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Sustainable Waste Management: A Footpath Towards Biogas Production

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Abstract

The paper explores sustainable waste management, by using anaerobic digestion to produce biogas from cow dung using agricultural wastes in Akure, Nigeria. The objective was to determine the potential biogas production by co-digesting cow manure with agricultural wastes such as yam peel, cassava peel, and maize husk as catalyst for biogas production. The biogas output from co-digesting cow dung with wastes such as yam peel, cassava peel, and maize husk was investigated using laboratory digesters. The data gathered over a 7-week period was analyzed statistically to reveal the impacts of the catalysis on biogas generation. A prototype using cassava peel and chicken dung for co-digestion was developed to calculate biogas output using a non-continuous feeding strategy. The study found that co-digesting crop waste and cow dung can have a positive economic impact by recovering energy and producing valuable compost. The total biogas yield after the period for yam peel with cow dung, maize husk with cow dung, cassava peel with cow dung and cow dung only were 487.20 ml, 316.7 ml, 99 ml, and 205.4 ml respectively with the highest being yam peel with cow dung. This approach is sustainable for managing agricultural waste, providing financial benefits like compost for increasing agricultural yields. Additionally, co-digestion could be a viable method for optimizing anaerobic digesters, enhancing renewable energy production and better municipal solid waste management. The recommendations emphasize the importance of stable pH levels, ideal C/N ratios, and precise co-substrate composition for improving anaerobic digester efficiency. Future studies should focus on renewable energy generation and waste treatment techniques. Collaboration between public and private sectors can provide resources for in-depth research, promoting sustainable waste management and renewable energy projects. Benefits include improved biogas production, waste management system advancements, anaerobic digestion understanding, and policies promoting renewable energy resources.

Keywords: anaerobic digestion, agricultural waste, biogas, co-digestion, sustainable waste management

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Introduction

Municipal Solid Waste (MSW), also known as "trash" or "garbage," comprises wastes like nondurable items (like newspapers, plastic plates and cups), durable goods (like tires, furniture), containers and packaging (like milk cartons, plastic wrap), and other wastes (like yard waste, food). Center for Sustainable Systems, University of Michigan (2023) explains this further. Wastes classified as industrial, hazardous, and construction wastes are not included in this category. Typically, it includes wastes from offices, retail establishments, and ordinary homes. Despite the greater costs, sanitary landfills emerge as the sole long-term alternative for properly managing emissions and contamination (Bello *et al*, 2022).

Extended Producer Responsibility (EPR) is a regulatory mechanism that may be used by developing nations to reduce waste generation and encourage source reduction (Ferronato and Torretta, 2019). If this is not feasible, garbage should be diverted from landfills and instead recycled, collected, and utilized again for energy (Ferronato & Torretta, 2019). Anaerobic digestion is critical for waste management since it reduces pollutants and trash volume and generates cleaner energy like biogas, all of which contribute to a more sustainable environment (Zhao et al., 2021; Caposciutti et al., 2020; Manyi-Loh et al., 2013). The complexity of anaerobic digestion (AD) processes for waste treatment involves taking into account elements such as waste composition and operating parameters, resulting in a wide range of reactor designs classified by solid content, number of stages, and mode of operation. Biogas digesters, which are commonly built with bricks, have problems such as cracks and corrosion (Deng, L. et al., 2020), which cause operational issues and increased expenses (Obileke et al., 2020).

In Nigeria, the generation and characteristics of solid waste present complex challenges, with high organic content and inconsistent waste management data contributing to these issues (Zurbrugg, 1999). A comparative analysis of solid waste composition in major Nigerian cities reveals a predominance of organic waste, emphasizing the need for effective treatment methods (Table 1.1). Waste composition varies based on moisture content, posing challenges for incineration and favoring alternative approaches like AD (Ogunjuyigbe et al., 2017).

