Biogas production as energy source and strategy for managing waste and climate change

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Abstract

The study presents technical and economic approaches of upscaled laboratory experiment using yard waste (YW) and heterogeneous slurry (HS) to produce heat and power, as a means of bridging the gap between energy production and climate change management strategies. A combination of YW:HS in ratio 2:3 with slurry obtained from a functional digester serving as inoculum was fed into the digester. These were mixed in the ratios of substrates/inoculum/water of 3.5:0.173:6.28 and theoretically upscaled for field-scale biodigesters. The modeled result shows that about 2.5 m³ gas is produced per 5-m³-sized digester over a 30-day hydraulic retention time and estimated project life of 20 years. A business model was adopted for cost recovery of the proposed waste-to-energy system and life cycle cost analysis for the production costs of the seven 5-m³ digesters. Avoided emissions of CO₂ from other equivalent energy sources are 4.36 kg, 10.16 kg, 10.37 kg, and 81.32 kg, respectively, for LPG, kerosene, diesel and fuel wood/charcoal. The project is sustainable in for profit, people and planet.

Keywords Biogas · Waste-to-energy · Climate change management · Energy source · Waste · Strategy

1 Introduction

Degradable wastes do contribute to release of greenhouse gases (GHG), particularly methane, to the atmosphere [1]. This could have negative climate change effect through the release of greenhouse gases to the atmosphere. However, proper management of these wastes, particularly through energy recovery and recycling amongst others [2], could mitigate this effect. Global waste generation is estimated at 0.26 tons per capita, and it is projected to increase by 70% in 2050 [3]. Per capita waste production in sub-Saharan Africa has an average of 0.65 kg per person per day [4]; in Nigeria, it is 0.43 kg/head per day and 60–80% of it is organic [5, 6]. Organic wastes produced within human settlements include food waste (FW),

agricultural waste, yard waste (YW), human and animal waste [7, 8]. Studies show that wastes, particularly organic wastes, are improperly managed in Nigeria [7, 8], inducing the necessity to find and implement suitable methods of waste management, such as the use of anaerobic digestion. Anaerobic digestion (AD) is a nonthermal technological approach to waste management.

The use of AD as a waste management technology has huge potential to meet both purposes of mitigation and adaptation approaches in climate change management strategies [9]. AD produces biogas that can be used as a substitute in various sectors, including transportation, agriculture, residential/household and industrial sectors. The gas can be particularly helpful in cottage industries in the rural areas for processing of agricultural products

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such as provided needed energy for frying of milled cassava to garri. For example, the use of biogas produced from AD technology has been shown to reduce the use of fuel wood and this in turn lessens forest degradation [10] (energy need for garri processing is discussed in more detail in a later section). Also, AD of vegetal organic waste could reduce particulate matter by 5.3%, climate change by 6.4% and ozone depletion by 13.4% as opposed to using them directly as fertilizers in farms [11]. These facts highlight the need to develop integrated AD systems that not only mitigate the GHG emission from by-products of agriculture but will also serve as energy source which can then be put into agricultural processing. However, implementing the production of biogas for energy production in Nigeria is faced with a number of challenges, insufficient amounts of substrate for biogas generation [12] and unavailability of local technology in developing countries leading to increased cost of putting biogas to use [13]. Despite these, however, biogas production can still play a vital role in augmenting communal energy needs particularly in rural settings, hence this study.

Broadly, the study evaluates the means of using an upscaled-sized digester for biogas production in energy utilization as a climate change mitigation strategy. A business model was developed for scaling up laboratory experiment to a field-scale level. Specific objectives are to: design series of stainless steel digesters to the capacity of 35 m³; scale up experimental data on yard waste, heterogeneous slurry and inoculum as seed from a functioning digester to generate biogas as an alternative fuel to existing fossil fuel resources [14], formulate a business model of life cycle costs and revenue stream; and estimate avoided emissions for other fuel types used for cooking or electricity generation.

