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Performance Evaluation of the Co-Digestion of the Organic Fraction of Municipal Solid Waste with Biogas Production Enhancers from Livestock

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Abstract
A bench-scale anaerobic biodigester was improvised using locally sourced, readily available and unbelievably affordable materials. The biodigester was used to generate biogas from organic fraction of municipal solid wastes (OFMSW) enhanced with two different livestock wastes: cow dung (CD), poultry droppings (PD) and, urea fertilizer (UF) in equivalent mixtures that gave literature reported 30:1 optimum carbon to nitrogen ratio (C/N). The slurries were sampled; biogas generated and collected using a simple, improvised but remarkably effective system. The CD, PD and UF in the improvised biodigester proved to be viable enhancers for biodegradation and greatly improved the biogas evolution by 20.97%, 12.15% and 29.67%, respectively. Presence of CD, PD and UF also reduced the chemical oxygen demand (COD) of the process by 86.47, 80.99, and 90.17%, respectively. Hydraulic retention time (HRT) of the enhanced biodegradation of the OFMSW was impressively reduced to 15 days. Modified Gompertz equation was used to model the biogas evolution parameters using non-linear regression analysis which showed that the mixture of OFMSW applying UF gave the best performance with gas production potential of 45390ml, maximum gas production rate of 3785ml/day and a lag time of 0.4647days.

Keywords: *Improvised biodigester, Biogas, Anaerobic biodigestion, Modified Gompertz equation, Organic fraction of municipal wastes*

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1. Introduction

Increasing energy demands and the need to explore newer, safer and more affordable sources of energy has received tremendous attention in the last few decades. This is primarily due to factors which include climate change concerns and policies (Ben-Iwo *et al.,* 2016), availability of varieties of unexplored renewable energy resources (Mshandete and Parawira, 2009), environmental friendliness and breakthroughs in biodigester developments (Thornley *et al.,* 2014) and the geometric increase in the costs of traditional sources of energy (Msibi and Kornelius, 2015).

Ravindranath (2000) described anaerobic digestion as a biological process which involves the breakdown of organic matter by a wide range of micro-organisms in the absence of oxygen, which can take place in airtight containers called digesters. The two main products of anaerobic digestion as reported by Jyothilakshmi and Prakash (2015) include biogas, a very important renewable fuel, and digestate which is the nutrient-rich, decomposed substrate that can be used as a plant fertilizer as well as a soil amendment (Castillo, 2006).

As observed by Gamble (2014), there are numerous process variables associated with the anaerobic digestion process which must be studied side by side in order to ascertain their various contributions to the overall process which makes the optimisation of the process for the multiple substrates available very demanding. Bench-scale experiments according to the author, is one sure way of obtaining relevant correlations which can drastically reduce optimisation costs. Laboratory scale anaerobic biodigestion of wastes was utilised by Liu et al. (2009) to treat food waste and green wastes, Sunarso et al. (2012) to study the anaerobic digestion of cattle manure, Kheiredine et al. (2014) for the treatment of dairy wastewater, and Owamah (2018) to optimise biogas yield by the co-digestion food waste and maize husks. Abudi et al. (2016)

had identified OFMSW as a commonly utilised feedstock.

Some researches that made effort in enhancing the biodegradation of OFMSW using livestock wastes and urea fertilizer include the use of cow dung (Hartmann, 2002), use of pig and cow dung (Membere et al., 2013) urea, cow and horse dung and urea fertilizer (Budiyono*et al.*, 2013) and, cow dung, sewage sludge and poultry manure (Sangodoyin and Amori, 2013).

Lo et al.(2010) reported that biogas production rate from the anaerobic biodegradation of MSW can be simulated using linear, exponential, Gaussian and, the use of the non-linear regression of the modified Gompertz equation as reported by Kumar et al. (2004), De Gionniset al. (2009), Lo et al. (2010) and Altas (2009), respectively. Syaichurrozi and Sumardiono (2014) reported that the modified Gompertz model was developed by Zwietering*et al.* (1990) to predict bacterial growth and to simulate biogas accumulation. Lo et al.(2010), Yusuf et al.(2011) as well as Agulannaet al. (2012) presented the modified Gompertz equation in the form:

$$B_t = B_{max} \exp\left[-\exp\left\{\frac{R_b}{B_{max}}.e.(\lambda - t) + 1\right\}\right] (1)$$

where B_t is the cumulative of gas produced (ml) at any time, B_{max} is the gas production potential (ml), R_b is the maximum gas production rate (ml/day), e is the Euler's constant= e (1) = 2.7182, λ is the lag time (days) and, t is the period of biogas production (days).

