Design of a Community-Based Anaerobic Digester for Sustainable Solid Waste Management in Ile-Oluji Ondo State Nigeria

R. I. Areola[1] and O. O. Ipindola[1*]

[1]*Federal Polytechnic Ile-Oluji, Ondo State, Nigeria.*

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Aim: A Community-Based Anaerobic Digester was designed in this study for sustainable solid waste management in Ile-Oluji, Ondo state Nigeria.
Methodology: Waste samples were collected from selected households for a period of one month and the components and percentage composition were determined. Afterwards, the physico-chemical characteristics of the substrate was investigated and the result used to design a community-based anaerobic digester.
Results: The quantity, components and characteristics of waste generated was determined. The rate of waste generation was found to be 0.2kg/capita/day while the organic fraction of the total waste generated was found to be 55.7%. Physico-chemical characterization of the substrate was also investigated. The pH was found to be 6.36 ± 0.18, while the alkalinity 692.81 ± 78.62. The moisture content was found to be in the range of 71.20 ± 4.63%. Total solid was in the range 38.91 ± 5.25 while volatile solid was found to be 26.44 ± 2.83. carbon oxygen demand was found to be 834.33 ± 12.61, total phosphorus was in the range 4.20 ± 0.33. The Carbon on a dry weight basis was found to be in the range 60.41 ± 2.38, while nitrogen was found to be 4.79 ± 1.03. The C/N ration

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Corresponding author: Email: olajideipindola@gmail.com;

was found to be 21.61. The biogas yield ranged from $0 – 320$ cm^3 and $0 – 380$cm^3 per litre of substrate for biodegradable-only samples and biodegradable-cow dung samples respectively, for a forty days period of retention. The cylindrical dome type biogas digester was chosen for this study because of its simplicity in design and maintenance coupled with lower set up cost. The optimum volume of hydraulic chamber and gas storage chamber were designed to be the same as 850m^3. Volume of fermentation chamber and sludge layer were calculated to be 2014m^3 and 246m^3 respectively, while the height and diameter of the fermentation chamber were 7m and 17m respectively.

Conclusion: Anaerobic digestion of the biodegradable fraction of solid waste is a viable alternative that government and non-government organizations can key into for the improvement of public health especially in developing countries. The standardization of digester design parameters may pose challenges because of varying climatic conditions and complex socio-economic factors across different geographical contexts. Solutions may have to be adapted and localized to achieve a sustainable world.

1. INTRODUCTION

Million tons of solid waste is generated from agriculture, industries and municipal sources yearly and this has become a global concern as the rate of generation is greater than rate of degradation under natural conditions. The CO_2 and methane released from improper disposal of these wastes are aggravating the problems of public health, climate change and global warming [1]. The organic fraction of these wastes must be collected and processed to reduce its negative impacts [2]. Anaerobic digestion has proven to be helpful in this regard as it reduces the volume of waste going to dump sites and landfills. In addition to sustainable waste management, biogas production from the digestion process provides a green alternative to dependence on fossil fuels. Furthermore, the residues obtained after biogas production are used as manure for enrichment of soil nutrients [3].

The collection and utilization of the methane component of biodegradable wastes presents a viable and valuable source of renewable energy and opportunity to reduce the migration of a major greenhouse gas (methane) into the atmosphere thus mitigating the effect of global climate change [4]. Reducing methane emissions from landfills and open dumpsites by digesting wastes anaerobically and using it as an energy source can yield substantial energy, economic, and environmental benefits. This is an option that needs to be brought to the fore by relevant stakeholders in the Nigerian energy sector as we continue to witness an upsurge in electricity self-generation which comes with its own environmental and economic implications [5].

In Nigeria, municipal solid waste is collected by formal and informal sectors and burnt in open dumpsites chosen without any recourse to their environmental and health impact. This practice falls short of the UN sustainable development (SDGs) goals for the following reasons: the dump site serves as breeding grounds for disease carrying rodents and flies, the open burning of wastes releases CO_2 and other dangerous fumes that further compounds the problem of climate change, respiratory diseases, offensive odour and unpleasant sights. Furthermore, leachates from such sites pollute surface and ground water which constitute a serious threat to the environment and public health. This problem becomes more pronounced in low-income communities who are majorly agrarian with high percentage of vulnerable citizens. Developing a sustainable system of solid waste management has the potential to improve public health in these areas and improve food security because a large percentage of the food consumed in city centres are produced in these low-income communities. Considering this backdrop, the design of a sustainable and cost-effective solid waste management system adaptable for low-income communities in Nigeria is imperative.