2 Theoretical development

2.1 Biodigesters and biogas production

There are several types of commercially utilized digesters. These include the fixed dome, plug flow and bag types [15–17]. The type used for this study is the plug flow fixed dome digester chosen because of ease of construction and the relatively low cost of materials. For the experimental study, the feedstock used for the substrates is food waste (FW) because of its relatively high degradability, nutrient content and methane yield [18, 19], and YW to balance the C/N ratio of FW [20]. However, because of other competing uses to which FW is put to, the scaling up process only considered the use of YW mixed with heterogeneous manure involving swine manure, poultry litters and drop-pings. Co-digesting YW with this heterogeneous manure

leads to higher biomethane potential (BMP) yields [21]. Co-digestion is usually influenced by C/N ratio, and it has been shown that the optimal ratio is 25–30:1 [22], [23].

Biogas is produced when organic matter is anaerobically broken down. It is largely composed of methane (CH₄) and carbon dioxide (CO₂) with small amounts of water and other gases. The composition of the biogas depends on the substrate and the conditions of digestion [24]. Biogas is produced in four stages: hydrolysis, acidogenesis, acetogenesis and methanation [25], with its production being influenced by several factors including temperature, pH and inoculation [26]. Estimating the performance of substrates in a biodigestion process involves carrying out a number of preliminary tests on the substrate including biomethane potential (BMP) [27], total solids (TS) and volatile solids (VS) [28], carbon–nitrogen (C/N) ratio [29] and nutrient content analysis [19].

2.2 Energy need for garri processing

Garri is an important staple food made from grated cassava (*Manihot esculenta*) in Nigeria and probably all the countries in West Africa. It is usually processed by women through peeling, washing, grinding, fermenting and roasting of the milled cassava (see Fig. 1). This analysis focuses on roasting milled cassava to garri. Between 22.6 and 33.8 kJ, or an average of approximately 28.2 kJ of thermal energy is needed for the production of garri from 1 kg of milled cassava (Jekayinfa [30, 31]).

3 Methodology

The laboratory-scale study focused on the use of food wastes (FWs) and yard wastes (YWs) as substrate. The FW used is mainly leftovers of cooked rice in all forms, while YW is taken to include but not limited to, leaves, wood chips and twigs. These were mixed with heterogeneous manure from swine and poultry sources, used as substrates in the digester. The mixture ensured a carbon–nitrogen (C/N) ratio for effective production of methane and to also dilute inhibitors and toxic compounds [20]. Through the laboratory-scale experiment, basic data needed to design field-scale digesters were generated. Field-scale digesters are needed to handle municipal solid wastes (MSWs) of any kind to generate biogas. The steps taken included constructing laboratory-scale biodigesters, collecting and preparing required wastes to be fed into the biodigesters, batch feeding of the biodigesters, taking of daily readings of biogas yield and temperature per digester, and conducting laboratory tests on the substrates. Scaling up the laboratory-scale to field-scale production involves business model formation Fig. 2.

Fig. 1 Semi-mechanized garri processing plant—[32]

Fig. 2 Processing steps for garri, a cassava-based product—[30]

3.1 Business model formulation

Scaling up biogas production from the laboratory-scale to field-scale level requires implementing a business model. A business model describes the rationale of how an organization creates, delivers and captures value in economic, social, cultural or other contexts while business model innovation is the process of formation of a business model [33], [34]; it encompasses a wide range of factors [35]. There are two broad types of business models: traditionally funded business models that are typically government-owned and private market-driven business models. The private market-driven models are further subdivided into one-hand business model, two-hand business model, fee-for-service or pay-as-you-go (PAYG) business model and lease/hire purchase business model [36]. Further classification of business models can be found in [37] and [38]. Most businesses usually operate by making use of any combination of these models.

3.2 Materials and methods

The feedstock is made up of a mixture of food wastes (FWs), which was collected from various restaurants and food production outlets, and yard wastes (YWs), collected from various sources such as small-scale farms, and the lawn mowing, hedge and tree trimmings. The slurry was collected from an operational heterogeneous digester for inoculum.