Budiyono et al.(2010) applied the Gompertz equation in the modified form to describe biogas yield from cattle manure, Yusuf et al.(2011) to describe the cumulative biogas production from varying ratio of mixture of horse and cow dung, Lo et al.(2011) and Agulanna et al.(2012) for modeling biogas production from OFMSW while Owamah (2018) used it to stimulate the optimisation of biogas production by selecting appropriate inoculums to substrate ratios.

This work aims to investigate the potentials of using a bench-scale, improvised biodigester for generation and collection of biogas from OFMSW enhanced with two different livestock wastes that included CD, PD and UF in equivalent mixtures that produced C/N of 30:1. The efficiency of the system performance was explored and explicated.

2. Materials and methods

2.1 Sample collection and preparation

Municipal solid wastes (MSWs) samples were aseptically collected in sterilized, thin-walled, black polyethylene bags from randomly selected waste dumpsites in Samaru- a university community of the Ahmadu Bello University, Zaria, Kaduna State, Nigeria, using the stratified random sampling method.The samples were inspected to remove non-degradable components by hand sorting then reconstituted and separated into constituent organic components which include leaves and grasses, officepaper, fruit peels, foodwastes,old newsprintand vegetables. The various components were weighed, remixed and blended as described by Carboo and Forbil (2005).The sample was then categorized into two portions: for immediate use and for processing and subsequent analyses. The portion for analyses was air-dried by spreading on a flat, clean surface placed under the sun for 96 hours.The chemicals and reagent used that included potassium dichromate, ferrous ammonium sulphate, sodium chloride, distilled water and UF were of analytical grade and were obtained from the chemistry laboratory, ABU Zaria, Nigeria. Livestock waste enhancers comprising of CD and PD were collected from the National Animal Production Research Institute (NAPRI), Shika, Kaduna state, Nigeria.Proximate and ultimate analyses of relevant factors that affect the extent and rate of biodegradation of organic wastes were determined on the OFMSW, CD and PD at the Chemistry Department and the Institute of Agricultural Research (IAR), ABU, Zaria using a muffle furnace and a FlashEA 1112 elemental analyzer.

2.2Total Solid loading of the biodigesters

Based on the C:N ratio obtained from the ultimate analysis of the enhancers and the OFMSW, four biodigesters were made in triplicates as follows: Biodigester A (62%OFMSW+38%CD), B (80% OFMSW+20% PD), and C (98% OFMSW + 2% UF) and D (100% OFMSW) on weight percent basis.

2.3 Operating conditions

The research was carried out at room temperatures that varied between 26 and 29°C, which represents mesophilic condition. pH values for CD, PD and urea were 7.29, 7.13 and 6.69, respectively, which were all within the pH range for biogas production. Also, a hydraulic retention time of 15 days and a C/N ratio of 30:1 were selected for this work based on the findings of Ojolo et al.(2007).

2.4 Measurement of the volume of evolved gases

Measurement of the volume of evolved gases was carried out using the water displacement method described by Bareither et al.(2009) and as modified by Yusuf et al.(2011) in which the amount of saline water (20% NaCl (w/v), pH 4) displaced was proportional to the volume of gas produced.

2.5 Measurement of leachate COD

Measurement of leachate COD was conducted using the dichromate method utilising the closed reflux, 5220C, titrimetric method as described in the Standard Methods for Examination of Water and Wastewater (2012).

2.6 Biodigester configuration and construction

Ali and Imran (2004) as well as Al-Imam et al.(2013) reported the following optimum relationships between the diameter (D), the height (H) of a biodigester and its total volume (V).

$D = 1.3078V^{1/3}$ (2)

$H = \frac{D}{2.5}$ (3)

$\frac{f_1}{D} = \frac{1}{5}$ (4)

$\frac{f_2}{D} = \frac{1}{8}$ (5)

Slurry volume = 80% of total volume (6)

where f_1 is the height of gas headspace, f_2 the height of bottom (gravel) layer, Φ_1, Φ_2 and Φ_3 are the diameter for openings for thermometer, the outlet for gas and for the effluent respectively = 1.0cm.