Table 1: Composition of waste stream characteristics

	Nsukka β	Lagos µ	Makurdi ±	Kano µ	Onitsha ¥	Ibadan α	Maiduguri #
Putrescible	56	56	52.2	43.0	30.7	76	25.8
Plastics	8.4	4	8.2	4.0	9.2	4.0	18.1
Paper	13.8	14.0	12.3	17.0	23.1	6.6	7.5
Textile	3.1	--	2.5	7.0	6.2	1.4	3.9
Metal	6.8	4.0	7.1	5.0	6.2	2.5	9.1
Glass	2.5	3.0	3.6	2.0	9.2	0.6	4.3
Others	9.4	19.0	14.0	22.0	15.4	8.9	31.3

Others = dust, ash, ceramics, rubber, soil, bones α Diaz and Golueke (1985) , β Ogwueleka (2003) , ± unepeleka (2006), ¥ Agunwamba et al (1998), µ Cointreau (1982), # Dauda and Osita (2003)

The problems associated with solid waste management in Nigeria include the prevalence of open dumps, inadequate waste disposal infrastructure, and limited government capacity and funding (Kum et al., 2004). While waste collection receives attention, treatment and disposal are often neglected, leading to open dumping and its associated environmental and health hazards (Nnaji, 2015). Current waste management systems in Nigeria, exemplified by Port Harcourt's degradation, suffer from illegal dumpsites and inadequate disposal practices, necessitating a shift towards environmentally beneficial waste treatment options (Ayotamuno & Gobo, 2004; Nnaji, 2015). The inefficiencies in traditional waste management methods highlight the need for sustainable alternatives, such as waste recovery, recycling, and waste-to-energy initiatives, which can address environmental concerns while contributing to economic development (Onwughara et al., 2010; Ben-Iwo et al., 2016).

This research aimed to conduct a comparative performance evaluation of a biogas digester, with specific objectives including the development of operational design criteria for mesophilic continuous operation and the examination of biogas production volumes from co-digesting cow manure with agricultural residue. The study's justification lies in the environmental benefits of generating biogas through anaerobic digestion, offering a reliable method to combat improper waste disposal, reduce pollution, and contribute to a cleaner and safer environment. The study aims to explore the potential of anaerobic digestion as a viable solution for organic waste treatment in Nigeria, considering the specific challenges and characteristics of the waste stream in the region.

Materials and Methods.

Experimental Set-Up

To determine some of the parameters that control anaerobic digesters, four small laboratory digesters were set up at the Soil and Water Laboratory (FUTA), Department of Agricultural and Environmental Engineering, Federal University of Technology Akure, Ondo State, Nigeria (FUTA). A 500-ml Erlenmeyer flask with a Dunlop slipper stopper was used for the anaerobic digestion tank. The cork should prevent gas leakage and make the control volume airtight. A wooden frame in the shape of a retort table to support the inverted cylinder. A 7 mm glass tube was attached to allow the generated gas to pass through, and the other end of the glass tube was opened into a reverse-caliber cylinder immersed in water. A reverse cylinder acts as a biogas collector. A set of syringes and a prescribed set were attached to the inverted cylinder to aid in the extraction of biogas. The volume of gas generated was measured by the movement of water down an inverted cylinder. This experiment was performed at a medium temperature (30ºC – 40ºC).

This study used four lab-scale digesters to test the potential of organic waste substrates for biogas production, the stability of a single substrate in anaerobic digestion, and the performance of co-digestion of bio-waste with other waste sources. The biogas yield from cow dung and crop residues as co-substrate was measured in batch mode using a cone-shaped flask digester (500 ml of working volume).

Batch A: This particular batch being studied exclusively consists of cow manure. The aim of the study is to determine the biogas production potential of the slurry, which is a mixture of 100 g of cow dung and 200 cm^3 of water.

Batch B: This batch contains cow manure and chopped yam peel. The biogas production potential was examined by co-digesting 30 g of chopped yam peel with 100 g of cow manure.

Batch C: This batch contains cow manure and chopped maize husk. The biogas production potential was examined by co-digesting 30 g of chopped maize husk with 100 g of cow manure.