The co-substrates were combined by targeting the standard carbon–nitrogen ratio (C/N) which is 25:1, the C/N of yard waste is 30:1 while that of food waste is 20:1 [39]. The calculation of the co-substrate C/N is shown below:

$$\text{Yard waste (YW)} = \frac{30}{50} \times 25 = 15 :$$

$$\text{Foodwaste (FW)} = \frac{20}{50} \times 25 = 10$$

YW:FW ratio in order to balance the carbon–nitrogen ratio is 15:10 which is 3:2.

The co-substrates were combined in a mass ratio of 3:2 that is YW to FW in order to balance the C/N ratios [20]. The ensuing mixture was then combined in the ratio of co-substrates/inoculum/water of 3.5:0:8 for the control digester, namely D1, 3.5:1.15:6.85 for the digester with 10% inoculation referred to as D2, and 3.5:0.173:6.28 for the digester with 15% inoculation referred to as D3. The digesters were fed with these substrate mixtures accordingly and sealed. Samples of the YW, FW and inoculum were used to determine VS, TS and BMP for characterization of the substrate.

The TS was determined by heating a pre-weighed sample to a constant weight at 105 °C and calculated using

$$\text{TS} = \frac{M_a}{M_b} \times 100 \quad (1)$$

where M_a and M_b represent the final and initial masses, respectively

The VS was then determined using the same sample mass by heating at 550 °C till; again, a consistent mass is reached and then the VS content is determined using Eq (2):

$$\text{VS} = \frac{M_c}{M_d} \times 100 \quad (2)$$

where M_c and M_d represent the final and initial masses, respectively.

The BMP was determined by first obtaining the Infrared (IR) spectra of the samples using a Shimadzu FTIR 8400S Fourier transform infrared (FTIR) spectrophotometer and then followed by calculation of the BMP using the partial least squares model as described in [40], [41]. The temperature and volume of gas produced by each digester were measured each day. Data obtained were used to determine the optimal conditions for anaerobic digestion of the mixture of food and yard wastes.

These laboratory-scale results were then adapted for upscaling of the biogas digester size and the substrates to be used through business model formation. The template used for this study is a private market-driven business model, particularly for the sales of biogas to enable cost recovery. The private market-driven business model will cater to lack of technology and technical competence in the target areas, customers' commitment to long-term use of the product or customers being able to pay for the

Table 1 Result of TS and VS tests

	TS	VS	VS/TS
Inoculum	2.462063	1.740963	0.707116
YW	83.03881	25.31098	0.304809
FW	36.60695	29.02401	0.792855
Digester 1	22.44509	9.22089	0.41082
Digester 2	26.21811	4.82491	0.184030
Digester 3	10.9981	1.29040	0.117329

Table 2 Calculated BMP values

Digester	BMP (ml CH ₄ per gram VS)
YW	1396.78
FW	424.1549

product in affordable increments also known as pay-as-you-go, as opposed to paying a one-time upfront investment [42].

In the business model, biogas is an energy product intended to bridge a gap in terms of cooking needs and electricity supply. The market for biogas in rural areas is quite huge, but it is yet to be accepted as an energy source in Nigeria, whereas in Norway, Germany, India and parts of China, for example, the use of biogas is common place as compared to Nigeria, where biogas utilization is near zero. To mitigate business risks, communities in target areas will be made shareholders or asked to provide equity.

4 Results and discussions

The results of the laboratory-scale experiments including tests/analysis conducted and readings that were taken are presented. The tests/analysis conducted is for the TS, VS and FTIR to determine BMP, and the readings taken are for daily temperature and gas yield, respectively. The result of the TS and VS tests is shown in Table 1. The table shows the characterization of the inoculum and the FW having high solid content at over 70% each, while that for the YW is low at about 30%. This characterizes the process as solid-state anaerobic digestion (SS-AD) [43]. SS-AD has multiple advantages including high organic loading, minimal digestate generated and low energy requirement for heating. In contrast, SS-AD has long solid retention time, incomplete mixing and an accumulation of inhibitors [44]. The mixture in the digesters showed a lower rate of volatile solids after they were diluted with water.