The sustainable management of municipal solid waste has been an area of interest to researchers in the field of Civil and Environmental engineering for decades [6]. The potential of several techniques such as land filling, incineration, composting and bio-digestion to effectively manage solid wastes has been documented [7]. Among these techniques, anaerobic digestion has proven to be the most sustainable method of managing the

biodegradable fraction of municipal solid wastes [8]. Anaerobic digestion of biodegradable wastes has been employed to manage wastes from farms, industries and municipality in developed nations [9]. However, this practice has remained underexplored in a developing country such as Nigeria, where a large fraction of her solid waste composition is biodegradable [10]. Though researchers have documented the potential of biogas generation from solid wastes in Nigeria [11], most of these studies focused on cities where the waste composition and management practices differ from the conditions prevalent in rural communities [12]. Considering the vulnerability of the low-income population and their immense contribution to food security, it is important to design a sustainable system of solid waste management that contributes towards the achievement of the Sustainable Development Goals (SDGs), one, three, six and seven [13].

While designing an anaerobic digester, it is important to consider factors such as: waste characteristics, nature of digester, temperature, pH value, retention time, organic loading rate, Carbon/Nitrogen ratio, moisture content, economic conditions etc. [14]. These factors have spatial variations due to local environmental conditions, feeding habit, socioeconomic lifestyle, level of education etc. [15]. Analyzing these factors in a local context informs effective designs suitable for such context. This research analyzes the composition and characteristics of solid waste generated in Ile-Oluji, investigated the biogas generation potential of its biodegradable fraction and used the findings to design a community-based anaerobic digester for effective and sustainable solid waste management.

2. METHODOLOGY

2.1 Case Study

Ile-Oluji is the headquarter of Ile-Oluji/Okeigbo local government area of Ondo State Nigeria, located on Latitude 7.201741^0 N and Longitude 4.867622^0 E (Fig. 1) and covering a land area of 698 km^2 with a population of 172,870 at the 2006 census. The climate is tropical with average annual temperature and precipitation of 26^0C and 230mm respectively. Agriculture and small-scale retailing are the major businesses of the populace. The town hosts the fastest growing polytechnic (Federal Polytechnic Ile-Oluji) in Nigeria.

In order to achieve the aim and objectives of this research, the following methodologies were adopted:
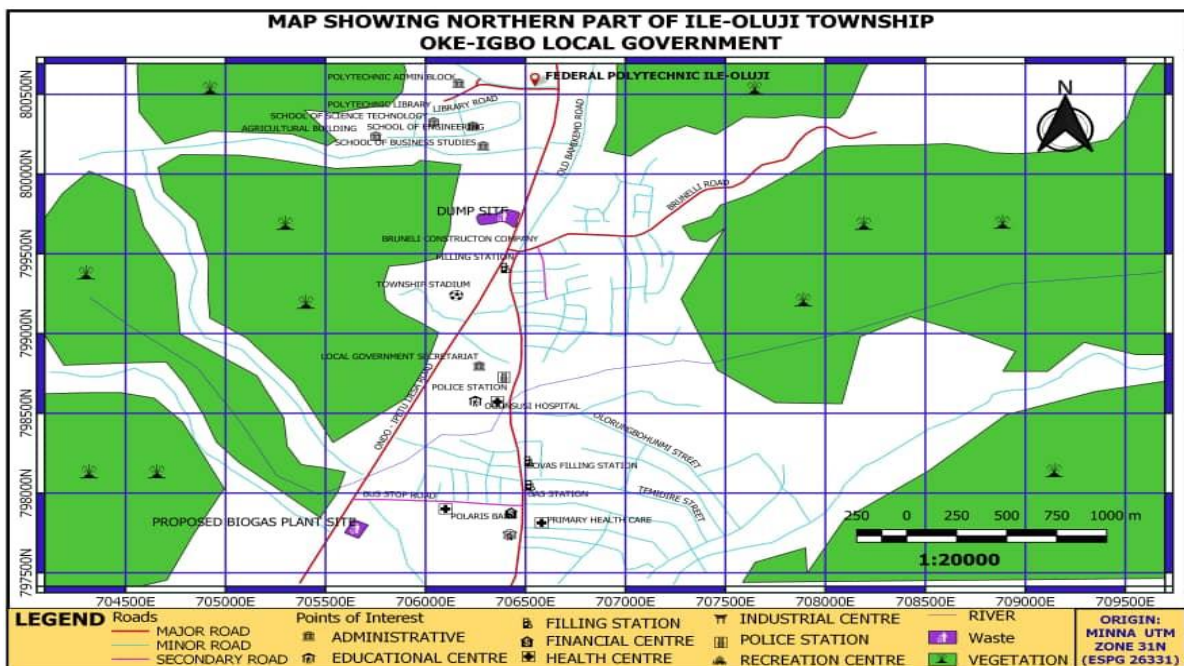

