Anaerobic Co-Digestion of Food Waste and Cow Dung in a Pilot Fixed-Dome Bio-digester for Biogas Production

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Abstract- This study investigated the anaerobic co-digestion of cow dung and food waste for biogas the production. A fixed-dome biogas digester was constructed using a modified Gobar digester design. The developed digester has a capacity of 6m^3 with a retention time of 40 days. The entire biogas plant was constructed using reinforced concrete. The digester was charged with 100 kg blend of cow dung (CD) and food waste (FW) daily, mix with water in a ratio of 1:1:2 and the produced biogas ws collected using a 5m^3 gasbag. Biogas production commenced after the 7th day of charging the digester with substrate. Performance test was done on the produced biogas to determine its composition and burnability. The percentage composition of produced biogas revealed a methane (CH4) content of 59.689%, carbon dioxide (CO2) content of 32.734% and nitrogen (N2) content of 7.547%. The biogas burnt with a stable blue flame during the burn test. The biogas was deployed for cooking purposes using a cook stove in a staff food restaurant. This study is relevant for the implementation of Sustainable Development Goals (SDGs) and strengthening of the bio-based economy with regards to energy security and solid waste management. This can promote environmental and socio-economic sustainability and contribute to reducing carbon footprint of solid waste accumulation.

Keywords Anaerobic co-digestion, Biogas, Digester, Municipal solid waste, Waste management.

1. Introduction

Nigeria has the highest population with a reported annual growth rate of about 2.5% [1]. This ever growing population has put the country in a quandary over the years with respect to energy and solid waste management. For several decades now, Nigeria has never been able to generate enough energy to satisfy the demand of her teaming population [2]. A 2019 report from the National Population Commission of Nigeria revealed that about 43.5% of Nigerians have no access to grid electricity with over 50% of that number living in rural areas [3]. This has hampered social and economic development in the country. Furthermore, Nigeria generates approximately 60% (i.e. about 42 million tons) of the total solid wastes generated annually in sub-Saharan Africa [4]. According to [5], about 50% of these wastes are biodegradables, and these are significant resources from which energy can be generated. However, poor wastes management frameworks have led to inadequate collection and improper management of the majority of municipal solid wastes (MSW) generated in Nigeria over the years [6]. Reports have it that in Nigeria, 68% of MSW are dumped indiscriminately, 21% are landfilled, while 11% are burnt in open air [7-8]. These practices contributes largely to Green House Gas (GHG) emissions with 3% of such emissions recorded between 2000 and 2018 [9]. This figure is expected to double within the next five years, considering the growing population, an estimated daily waste generation rate of 0.75kg per person [7], and increasing poor waste management practices in Nigeria.

In addition, there are currently over 20 million cattle in Nigeria. Majority of these cattle are slaughtered in abattoirs for meat, a process that generates wastes (mainly cattle dung). These wastes are also anticipated to increase significantly with increase in population and demand for meat [10]. Poor wastes management in abattoirs have seen their wastes been disposed indiscriminately. Indiscriminate disposal of MSW has been shown to have adverse effects on the environment and human health [11-12], such as contaminating ground water, pollution of the atmosphere, bio-chemical poisoning of food supplies [13] and greenhouse gas emissions [14]. In addition, annual contribution of food waste alone to greenhouse gas emissions is projected to be about 3.3 billion tonnes of CO_2 [15]. Poor MSW management practices in Nigeria has been adduced, amongst other factors, to inappropriate treatment technology, poor wastes management infrastructures and nonchalant posture of waste managers [16.

Eco-friendly technologies such as anaerobic digestion can be deployed to treat food wastes and cattle dung to produce biogas to enhance energy security and address waste management. Anaerobic digestion (AD) is an established sustainable process of treating biodegradables by converting them to energy carriers (such as biogas) and digestate (a rich organic fertilizer) [17]. Biogas comprises mainly methane (50 - 75%) and carbon dioxide (30 - 50%) with traces of hydrogen sulfide, nitrogen, and carbon monoxide [18-19]. Biogas can serve as substitute fuel for cooking electricity generation and vehicles. Consequently, biogas presents a plausible avenue to ameliorate energy poverty, which has largely been responsible for slow development in the economy of Nigeria and poor living standard of most Nigerians [20]. Biogas burns more effectively when the methane content is higher than 50% [21].