In the laboratory experiment, the measured values of TS and VS differed from what was expected. This could be adduced to the disadvantage of incomplete mixing in the

SS-AD constituents which were not homogenous when withdrawn for sampling. However, the calculation Table 2 of TS and VS values of H, FW and YW showed consistency with what obtains in the literature as (see [20], [45]). The VS/TS ratios of the digester substrates lie between those for YW and FW because the substrates are a mixture of the YW and FW. digester 1 had the highest VS/TS ratio followed by digesters 2 and 3, respectively. This implies that digester 1 has the predisposition to produce the highest amount of gas followed by digesters 2 and 3, respectively.

The IR spectra of the samples acquired using Shimadzu FTIR 8400S spectrophotometer are shown in Figs. 3 and 4. The combined spectra, obtained using MATLAB, are shown in Fig. 3. The spectra were then used to obtain the functional groups and BMP of the substrates.

The functional groups in the YW sample were determined using the peaks in zones 1–5 of the acquired

IR spectra for the YW. The peak 3417.98 cm^{-1} indicates the presence of alcohol, 2920.32 cm^{-1} , aldehyde, 2850.88 cm^{-1} , alkyl, 2166.13 cm^{-1} and 2054.36 cm^{-1} , alkynes, 1722.49 cm^{-1} , aldehyde, 1620.26 cm^{-1} , alkyne, and 1514.17 cm^{-1} , benzene ring. For the FW, the peaks in zones 1–5 of the acquired IR spectra were also used to identify the functional groups. The peaks 3558.48 cm^{-1} and 3414.12 cm^{-1} are indicative of the presence of amines, 3010.98 cm^{-1} and 2926.11 cm^{-1} , aryl groups, 2854.74 cm^{-1} , alkyl group, 2168.06 cm^{-1} and 2052.33 cm^{-1} , Alkyne, 1745.64 cm^{-1} , aldehyde, 1639.55 cm^{-1} and 1550.82 cm^{-1} , benzene ring, and 1465.95 cm^{-1} alkane group. The combined spectra Fig. 5 present a combined peak for FW and YW as has been described.

The daily gas yields for each digester are shown in Figs. 6, 7 and 8. The gas yields were measured in liters using water displacement.

Fig. 3 IR spectra of YW

Fig. 4 IR spectra for FW

Fig. 5 Combined IR spectra

Fig. 6 Graph of gas produced daily by digester 1

Fig. 7 Graph of gas produced daily by digester 2

The volume produced per day per digester in the laboratory-scale experiment was analyzed using one-way

Fig. 8 Graph of gas produced daily by digester 3

Fig. 9 Graph of temperature and volume for digester 1

ANOVA with $\alpha = 0.05$. The ANOVA test showed that the inoculum has a significant effect on the volume of gas produced. The data were further subjected to t test with two samples and the assumption of equal variance at the same value of α , and the analysis showed that although

Fig. 10 Graph of temperature and volume for digester 2

Fig. 11 Graph of temperature and volume for digester 3

the influence of addition of inoculum was significant, there was no statistically noticeable difference between the volumes produced by digesters 2 and 3 and hence the 10% and 15% inoculum addition.

The relationship between volume of gas produced and digester temperatures is shown in Figs. 9, 10 and 11.

Estimated energy from the expected quantity of biogas to be produced from the biodigesters is used to calculate the quantity of milled cassava that would be processed into garri using the postulated biogas setup. Theoretically, the digesters are estimated to produce about 213.5 kg of biogas with equivalent energy of 332.5 MJ within a 30-day period or an average of 7.11 kg per day. From the earlier assessment, the average energy needed to produce garri from 1 kg of milled cassava is put at 22.8 kJ. Therefore, the average amount of biogas produced per day will theoretically be enough to process about 400 kg of milled cassava into garri with efficiency of the biogas burning assumed at 100%.