Fig. 1. Map Showing Land Use and General Layout of Ile-Oluji, Ondo State, Nigeria.
(Source: Authors)

2.2 Reconnaissance Survey

A reconnaissance survey was carried out to determine the prevailing waste management practices which included: method of collection, transportation and treatment of solid waste in Ile-Oluji. The volume and composition of waste being transported to the approved open dump site for the community (Fig. 2) was observed and recorded for a period of one month. This aided in the estimation of the waste generation rate per capita per day. Though the rate of waste collection coverage was not 100%, the composition and generation rate per household were estimated by extracting the data of house-to-house collection rate from the operators and dividing it by the volume of waste brought to the dump site daily.

2.3 Analysis of Waste Components

Representative samples of municipal solid waste were collected using appropriate methods from points of generation (households) and characterized based on ASTMD 5231-92 (Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste) [16]. The layout of case study was divided along four political wards and units, then, ten houses were selected from each political unit using stratified random sampling technique and the waste generated in these houses collected and analyzed for a period of three months (March to May, 2021) which happens to be a dry season in Nigeria. A total number of 36 polling unis comprising 360 households were selected for data collection. It is assumed that the physical and chemical characteristics of the waste samples do not vary significantly for the duration of study. The MSW sample collected weekly was homogenized by dividing the total sample into four portions and discarding two portions, then repeating the procedure until a significant weight sample of 30 kg was obtained. Afterwards, the waste sample was sorted into individual components such as food wastes, paper/cardboard, wood, metal, electronic, hazardous and plastic. The weights of the components were measured and recorded.

2.4 Characterization of substrates

The physico-chemical characterization of substrate was carried out prior to experimental set up. The parameters measured include: Total Solid (TS), volatile solid (VS), pH, chemical oxygen demand (COD), Volatile Fatty Acid (VFA), Total Phosphorus, Nitrogen, Carbon, and Carbon/Nitrogen ratio.

The sample preparation procedures described by [17] was adopted for this research. Total solid and volatile solid were measured according to the standard method described in [18]. The pH was determined using a PH meter. Chemical oxygen demand (COD) was measured using COD ampoules (Hach Chemical) and a spectrophotometer (DR/2010, Hach) according to ISO 6060 [19]. Hach COD low range digestion solution and deionized water was used as reagents, while, 1000mg/l KHP stock was used as the standard. In order to prepare the standard solution, 1g of primary standard grade potassium hydrogen phthalate (KHP) was dried overnight at 120^0C, cooled in a dessicator and 0.850g of the dried KHP transferred to a 1000ml volumetric flask. It was thereafter dissolved in 800ml deionized water. Samples of substrate were collected with holding time of 28 days and refrigerated under 0^0C – 6^0C, pH 2 with H_2SO_4. The spectrophotometer used in measuring the COD was calibrated with a wavelength of 420nm and the standard and samples read according to the method outlined in QAM-1-104.

Fig. 2. Government Approved Dump Site for Ile-Oluji Community (13.03.2021)

2.5 Biogas Generation Experimental Procedure

Two sets of lab-scale digesters (1litre each) were assembled and prepared for experimentation as described by [20]. The main reason for development of this lab-scale digester was to study the anaerobic digestion process in identical batch digesters using different process parameters, in order to optimize these parameters before development of the design of a larger (community-based) digester. The substrate in the first set of lab-scale digesters contained food waste and other biodegradables generated in households while the second set of model digesters contained food waste mixed with cow manure. Based on the dry matter content of each substrate the mixing ratio with water was determined, then the required amount of water was added to the substrate to bring the substrate to a standard 10% dry matter content, and subsequently mixed by shaking until a homogeneous mix was obtained. The mixture was then placed inside the digester up to the working volume (75% of the total volume), and the digester top covered tightly. Manual agitation was performed on the digesters daily in order to ensure intimate contact between the microorganisms and the substrate for effective biogas production. Readings of temperature inside and outside the digester, pH and volume of biogas produced were measured and recorded on a daily basis. Biogas generation was determined using Ircd4 Biogas Analyzer with British Sensor Biogas Detector while the pH was measured using a pH meter. Hydraulic Retention time (HRT), that is, time taken until biogas production ceases for each lab-scale digestion was equally measured and recorded.