Thus, for a 4000 cm^3 biodigester,

$D = 1.3078V^{1/3} = 1.3078(0.004)^{1/3} =$ 0.208m =20.8cm

$H = \frac{D}{2.5} = \frac{20.8}{2.5}$ = 8.32cm

$$\frac{f_1}{D} = \frac{1}{5}$$

$\Rightarrow f_1 = \frac{1}{5} D = \frac{1}{5}(20.8) = 4.16$ cm

$f_2 = \frac{1}{8} D = \frac{1}{8}(20.8) = 2.6$cm

Slurry volume = 80% of total volume = $4000cm^3(0.8) = 3200\ cm^3$

Consequently, a biodigester of $4000cm^3$ working volume was employed as adopted and modified from Bayard et al.(2005). The digester was made using empty plastic containers 150mm diameter, 200mm in height and a wall thickness of 5mm. The port, Φ_3 of diameter 1.0cm was made at a height of 2.6cm from the bottom of the digester to serve as the leachate collection port. The biodigesters were equipped with a layer of gravel and a wire mesh at the bottom for leachate collection and for preventing waste saturation and a layer of wire mesh at the top of the biodigester for the homogenous escape of the gases from the top as adopted from Bayard et al.(2005). Figures 1 and 2 respectively show the layers of gravel and wire mesh at the bottom of the biodigester.

Fig. 1: Bottom gravel layer

Fig. 2: Bottom wire mesh layer

Two perforations each of diameter 1.0cm were also made on the cover of the biodigester through which the biogas delivery tube and thermometer were tightly fixed. The biogas as well as effluent delivery and sampling lines were made using the common medical safety infusion set of tube length 180cm with a Luer lock fitting which prevents leaking and protects against contamination as well as an air stop which serves as a particle filter with a high filtration efficiency. The sharp piercing spike at the tip of the infusion set as shown in Figure 3 eased piercing the biodigester cover ensuring tighter grip. The thermometer was fixed tightly into the other hole on the biodigester cover.

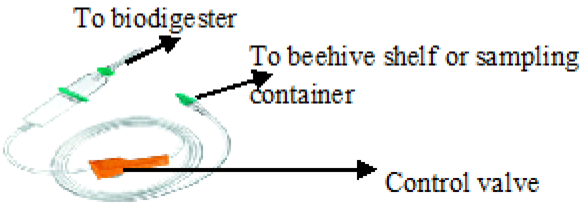

Fig. 3: Safety infusion set to serve both as produced gas and effluents delivery tube

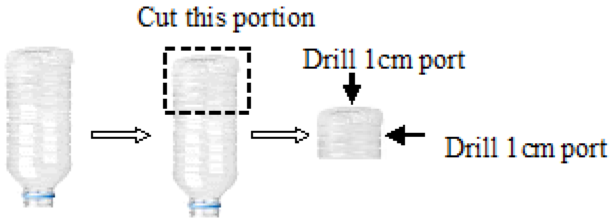

Fig. 4: Constructing the beehive shelf

The gas collection system comprises of a plastic bowl into which is placed an improvised beehive shelf made of a cut lower part of an empty, table water plastic bottle on which two holes at the bottom and at the top were made to pass the delivery tube and bubble out the evolved gases respectively. The biogas delivery tube passes the evolved gas from the biodigester into an inverted 250 ml graduated measuring cylinder filled with saline water and held in position in a trough of saline water by a clamp mounted on a retort stand. All fittings to the biodigester, its cover and to the beehive shelf were ensured to be leak proof using commercial plastic epoxy. Three layers of heat-insulating materials were employed to prevent loss of conductible heat. These include a heavy-duty aluminium foil placed on the inner and outer layers for reflecting heat and polyurethane foam insulation used to fill the spaces between the heavy-duty aluminium foil to serve as lagging as modified from Li et al.(2008) and pictured in Figures 5(a) and (b).

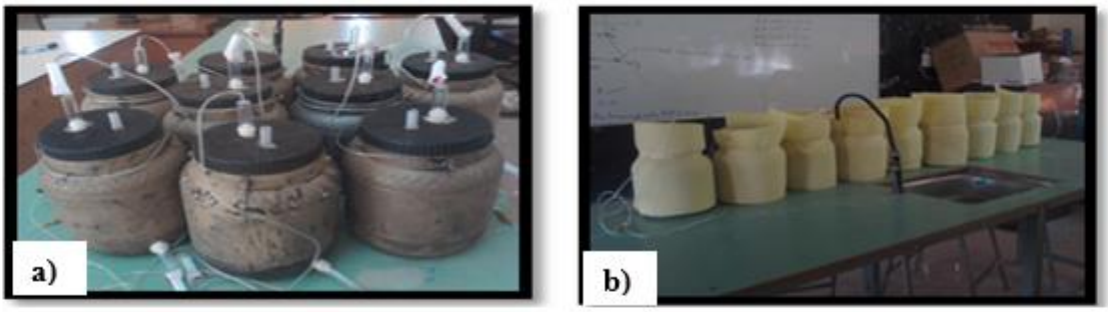

Fig. 5: Construction of the biodigesters by inserting (a) the ports and (b) polyurethane insulation

2.2 The improvised biodigester and gas collection system

The improvised biodigesters and biogas collection systems were done in triplicates for each of the substrate combinations, a cross-section of which is shown in Figure 6.