Anaerobic digestion is the breaking down of biodegradables through successive oxidations and reductions to their most oxidized state (carbon dioxide (CO_2)) and reduced form (methane (CH_4)) by microorganisms in the absence of oxygen [21-23]. The decomposition occurs over four stages (listed from 1st to last): Hydrolysis, Acidification, Acetogenesis and Methanogenesis [21, 24-25]. According to [26], anaerobic digestion has played a crucial role in reducing the volume of organic matter MSW, especially sewage sludge and wastewater, which led to the development of several digesters in Europe. AD also reduces the emission of greenhouse gases from biodegradables in landfilled wastes by reducing the volume of wastes sent to landfills [27-28]. Anaerobic digestion can also be deployed for hydrogen production, by either inhibiting the methanogenesis of hydrogen into methane or deploying a co-production process in which the acidogenesis and methanognesis processes are facilitated in separate bio-reactors [22]. Recent studies have revealed that co-digestion of two or more biodegradables can improve the AD process and biogas yield. This has been adduced to the enabling environment co-digestion creates for microorganisms to thrive and effectively interact amongst themselves [23]. Furthermore, the addition of carbon-based conductive materials can enhanced the methane production process [29].

Anaerobic digestion occur in airtight vessels, known as digesters or bio-digesters. Bio-digesters designs have evolved over the years from the dug-in concrete bio-digesters to household plastic containers. However, irrespective of the designs, the biogas storage compartment is either fixed (fixed dome bio-digester) or variable (floating dome bio-digester or flexible balloon bio-digester) [30-31]. Examples of commonly used feedstock for biogas production include animal wastes, human faecal matter, agricultural residues and food waste [26]. Despite a long history of research and advancement in the development, optimization and deployment of bio-digesters, little has been reported of such in Nigeria. This study aims to develop a pilot fixed dome bio-digester for production of biogas from the co-digestion of blend of food wastes and cow dung with the intention of enhancing MSW management and sustainable energy security in Nigeria.

2. Materials and Methods

The pilot fixed dome bio-digester was constructed at the National Centre for Energy and Environment, University of Benin, Benin City, Nigeria. The goal was to produce biogas for cooking in the centre's kitchen as well as for research purposes. The feedstock was blend of cow dung and food wastes collected around Benin Metropolis. The Gobar bio-digester design with a capacity of $6m^3$ was adapted for the study [32]. The Gobar bio-digester comprises an inlet tank, a digestion compartment, a fixed dome and an outlet chamber. A given quantity of feedstock is mixed with water inside the inlet tank to form a slurry, which is discharged to the digestion compartment. The produced biogas is stored in the fixed dome, and the digested slurry (digestate) is evacuated through a manhole to the outlet chamber, from where it is collected and treated for use as organic fertiliser. A flexible rubber hose is used to transport the biogas from the dome to the point of usage. The outlet chamber of the bio-digester serves as a compensation tank for the slurry. When the biogas pressure is high, the slurry is pushed to the outlet chamber. The slurry returns intothe digestion chamber when the biogas pressure reduces [33]. Figure 1 shows the adopted Gobar bio-digester design and Table 1 shows the dimensions of several bio-digester sizes. In this study, the inlet tank was connected to the digestion chamber using a 4 inches PVC pipe inclined at an angle of 48° to the wall of the digestion chamber.