2.6 Design of Anaerobic Digester

The cylindrical dome type digester has been chosen for this study because of simplicity in design and maintenance and lower set up cost compared with other types as shown in Fig. 3 below. It also has the advantage of being used in small scale (household systems) and large scale (community) systems. The assumptions for sizing the digester are presented in (Table 1).

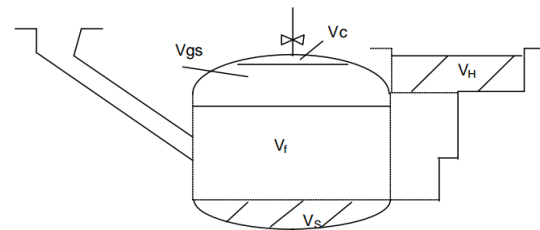#### 2.6.1 Sizing of components

Cross-section of the digester:

Fig. 3. Cross-section of Cylindrical-Dome Digestion

Volume of gas collecting chamber = V_c
Volume of gas storage chamber = V_{gs}
Volume of fermentation chamber = V_f
Volume of hydraulic chamber = V_H
Volume of sludge layer = V_s
Total volume of digester $V = V_c + V_{gs} + V_f + V_s$
Geometric Dimensions of the Cylindrical Shaped Biogas Digester Body:
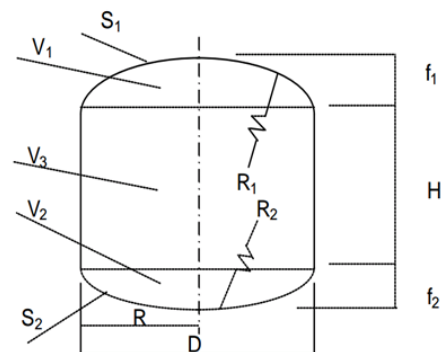

Fig. 4. Geometric Dimensions of the Cylindrical Shaped Biogas Digester

3. RESULTS AND DISCUSSION

3.1 Reconnaissance Survey

A survey of the approved dump site for the case study was conducted for a period of one month. It was observed that the prevailing method of managing solid waste include: house to house collection of unsorted solid waste by informal collection companies using mid-sized trucks once every week and dumping them at the approved community dump site. The dumped waste is not subjected to any form of treatment before they are burned. At the beginning of every rainy season, pay loader machinery is used to heap and compact the dumped waste so as to create space for trucks to dump fresh solid waste.

Table 1. Assumptions for Sizing Biogas Digester

For Volume	For Geometrical Dimensions
$V_c \leq 5\%\ V$	$D = 1.3078 \times V^{\frac{1}{3}}$
$V_s \leq 15\%\ V$	$V_1 = 0.0827\ D^3$
$V_{gs} + V_f = 80\%\ V$	$V_2 = 0.05011\ D^3$
$V_{gs} = V_H$	$V_3 = 0.3142\ D^3$
$V_{gs} = 0.5(V_{gs} + V_f + V_s)\ K$	$R_1 = 0.725D$
Where K = Gas production rate per m3 digester volume per day.	$R_2 = 1.0625\ D$
It is assumed 0.5 for Nigeria.	$f_1 = \frac{D}{5}$
	$f_2 = \frac{D}{8}$
	$S_1 = 0.911\ D^2$
	$S_2 = 0.8345\ D^2$

The activities of informal recycles was equally observed at the dump site. They come in every day to scavenge waste metals which they in turn resell to large scale recyclers to sustain themselves and their families. A lot of progress can be achieved if these informal recyclers can be incentivized and empowered by the government in collaboration with the waste generators presorting their wastes and preparing them for collection.

3.2 Estimation of Solid Waste Generation

A total of 18 trips was estimated to be made per week by private waste collectors to the dump site with each truck having an estimated carrying capacity of 10 tons. In view of this, the total weight of solid waste received at the dump site daily is;

No of trips x 10 tons / 7 days = 18 x 10/7 = 25.71 tons per day = 25710kg per day.

The population of Ile-Oluji is estimated to be 138, 894 (NBS, 2016).

Waste generation per day is calculated as: 25710kg/138,894 = 0.2kg/capita/day.