The business is expected to operate by getting substrate from the community, and revenue from selling the gas generated, and the technology, which is the basis for the business model formulation. The preferred method of payment follows the pay-as-you-go (PAYG) model, and the reasons for this have been highlighted in the preceding section.

The cost estimate used in this study is an approximate method which is based on limited cost and design information just to show that the project is economically feasible. The gas produced is assumed to be used for two things: heating and electricity generation using gas burners for cooking and an internal combustion (IC) engine for electricity generation. The IC was chosen because it is the most used for landfill electricity generation and is cheaper to operate than both gas turbine systems and steam turbine systems [46].

This design is based on seven different 5-m³ digesters to give a total of 35 m³; these are projected to service 100

Table 3 Total capital cost

Item	Estimated cost	Estimated quantity	Cost
Digester tanks 7 5 m ³ tanks	\$1111.11	7	\$7777.78
Storage tanks	\$555.56	14	\$7777.78
Different sizes of PVC pipes	\$1.39	25	\$34.72
Different sizes of connecting tubes	\$0.69	60	\$41.67
Valves	\$2.78	25	\$69.44
Site construction	\$277.78	1	\$277.78
Transportation	\$138.89	1	\$138.89
Labor costs	\$27.78	25	\$694.44
Construction of 3-burner gas stoves	\$16.67	50	\$833.33
Communication	\$55.56	1	\$55.56
Substrate collection first time	\$1138.89	0	–
R&D	\$2777.78	1	\$2777.78
Vaporizer for generator	\$2777.78	1	\$2777.78
Sum			\$23256.94

Table 4 Operation and maintenance costs

ITEM	Estimated cost	Estimated quantity	Cost
O&M	\$2777.78	1	\$2777.78
Iron filling and steel wool	\$69.44	350	\$24305.56

Table 5 Energy content of various fuels on a basis of 21.35 kg of methane generated per day

	Mass (kg)	Energy content (MJ)
Biogas	21.35	332.5
LPG	7.875	26565.7
Kerosene	10.5	29347.8
Fuel wood	61.25	66195.7
Petrol	12.25	41086.9
Diesel	8.75	28695.7

rural households. The total capital cost of the system is estimated as shown in Table 3. It is anticipated that revenue would be generated via selling the digestate to farmers as organic fertilizer and the electricity to the local consumer. The price of the digestate was pegged at about \$5.6 per Mg while that of the electricity was pegged at \$0.0027 per kBTU. These prices were chosen with respect to the prevailing market prices in SW Nigeria as at when this study was conducted.

For the recurring costs, the YW and HS will be sourced from local farmers. Since yard waste was hitherto a waste product in these communities, the authors felt the price of \$0.06 per kilogram was justified. The iron and steel filings for the gas pipes are estimated to cost \$69.44 per month for 350 months, and the general operation and maintenance cost on a yearly basis are estimated to be about \$2800 shown in Table 4.

The expected emissions were estimated, and their values are compared with those from conventional fuel sources on the basis of energy generated. The results are shown in Tables 5, 6 and 7.

Table 7 Avoided emissions when biogas is compared with other fuel sources

	Avoided emission CO ₂ (kg)	Avoided emission CH ₄ (kg)	Avoided emission NO ₂ (kg)
Biogas	0	0	0.00E+00
LPG	4.33576	2.39225E-05	2.39E-06
Kerosene	10.15613	0.00084875	2.03E-04
Fuel wood	81.3155	0.02631125	3.55E-02
Diesel	10.374	0.0008225	1.51E-03

As seen from Table 7, since all the values of avoided emissions from comparative fuels show positive values, it follows that switching from these conventional fuel sources to biogas for meeting rural energy needs will be of immense benefit to humans as well as the environment at large due to the health effects and greenhouse effect of these gases.