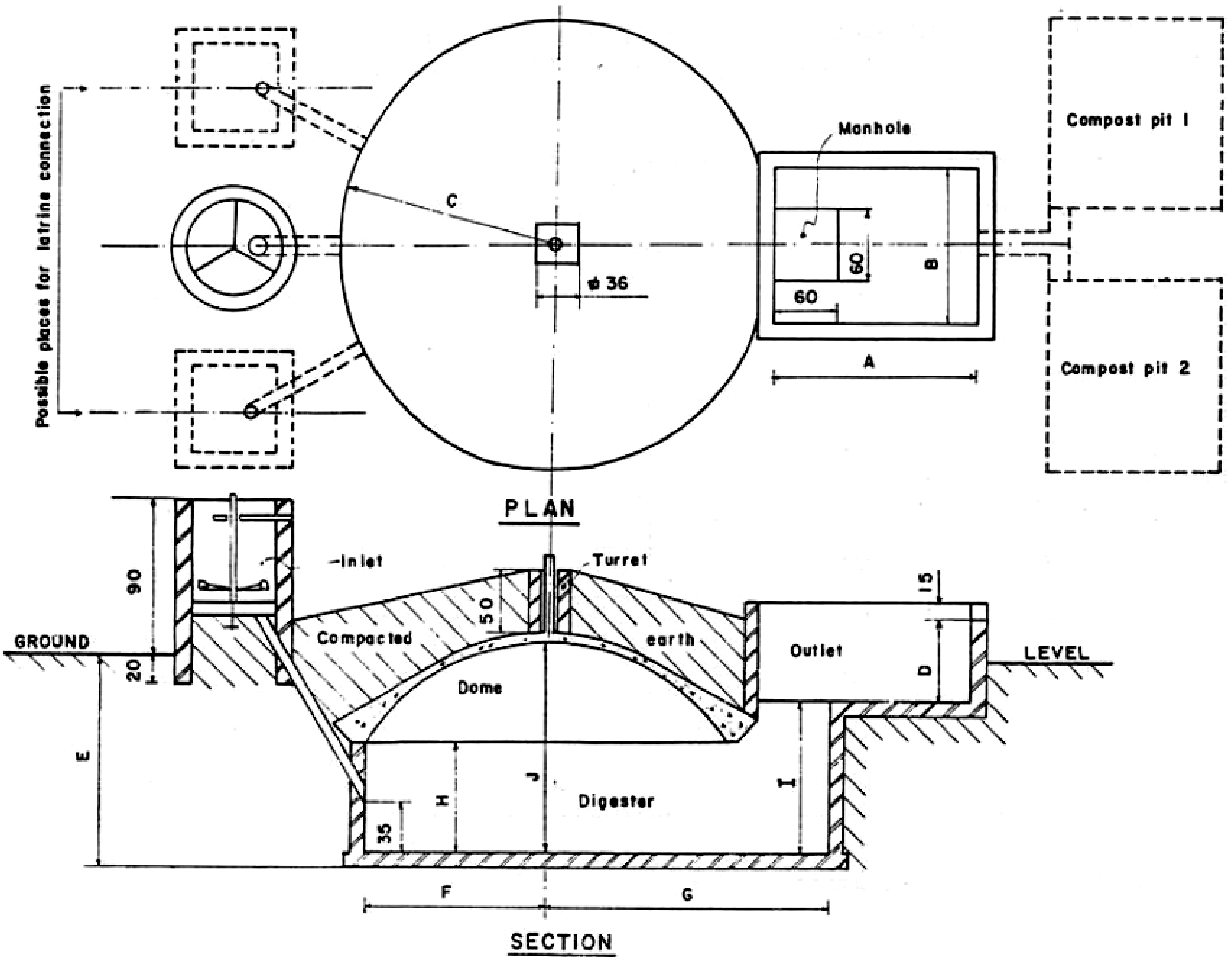

Fig. 1: Gobar bio-digester design [32]

Table 1: Dimensions for different Gobar bio-digester capacites [32].

Components dimensions in m	Bio-digester capacity (m^3)					
	4.0	6.0	8.0	10.0	15.0	20.0
A	1.40	1.50	1.70	1.80	2.48	2.64
B	1.20	1.20	1.30	1.25	1.25	1.76
C	1.35	1.51	1.70	1.83	2.05	2.33
D	0.50	0.60	0.65	0.68	0.84	0.86
E	1.54	1.55	1.72	1.68	1.80	2.03
F	1.02	1.22	1.35	1.54	1.75	1.99
G	1.95	2.11	2.30	2.43	2.65	2.93
H	0.86	0.92	1.05	0.94	1.15	1.15
I	1.12	1.16	1.27	1.24	1.32	1.37
J	1.51	1.60	1.75	1.71	1.93	2.03

2.1. Construction of Bio-Digester

The construction commenced with site investigations and selection of materials (sand, cement, aggregate, rods, waterproof membrane). The selected location was premised on the procedures adopted by [33-34], which prescribed proximity to point of biogas usage, expose to direct sunlight and ease of waste accessibility. After identifying the appropriate site, soil evacuation was done to commence construction work. The bio-digester's floor was constructed using two layers of reinforced concrete (4 and 6 inches thick respectively) with a water-proof membrane in between the layers. A rod was placed vertically at the centroid of the floor, from which the wall's reinforcement was positioned and linked to the floor reinforcement at a radius of 1.14m. The walls were also formed with concrete and plastered with mortar. The inner and outer diameters of the wall were 2.20m and 2.35m respectively.