Waste generation rate is highly impacted by the socioeconomic status of households. It is typical of high-income earning cities to generate more waste and less organic wastes than low-income communities. This result is consistent with those of other researchers in the same context [21,22]. Though the percentage of subscription to waste collection by households at case study is not known, interactions with the waste collectors gives an estimate of 45% which is low for an emerging economy. There is need for more education and awareness of the need to subscribe to sustainable waste management approaches.

3.3 Physical Characterization of Waste Components

The physical components and percentage composition of wastes generated at the case study, are presented in (Table 2) below. The analysis of physical composition of solid waste revealed that food/putrescible waste comprise 55.7% of the total waste received at the dump site, followed by rubber waste with 11.7%. Others are plastic – 10.7%, metals – 6.0%, glass/ceramics – 4.3%, paper – 3.0% and others (wood, ashes, leaves etc.) – 8.7% as shown in (Fig. 5). The high percentage of food and organic waste is typical of an agrarian and low-income community where most of the food are prepared fresh and eaten at home as rightly noted in the findings of [23]. The high percentage of food/organic waste makes anaerobic digestion and composting the most sustainable methods of managing the solid waste generated at the case study. The gas generated from the digester is useful for lighting and other energy use, while the slurry is a good source of organic fertilizer for crops.

3.4 Physico-chemical Characterization of Substrate

The result of physico-chemical characterization of the substrate fraction of the solid waste is presented in (Table 3). The pH was found to be 6.36 ± 0.18, while the alkalinity 692.81 ± 78.62. Adequate alkalinity is required to maintain stable pH in any anaerobic digestion process. These results are in agreement with [24]. pH value in anaerobic digestion is very important factor as methanogenic bacteria are sensitive to acidic environment by which growth and gas production is inhabited. The pH value varies along the different stages of anaerobic digestion [25]. Hydrolysis and acetogenesis occur at pH

between 5.5 and 6.5, respectively [26]. The moisture content was found to be in the range of 71.20 ± 4.63%. High moisture content is a necessary requirement to facilitate anaerobic digestion. Total solid was in the range 38.91 ± 5.25 while volatile solid was found to be 26.44 ± 2.83. carbon oxygen demand was found to be 834.33 ± 12.61mg/l, total phosphorus was in the range 4.20 ± 0.33. The carbon on a dry weight basis was found to be in the range 60.41 ± 2.38, while nitrogen was found to be 4.79 ± 1.03. the C/N ration was found to be 21.61. This finding is well in tandem with [24].

3.5 Biogas Generation

3.5.1 Substrate temperature, pH, Biogas variations

The variation in the temperature of samples and ambient is presented in (Fig. 6). The internal temperature of the digester sample prepared with household biodegradables was found to vary between 26^0c – 32^0c, while the temperature of

the sample containing household biodegradables and cow dung was found to range from 24^0c – 33^0c. the ambient temperature of the laboratory environment was found to range from 24^0c – 34^0c. The observed pH of the two sets of samples prepared was quite close. The biodegradable only sample was found to range from 4.8 – 8.1, while the sample mixed with cow dung ranged from 5.1 – 7.4 as shown in (Fig. 7). this result agrees with the findings of [27].

The result of daily biogas yield presented in (Fig. 8) shows that maximum yield was recorded in the third and fourth weeks for the biodegradable plus cow dung and biodegradable only samples respectively. The biogas yield for biodegradable only sample ranged from 0 – 320 cm^3 for the forty days period of retention, while biodegradable plus cow dung sample ranged from 0 – 380cm^3. The increase in the yield of the second sample can be explained by its mixture with cow dung which is rich in Methane. This result is consistent with the findings of [24].

Table 2. The Components and Percentage Composition of Solid Waste Generated at Case Study