Batch D: This batch contains cow manure and chopped cassava peel. The biogas production potential was examined by co-digesting 30 g of chopped cassava peel with 100 g of cow manure. The same volume of water was used for all the batches. The cumulative biogas production was observed daily, the volume of biogas produced was measured daily, and the total volume of biogas produced weekly was measured.

Sampling, Collection and Preparation

The study utilized cow manure, cassava peel, maize husk and yam peel as materials for anaerobic digestion. The cassava peel, yam peel and maize husk were obtained from the FUTA farm, while cow manure was collected from an abattoir located at RoadBlock Junction, behind Chicken Republic, Akure Ondo State. The crop residues were used to adjust the carbon/nitrogen (C/N) ratio, due to the high nitrogen content in cow manure. The crop residues were sun-dried for two weeks to reduce moisture content, souring, odour, and clumping problems. The crop residues were then ground and sieved to achieve the same particle size, maintaining homogeneity and accelerating microbial attack. The cow manure, crop residue, and water were homogenized to achieve a greater C/N ratio, and the digester was filled to 50% to allow gas accumulation. The average weight of the digesting material inside the digester was 380g. After sample preparation, a 20g substrate was analyzed to obtain initial values for C/N ratio, nutrient content (N, P, K).

Experimental Procedure

This study aimed to assess the practicality of co-digesting cow manure with three types of untreated agricultural residues, namely maize husk, yam peel, and cassava peel, for biogas production. To achieve an optimal carbon/nitrogen ratio, the amount of crop residue added to the cow manure was calculated. The crop residues underwent initial chopping and grinding, followed by sieving through a 1 mm pore size sieve to ensure homogeneity in particle size. The C/N ratio of each crop residue was optimized for better results.

Step 1: The finely ground crop residues were measured using a digital weighing scale with a weight of 30 g per portion. The cow manure was divided into three equal portions, each weighing 100 g. The conical flask used in the experiment was initially weighed and found to weigh 159.4 g. The volume of water used in the experiment was 250 cm^3.

Step 2: To create the experimental mixtures, 30 g of maize husk, yam peel, or cassava peel were combined with 100 g of cow manure in separate bowls. Each mixture was then thoroughly mixed with 250 cm^3 of water. In addition, 250 cm^2 of cow manure was added to another 100 g of cow manure and mixed well.

Step 3: The four types of slurry were carefully transferred into individual conical flasks, which were then labeled as Batches A, B, C, and D.

Step 4: The conical flasks were sealed with corks, and a 7 mm tube was inserted into the flasks and connected to an inverted cylinder. Syringes and sets were also connected to the inverted cylinder to enable the extraction of biogas. The experimental setup for biogas production from cow manure and the co-digestion of crop residues is illustrated in Plate 1.

Plate 1: Batches of laboratory scale digesters for the determination of biogas production potential of cow dung with crop residues

Data Collection

Data was gathered twice a day, once at 8 am and again at 4 pm, during the experiment. The weekly data was obtained by adding up the daily data collected. Additionally, the ambient temperature was monitored twice a day to maintain the mesophilic conditions.

Specific Determination of Parameters for Investigation

The C/N ratio, nutrient content (N, P, K) and heavy metals concentration (Fe, Zn, Cu) were analyzed using standard procedures. To determine the C/N ratio, conventional methods were used to determine the total carbon and the total nitrogen was measured using the total nitrogen Kjeldhal (TKN) method, following the procedures outlined by Bernal et al., (2009).

Nutrients

Samples of the substrate were taken for nutrient analysis. A 20-gram sample of the sun-dried crop residue was sifted through a 1 mm sieve and then mixed with 120 ml of distilled water. The solution was shaken for an hour using an orbital shaker, and then filtered through Whatman No.1 paper. The resulting filtered solution was utilized for the nutrient analysis in order to determine the total nitrate (NO3), phosphorus (PO43-), and potassium (K+) concentrations by utilizing a DR 2500 spectrometer.