A manhole opening (0.6 by 0.6m) was marked out on a portion of the wall at 0.65m from the floor. It was reinforced with rods and casted with concrete and plastered with mortar. The manhole acts as a conduit through which digested slurry flows to the outlet chamber. A polyvinyl chloride pipe (4 inches in diameter) was positioned at 0.35 m from the floor of the bio-digester to act as slurry inlet to the digestion chamber. The pipe was inclined at an angle 48˚ to the wall to prevent blockage during loading. On completion of the wall and manhole, the bio-digester was carefully backfilled with sand. A rod was attached to the vertical rod at the centroid of the floor, on it a height of 1.65m was marked out to indicate the height of the dome from the floor of the bio-digester. Thereafter, the dome was constructed using waterproof membrane, rods as well as concrete and plastered with mortar. At the top centre of the dome, provision was made for biogas outlet pipe (galvanized iron). Several pipe connections, fitted with valves, were made from this main pipe. The connections were to a gasbag, a tube (to indicate gas production) and for flaring. Upon completion, the bio-digester was sprayed with water three times daily for a week to enhance curing of the concrete. The construction processes of the biogas digester are highlighted in Fig. 2.

2.2. Feedstock Preparation and Characterisation

Cattle dung (CD) was obtained from an abattoir in Benin City, Edo State, Nigeria, while food waste (FW) was collected from households and restaurants within the main campus of University of Benin, Benin City. Contaminants (such as metal, glass, bones, bottles and plastics) in the feedstock were sorted. Blend of food wastes and Cow dung in a ratio of 1:1 (wet weight) was transferred into the inlet tank, where they were mixed with water in a ratio of 1:2 (i.e. 1 kg of feedstock to 2 litres of water) and stirred until the mixture is homogeneous. Samples of the individual feedstock and mixture were sent to the laboratory for analyses to ascertain their physiochemical properties.

The samples were analysed according to standard methods [35]. The analyses included determination for total solids (TS), volatile solids (VS), moisture content and chemical oxygen demand (COD). A calibrated pH meter (HACH instruments) was used to measure the pH. The method of [36] was applied to determine the Total Ammonia Nitrogen (TAN).

2.3. Biogas Production

On achieving a homogeneous mixture, the slurry is allowed to flow into the digestion chamber. The bio-digester was loaded at 100 kg daily for a week. Initially, the gas line to the tube was left open, while the line to the gasbag was closed until gas production was observed. The quantity of gas produced per day was estimated using equations (1) and (2) [31, 37] and the results of feedstock characterization.

$$G_B = C \times V_D \times VS \times \left(\frac{K}{1+KT}\right) \quad (1)$$

Where:

G_B = produced biogas (m^3/day)

C = biogas potential, which is the maximum amount of gas obtainable from 1 kg of feedstock volatile solids (m3/kg)

V_D = bio-digester volume (m^3)

VS = volatile solids in the slurry (kg/m^3)

T = hydraulic retention time (days)

K = constant indicating biogas production rate at a given temperature

$$VS = \frac{\text{feedstock volatile solids content}}{\text{daily feed volume}} \quad (2)$$

3. Results and Discussion

3.1. Feedstock Characterization

Table 2 shows the physicochemical properties of the cow dung (CD), food wastes (FW) and blend of cow dung and food wastes (CW:FW). The Total solids content of cow dung and food waste were 10.75% and 25.64% respectively while their volatile solids content were 88.00% and 86.53% respectively. These volatile solids percentages indicate large presence of readily degradable organic materials in the feedstocks, from which biogas can be produced [38]. These VS values were similar to values obtained for cassava pulp (93.8%) [39], goat manure and cotton gin residue (84.7% and 87.1 respectively) [40], and food waste (86.1%) [41].

A higher moisture content (86.20%) was recorded for cow dung than for food waste (75.74%). The higher moisture content of cow dung is crucial to ensure desirable moisture levels during co-digestion [17]. Similar values were obtained by [42] for cow dung (86%), [43] for food waste (76%) and [44] for cow dung, food waste and pig dung (85.6%, 81.1% and 81.3% respectively). The pH of cow dung (6.68) was slightly below the neutral pH while that of food waste was in the acidic range (4.21). Optimum pH for anaerobic digestion has been reported to range from 6.8 to 7.2 [45-46]. Low pH values of 3.50 and 4.30 were also obtained by [47] and [48] respectively for food waste.

Fig. 2: Construction stages of the biogas digester plant

Table 2: Feedstock physiochemical properties.

Property	**CD**	**FW**	**CD:FW**
Total Solids (TS) (%)	10.75	25.64	30.53
Volatile solids (VS) (%)	88.00	86.53	91.70
Moisture content (%)	86.20	75.74	88.85
C/N	23.70	15.60	25.50
pH	6.68	4.21	7.25
COD (mg/l)	13,270	13,037	13,015
Total ammonia nitrogen (mg/l)	6593.35	5450.68	7492.22

It can be observed from Table 2 that co-digestion of food wastes with a suitable substrate (in this case, cow dung) improved the pH from 4.21 to 7.25.