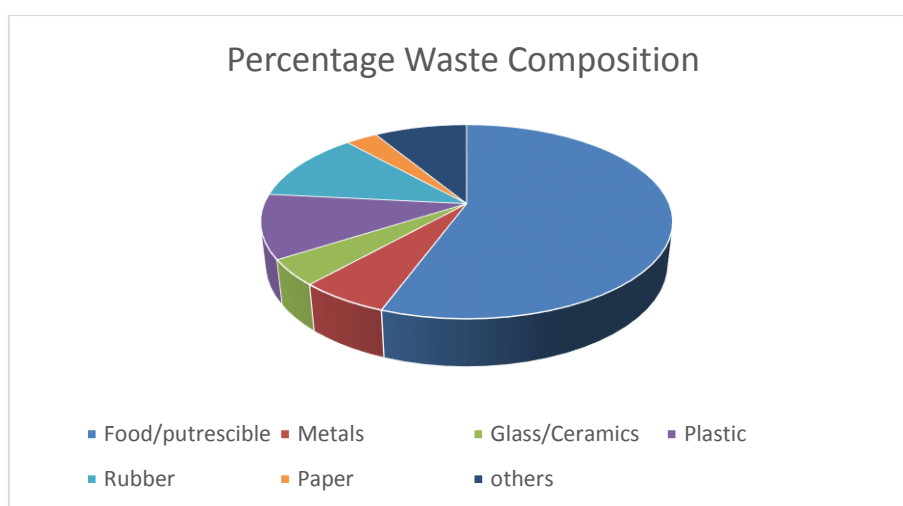| S/N	Waste Component	Mass (KG)	Percentage (%)
1	Food/putrescible waste	16.7	55.7
2	Metals	1.80	6.0
3	Glass/ceramics	1.3	4.3
4	Plastic	3.2	10.7
5	Rubber	3.5	11.7
6	Paper	0.9	3.0
7	Others	2.6	8.7
	Total	**30**	**100**

Fig. 5. Component and Percentage Composition of Solid Waste Generated in Ile-Oluji (February, 2021)

Table 3. Characterization of Substrate

Parameters	Waste
pH	6.36 ± 0.18
Moisture Content (%)	71.20 ± 4.63
TS (%)	38.91 ± 5.25
VS (%)	26.44 ± 2.83
VS/TS (%)	63.57
VFA (mg/l)	228.32 ± 51.24
Alkalinity (mg/l)	692.81 ± 78.62
COD (mg/l)	834.33 ± 12.61
Total Phosphorus (ppm)	4.20 ± 0.33
Carbon (% db)	60.41 ± 2.38
Nitrogen (% db)	4.79 ± 1.03
C/N ratio	21.61

Table 4. The Sizing of Anaerobic Digester

Item	Calculations	Output
Waste/day	No of trips x 10 tons / 7 days = 18 x 10/7 = 25.71 tons per day	25710kg
Food waste/ putrescibles	Food waste / putrescibles = 55.7% of total waste/day = 55.7% x 25710kg	14320kg
Total Solid (TS)	TS = 40% of food waste / putrescible = 40% x 14320kg	5728kg
Total Influent	The percentage of TS that makes the influent is assumed 8%, 1kg TS = 100/8kg influent Therefore: 5728kg TS = 100/8 x 5728 = 71600kg	71600kg
Water needed	Water needed to make 8% concentration of TS: 71600kg – 14320kg = 57280kg	57280kg
Working volume of digester ($V_{gs} + V_f$)	$V_{gs} + V_f$ = Q. HRT (HRT is assumed to be 40 days) 71600 x 40 = 2864000kg ($1000kg = 1m^3$) = $2864m^3$ From geometric assumptions: $V_{gs} + V_f = 0.8V$, 0.8V = 2864	$3580m^3$
D	$D = 1.3078 \times V^{\frac{1}{3}}$	17m
V_3	$\dfrac{3.14 \; x \; D^2 \; x \; H}{4}$	$1543m^3$
H	$\dfrac{4 \; x \; 0.3142 \; x \; D^3}{3.14 \; x \; D^2}$	7m
f_1	$\dfrac{D}{5}$	3m
f_2	$\dfrac{D}{8}$	2m
R_1	R1 = 0.725D	12m
R_2	R2 = 1.0625D	18m
V_1	$V1 = 0.0827D^3$	$406m^3$
V_2	$V2 = 0.05011D^3$	$246m^3$
Vc	Vc = 0.05V	$179m^3$
V_{gs}	$V_{gs} = 0.05(V_{gs} + V_f + Vs)$ K (k = gas production rate per m3 digester vol/day = $(0.3 – 0.7m^3$/kg TS)	$850m^3$
Volume of hydraulic chamber (V_H)	$V_H = V_{gs}$	$850m^3$
Volume of sludge layer	Vs = 15% of V = 15% x 3580 = $537m^3$	