Fig. 6: Set- up of anaerobic biodigesters and gas collection

3. Results and discussion

3.1 Cumulative biogas production

The overall plot of cumulative biogas production as a function of time as plotted using *MATLAB9.3, R2017b* software is shown in Figure 7. The daily and cumulative biogas production as a function of time showed that digester C produced the highest volume of 40,615ml in hydraulic retention time (HRT) of 15 days and was followed by digesters A, B and D with 37,890ml, 35,128ml and 31,322ml in 17, 18, and 18 days respectively.The higher volume biogas from the UF enhanced biodigester is attributed to its higher assimilation by the microorganisms due to the higher nitrogen content of 46.65% as against the

1.02, 2.86 and 2.93% in OFMSW, CD and PD respectively. Thus, the volume of biogas in digesters A, B and C that contain the enhancers was higher than that produced by digester D which was without enhancement by 20.97%, 12.15% and 29.67% respectively.

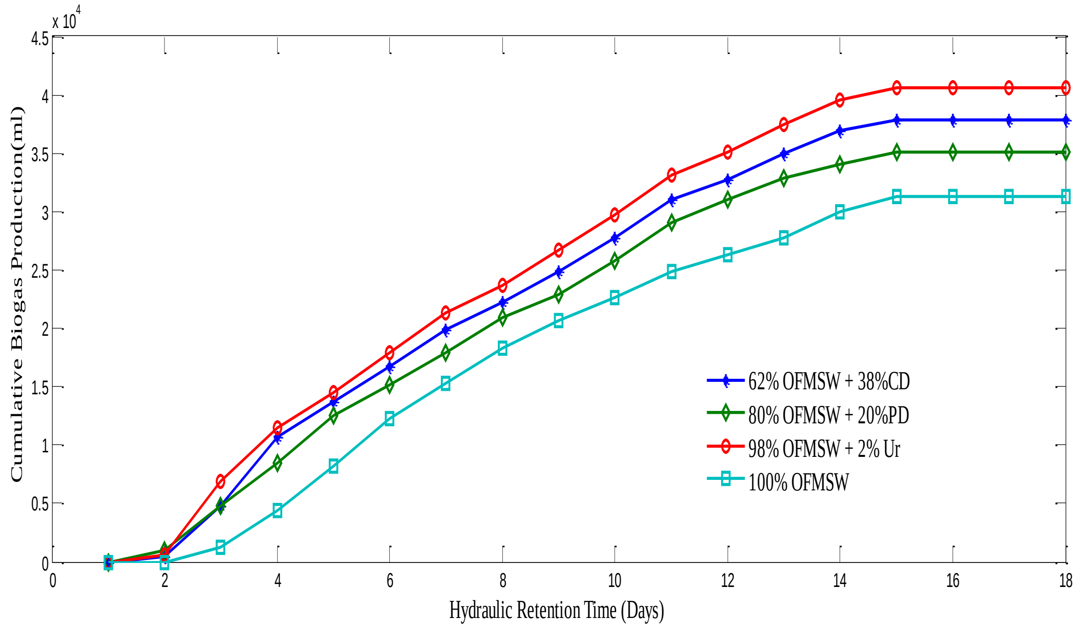

Fig. 7: Cumulative biogas production

3.2 Daily COD reduction

Table 1 shows the daily COD and percentage COD reduction in the four digesters. It was observed that digester C with 2% urea content produced the leachate with the highest initial COD content of 5096mg/l it was followed by digesters A, B and D with initial leachates of 4034, 2062 and 956mg/l respectively. Thus, both CD, PD and UF reduced the COD drastically by 86.47, 80.99, and 90.17% respectively. The high COD values obtained of more than 500 mg/l is indicative of high biochemical methane production (BMP) and can be used to characterize the biodegradation process as observed by Bricker (2009).