Such pH buffering due to co-digestion was also observed by [49] when the pH value of food waste was increased from 5.2 to between 6.3 - 7.2 by co-digesting it with corncob. Also from Table 2, cow dung and food wastes had a carbon to nitrogen ratio (C/N) of 23.70 and 15.60 respectively, which are within the recommended C/N range (9.00 – 30.00) for anaerobic digestion [50]. C/N ratio is vital to the survival and metabolic activities of the microorganisms hence, it needs to be at optimum levels constantly. Very high C/N ratios would make more carbon available for biogas production, but can limit microbial activity as the microorganisms need nitrogen to maintain adequate growth and metabolic activity. However, low C/N ratios implies high nitrogen presence, which can lead to ammonia inhibition. Co-digestion of different feedstock (for example cow dung and food wastes) can ensure constant optimum C/N ratios and consequently, adequate alkalinity levels [17]. A C/N ratio of 17.21 was reported by [51] for food wastes while [10, 50, 52] reported C/N ratios of 21.87, 20 and 22.69 for poultry wastes, goat dung and abattoir wastes respectively. Overall, the data in Table 2 indicate that both feedstocks are suitable substrates for biogas production and their co-digestion can help improve the process parameters and increase biogas yield.

3.2. Biogas Production and Composition

The bio-digester was charged with 100kg of feedstock (CD:FW = 1:1) mixed with water in a ratio of 1:2 daily. Biogas production was observed on the 7th day of loading, through inflation of the indicating tube. Samples of the produced biogas were collected from the gasbag using a gastight syringe after loading was completed and stabilization was achieved. The samples were analysed to determine percentage composition of constituents using a Gas Chromatography (GC), (HP 5890II Series USA) coupled with a Hayesep Q column and a Split Flame Ionization Detector (FID). This was done twice a week in duplicates. Table 4 presents the composition of the produced biogas. Approximately two gasbags filled with biogas were collected daily after the 10th day of production. Using equations (1) and (2) and values from Table 2 and Table 5, as well as considering mesophilic conditions with an average temperature of 34℃ and hydraulic retention time of forty (40) days, the gas production rate was estimated to be 3.90m^3 per day.

Table 3: Percentage biogas composition

Constituents	Volume fraction (%)
Methane (CH_4)	59.689
Carbon dioxide (CO_2)	26.734
Nitrogen (N_2)	13.547
others	0.03

Table 4: Properties of cow dung and food wastes in continuous plants [37, 53].

Temperature (℃)	Rate constant k (d^{-1})	Biogas potential C (m^3/kg)	
		Cow dung	Food wastes
34	0.083	0.402	0.367
25	0.069	0.289	0.245
16	0.033	0.178	0.157

3.4. Combustion Test

Combustion test was conducted on the produced biogas a week after biogas production was observed. The initial test was unsuccessful because the biogas failed to ignite. This indicated low volume of methane in the biogas [54-55]. The bio-digester was left alone for a week without charging with feedstock to stabilize it. Thereafter, the combustion test was conducted again, and the biogas ignited producing a steady blue flame. This is an indication of significant volume of methane in the biogas. The biogas produced was primarily utilized for cooking purposes through a biogas stove as shown in Figure 3 at the restaurant of the National Centre for Energy and Environment. When the canteen is not in operation, the produced biogas is flared to prevent biogas emission to the atmosphere and to protect the dome from excessive gas pressure using a flare outlet as shown Figure 4. The produced biogas was compressed into gas cylinders from the gasbag for later use.

Fig. 3: Cook stove connected to the biogas plant

Fig. 4: Biogas flaring

4. Conclusion

A fixed-dome bio-digester was successfully constructed at the National Centre for Energy and Environment, University of Benin, Benin City in accordance with the Gobar bio-digester designs. The bio-digester was charged with blend of cow dung and food waste (in a ratio of 1:1) for biogas production. Gasbags of 5m^3 capacity was connected to the biogas outlet for collection of the gas. Laboratory analyses revealed that the produced biogas comprises 59.689% of methane, 32.734% of carbon dioxide and 7.547% of Nitrogen. The biogas was deployed for cooking purposes through a cook stove at the Centre's restaurant. Anaerobic digestion of MSW not only provide clean energy but also help to clean up the environment by converting wastes to useful energy. Hence, local authorities and waste managers should consider the technology as an approach for sustainable waste management.

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