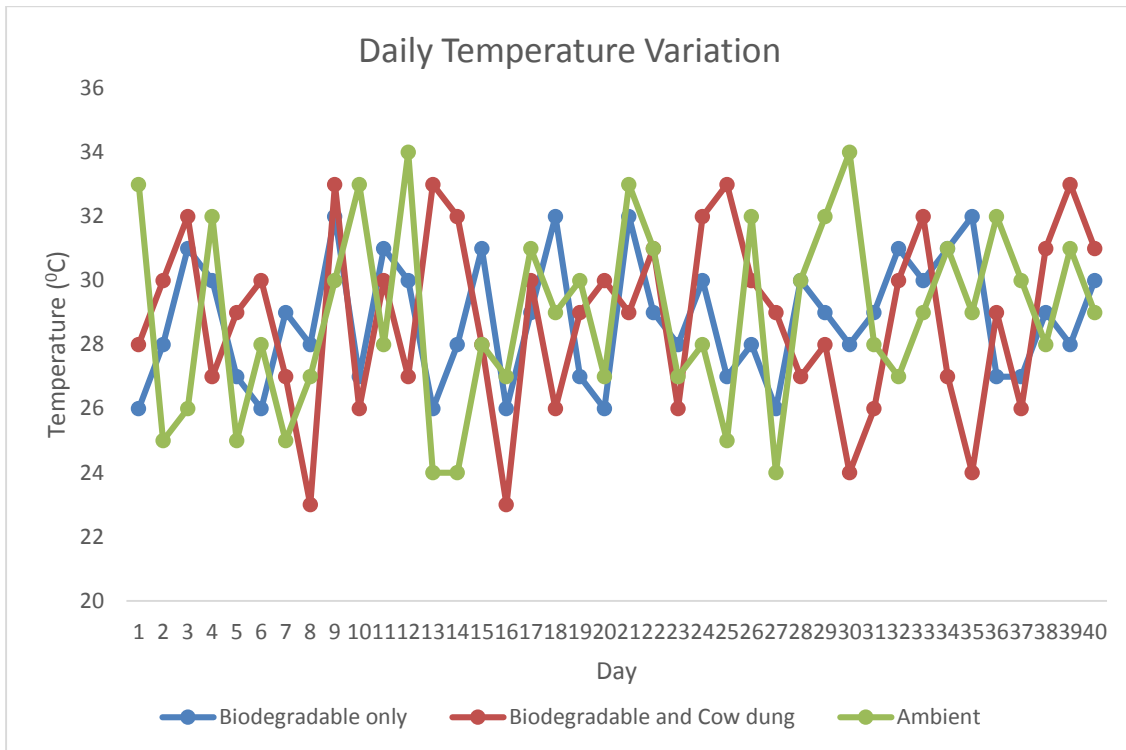| Item	Calculations	Output
(Vs)		537m^3
Vf	Vf + Vgs = 0.8V	2014m^3
S1	S$_1$ = 0.911 D^2	263m^2
S2	S$_2$ = 0.8345 D^2	241m^2