3.3 Modeling parameters from modified Gompertz equation

The cumulative volume of the biogas evolved (B_t) from each digester was further evaluated using the modified Gompertz equation as presented in Equation (1). The maximum biogas production rate, gas production potential and lag time were determined by the non-linear regression approach using *MATLAB9.3, R2017b* software at 95% confidence bounds. Table 2 shows the model modified Gompertz equations obtained as well as the corresponding goodness of fit for each of the four biodigesters. The values of maximum volume of cumulative gas evolved per kilogram of the 3.2kg raw feedstock slurry as obtained using the modified Gompertz equation for digesters A, B, C andD of 12.68, 11.78, 14.18 and 10.14L/kg conforms very closely with the experimentally obtained values of 11.84, 10.98, 12.69 and 9.79 L/kg of raw feedstock respectively. However, it was observed that the values obtained from the modified Gompertz equation were slightly higher than the experimental. This may be attributed to the level of conversion of the feedstock and the dependence of the anaerobic process on several other operative parameters.The lag time (λ) indicated that the time for the anaerobic biodegradation to begin was as short as 0.7084, 0.8368, 0.4647 and 1.847days for digesters A, B, C and D, respectively. Thus, the lag time was in the order C<A< B< D. Since the lag time determines the biodigester organic loading rate which in turn determines the biodigester size and thus its cost, these results show that the economy of the biodegradation process can be improved greatly through its enhancement using especially UF and to a lesser extent the livestock wastes CD and PD. The short lag times also unequivocally confirms the performance efficiency of the improvised biodigester and biogas collection systems.

Table 1: Daily COD and percentage COD reduction of produced leachates

Retention time (Days)	Biodigester							
	A		B		C		D (Control)	
	COD(mg/l)	% COD reduction	COD (mg/l)	% COD reduction	COD (mg/l)	% COD reduction	COD (mg/l)	% COD Reduction
0	4034	0.0	2062	0.0	5096	0.0	956	0.0
1	3944	2.23	2056	0.29	4856	4.71	939	1.78
2	3856	4.41	2031	1.5	4695	7.87	922	3.56
3	3668	9.07	2008	2.6	4539	10.93	912	4.60
4	3426	15.07	1846	10.48	3783	25.77	876	8.37
5	3186	21.02	1676	18.72	3272	35.79	847	11.40
6	2949	2690	1525	26.04	2946	42.19	762	20.29
7	2727	32.4	1448	29.78	2093	58.93	731	23.54
8	2090	48.19	1374	33.37	1850	63.70	702	26.57
9	1862	53.84	1145	44.47	1635	67.92	667	30.23
10	1658	58.89	972	52.86	1437	71.8	633	33.78
11	1440	64.30	837	59.41	1269	75.10	547	42.78
12	1250	69.01	721	65.03	850	83.32	527	44.87
13	834	79.32	621	69.88	666	86.93	507	46.97
14	730	81.9	569	72.41	515	89.89	485	49.27
15	653	83.81	522	74.68	514	89.91	464	51.46
16	565	85.99	395	80.84	501	90.17	415	56.59
17	546	86.47	392	80.99	-	-	370	61.3
18	-	-	-	-	-	-	370	61.3

Table 2: Model modified Gompertz equations and goodness of fits.

Digester /Combination	Modified Gompertz Equation	R^2
A= (62%OFMSW+38% CD)	$B_t = 40590 \exp\left[-\exp\{0.0919\, e(1)(0.7084 - t) + 1\}\right]$	0.9911
B = (80%OFMSW+20% PD)	$B_t = 37720 \exp\left[-\exp\{0.0933\, e(1)(0.8368 - t) + 1\}\right]$	0.9945
C = (98%OFMSW+2%UF)	$B_t = 45390 \exp\left[-\exp\{0.0834\, e(1)(0.4647 - t) + 1\}\right]$	0.9911
D =(100% OFMSW)	$B_t = 32460 \exp\left[-\exp\{0.1091\, e(1)(1.8470 - t) + 1\}\right]$	0.9958

4. Conclusions

A simple, improvised bench-scale 4000 cm^3 anaerobic biodigester proved to be a viable, affordable and effective means of generating and collecting biogas from OFMSW enhanced with CD, PD and UF in equivalent mixtures of optimum C/N of 30:1. Biogas evolution from OFMSW was improved 20.97%, 12.15% and 29.67% by CD, PD and UF, respectively. High COD values of more than 500 mg/l in all the biodigesters indicated high BMP which can be used to characterize the process. Non-linear regression analysis using the modified Gompertz equation was used to mathematically model the biogas evolution parameters which showed that the mixture of OFMSW applying urea fertilizer gave the best performance in a remarkably short HRT of 15 days with a biogas production potential of 45390ml, maximum gas production rate of 3785ml/day and a lag time of 0.4647days.

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