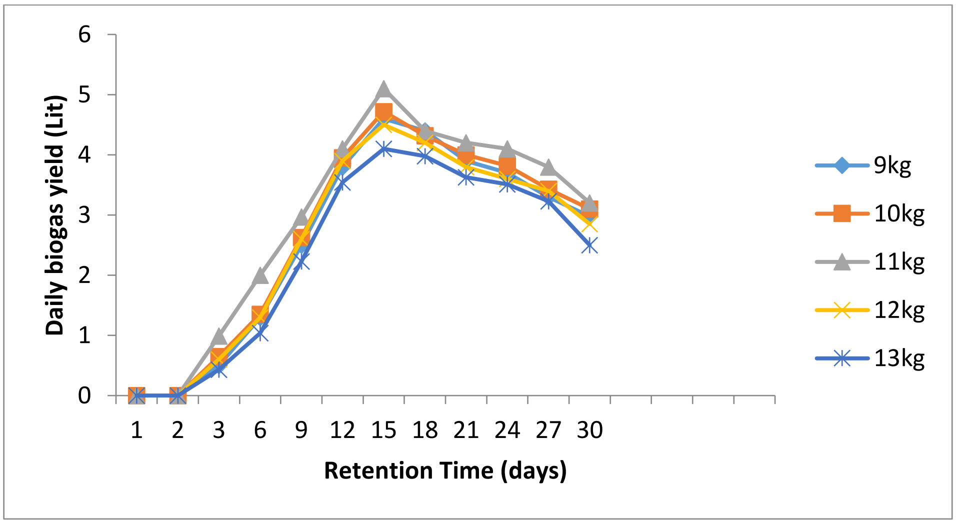

Figure 5: Effect of organic loading rate on biogas production from MSW

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EFFECT OF RETENTION TIME

It was observed from Fig. 6 that the optimal retention time for maximum biogas yield using CSTR in anaerobic digestion of MSW is 30days, beyond this time the biogas yield remain somehow stagnant.

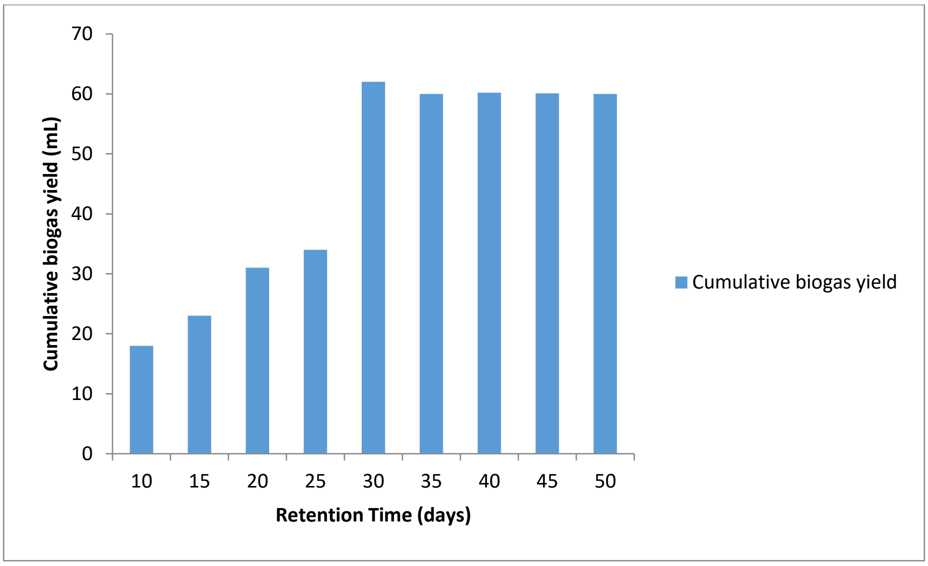

Figure 6: Effect of substrate retention time on biogas production from MSW

CONCLUSION

This study investigated CSTR for biogas production from municipal solid waste and the effect of process parameters. The stirring effect gave higher yield and this may be attributed to the distribution anaerobic microbes and temperature of the reactor of which resulted in availability of higher volatile solid for digestion. Under the optimize conditions, the digestion of the substrates subjected at different process parameters conditions averagely gave biogas yield of 62mL biogas/mg. Despite large variations in pollutants concentrations, improved performances of anaerobic digestion of the biodegradable fractions of the substrates were achieved with the slow intermittent stirring. The results showed that stirring of the feedstock (MSW) improves its potentials for biogas production. The conditions are pH of 7.8, retention time of 28days, and organic loading rate of 8kg with maximum yield of 62mL of biogas yield.

Conflict of Interest

There are no conflict of interest in this work.

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