The economic evaluation of the feasibility for upscaling this project was carried out via the life cycle cost of the project using three different scenarios. In scenario A, it was assumed that all the generated biogas would be channeled into cooking and the digestate would be sold to local farmers; in scenario B it was assumed that all the gas would be used for electricity generation while also selling the digestate to be used as biofertilizer; scenario C would involve the middle ground scenario by splitting the produced gas between cooking and electricity generation half-in-half. The sales price was calculated by adding 40% to the LCC split into 25% bank interest, 5% profit 5% VAT and 5% sales tax. From these prices and the quantity of gas and digestate expected, the revenue for the three scenarios was determined. The values calculated for each of the scenario are shown in Table 8.

The business model was developed by considering the peculiarities of the communities where the biogas plants are intended to be implemented and the available resources. The communities are agrarian in nature and have a relatively high number of unemployed people indicating that there is a ready workforce and a significant amount of material to be used as substrate. The business model is shown in Fig. 12. The revenue sources are sales of

Table 6 Amount of gasses emitted and avoided emissions when biogas is compared with other fuel sources

	Emission factor (CO ₂)	EF-CH ₄	EF-NO ₂	Amount emitted CO ₂ (kg)	AE-CH ₄ (kg)	AE-NO ₂ (kg)
Biogas	0.0546	0.000001	1.00E-07	18.1545	0.0003325	3.33E-05
LPG	0.0631	0.000001	1.00E-07	22.49025975	0.000356423	3.56E-05
Kerosene	0.0719	0.000003	6.00E-07	28.310625	0.00118125	2.36E-04
Fuel wood	0.112	0.00003	4.00E-05	99.47	0.02664375	3.55E-02
Diesel	0.0741	0.000003	0.000004	28.5285	0.001155	1.54E-03

Table 8 Revenues for scenarios A, B and C

	LCC	Sale price	Quantity	Revenue scenario A	Revenue scenario B	Revenue scenario C
Cooking	153.423	214.792	128100	\$76430.28	–	\$50953.52
Electricity	0.009	0.012	2280444600	–	\$76430.28	\$50953.52
Digestate	134.97	188.956	145615.461	\$76430.28	\$76430.28	\$50953.52

Fig. 12 Business model

generated biogas, and generated electricity—should the community choose to generate electricity—and of biofertilizers while the expected expenses are for purchase of waste, employing manpower and maintenance of biodigester facilities.

The cost and emission analysis show that scaling up the laboratory experiment, using a hypothetical community of 300 households, is both economically feasible and environmentally advantageous. In similar vein, if the postulated biogas is used for garri processing from milled cassava, it is able to service the production of about 0.4 tons of grated cassava per day. The venture would be a profitable and replicable one so long as the environmental conditions are similar and with readily available and cheaply acquired feedstock.

5 Conclusion

Good management of degradable wastes using SS-AD, an example of which is discussed in this study, is one important strategy that could be adapted for mitigating the effect of greenhouse gas emissions to the atmosphere (see [43]). This can also serve to meet energy deficit to

cottage industries in developing countries like Nigeria. In addition, our study shows that good waste management practice could be turned to an important wealth creation source. Good waste management, in global environmental sustainability concept, involves reducing waste, changing consumer habits or increasing the selectively collected and recyclable proportion of waste [47]. In our experiment to depict an example of good waste management procedure, we showed that gas production rate has a positive correlation with digester temperature, where the VS/TS ratio shows direct proportionality to the BMP of biogas substrates. Also, inoculum addition significantly affects the gas production. However, there is room for further studies on the influence of inoculum type, retention time and temperature on the rate and composition of gas production to help to know how the technology can be further improved upon. Biogas production is feasible and advantageous economically, environmentally and socially, and it can be used as an energy source in regions that are substrate rich but energy poor to supplement energy supply. The proposed business model stands to facilitate this by making use of existing resources efficiently.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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