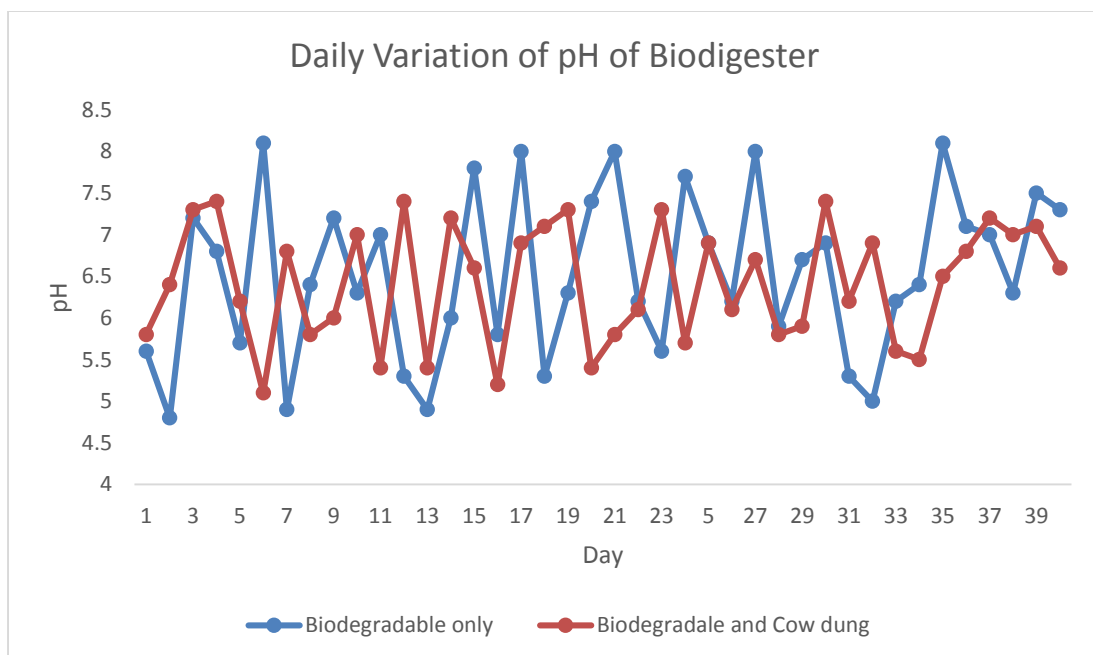**Fig. 6. Daily Temperature Variation of Digester and Ambient**
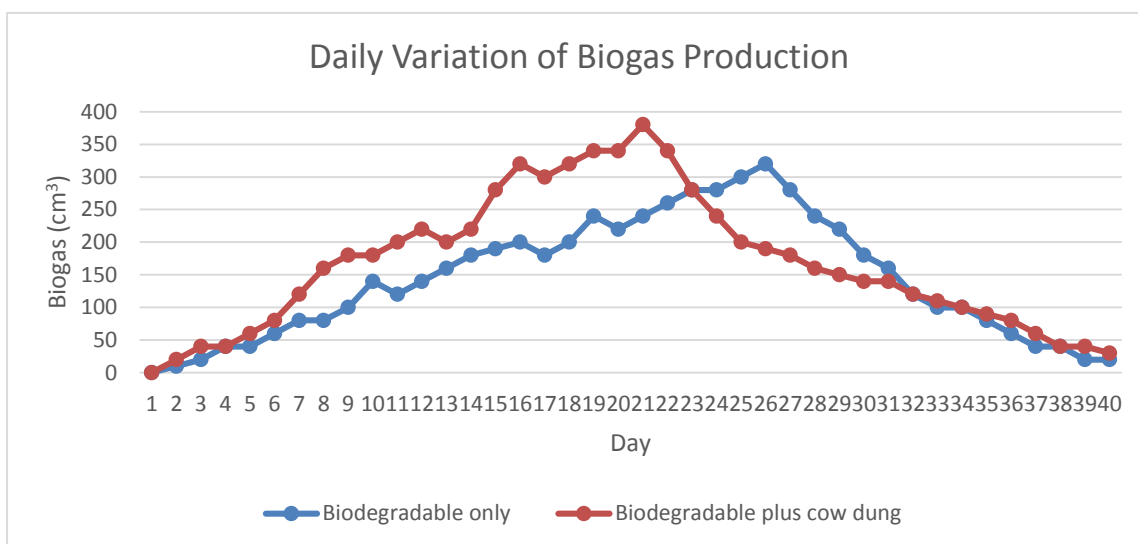

Fig. 7. Weekly variation of pH of Biodigester

Fig. 8. Daily Variation of Biogas Production from the Digesters

3.6 Sizing of Anaerobic Digester

The design as shown in (Table 4), was calculated based on the assumption that the substrate comprises of pre-sorted biodegradables generated from households which makes up an average of 55.7% of the total volume of waste generated daily at the case study. The volume of the fermentation and gas holding chambers were calculated to be 2014m^3 and 850m^3 respectively, while the diameter and the height of the chamber was estimated to be 17m and 7m respectively. Considering this geometry and the prevailing local conditions at the case study, reinforced concrete appears to be the most suitable material for the construction of the digester. Concrete is a very durable and easy to construct composite.

4. CONCLUSION

A community-based anaerobic digester for a low-income township has been designed in this study. The characteristics of the waste generated at the case study was found to be suitable for anaerobic digestion, though the practice is hitherto alien to the environment. Considering the agrarian composition of the case study, anaerobic digester holds a high promise for rural women empowerment, job creation, environmental sustainability, food security and improvement of public health. The simplicity of the technology also makes it a viable alternative for sustainably managing solid waste in a developing country.

It is recommended that the government at the federal, state and local levels enact policies to promote pre-sorting of wastes before disposal. Incentives in form of subsidized collection fees could be initiated to improve subscription of the populace to sustainable waste management. There is also need for aggressive education of rural populace by National Orientation Agency of the need to be aware of climate change and its consequences. Finally, the ministry of science and technology in collaboration with the ministry of education can collaborate with academics and industry practitioners to train rural youths on simplebio-digester technologies for decentralized and sustainable waste management techniques.

CONSENT

As per international standard or university standard, respondents' written consent has been collected and preserved by the author(s).

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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