Physical Changes

At the conclusion of the process, alterations in the physical characteristics such as the hue, aroma and consistency of the digested mixture were noted.

Data Analysis

Data analysis was carried out using descriptive analysis via the statistical package for social sciences (SPSS), aerobic software (version 16.0) and Microsoft Excel packages were used to analyze the data through the use of graphs and bar charts.

Field Set-up

This setup consists of a 50L digester tank container, a collector tank of 10L volume, PVC pipes, bends, valves, gas pipes, m-seal, silicon adhesive, drilling machine, scale and rubber seal.

Construction

In this prototype, two containers are 50L and 10L. The larger one is used as a digester and the other as a water storage tank for displacement to measure biogas production. The digester of 50L has an opening at the top with a control valve and also at the top of the container, there’s a manual stirrer made of iron to incorporate mixing and agitate the digester to increase biogas production. The container is also lagged to prevent heat transfer. This helps to regulate the temperature inside the container, keeping the digester at mesophilic operations. The control valve connects to a hose of 0.5-inch diameter sealed in place. This hose connects to a purifier held upright by a metallic retort stand. The biogas digested exit through another hose of same dimensions and sealed in place. This then connects to the 10 L container which contained water and allowed displacement with an inverted measuring cylinder that was used to measure the volume of biogas produced. The cylinder used was a 250 ml measuring cylinder.

Plate 2: Field setup consisting of digester, purifier, storage tank and measuring cylinder

Preparation of Feedstock

The optimal ratio of chicken dung, cassava peel, and water for biogas production may vary depending on factors such as temperature, pH, and the specific microorganisms present in the biogas digester. However, the ratio used for biogas production is 2:1:1 (by weight) of chicken dung, cassava peel, and water, respectively. This means that for every 1 kilogram of chicken dung, 1 kilogram of cassava peel and 2 kilograms of water are added to the biogas digester.

The slurry of 10kg is prepared using this ratio that is 6kg of chicken dung, 2g of cassava peel and 2kg of water. A retention period of 7 weeks was provided for the biogas to be produced.

Results and Discussion

Result of the Effect of Agricultural Residues on Biogas Productions

The findings from the study indicate that co-digestion of cow manure and crop residue has the potential to generate biogas. As shown in Figure 1.1, the addition of crop residues led to a significant increase in daily biogas production. The study concludes that the addition of carbon-rich crop residues can enhance biogas productivity during anaerobic digestion, provided that the amount of the added material is determined based on the C/N ratio requirement for optimal process performance.

Result of the Volume of Biogas Production

The graph depicting biogas production from the mixture of cow manure and yam peel shows a gradual increase in biogas production from the first week, with a steady increase in yield until the end of the second week. Thereafter, biogas yield decreased gradually from the third week until the seventh week when biogas production ceased. The peak biogas production occurred during the third week, with a yield of 223.00 ml, while the total biogas production for the seven week period was 487.20 ml.

The biogas production curve for cow manure mixed with maize husk indicated that biogas production started during the first week, which indicates that maize husk increased the biogas production rate faster compared to other co-digestates. The use of maize husk as a co-digestate resulted in a steady yield of biogas with a moderate decline over time. The maximum biogas yield of 140 ml was obtained during the third week, and the total biogas yield during the seven-week period was 316.7 ml.

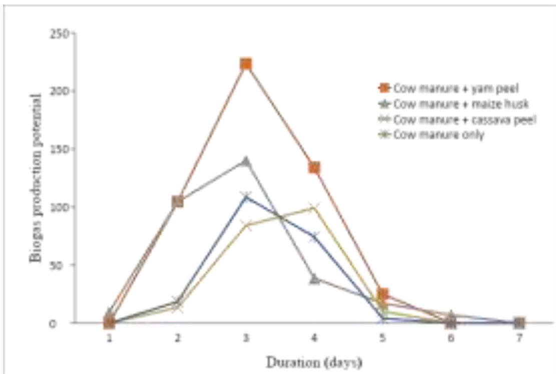

Figure 1: Comparison of the volume of biogas production

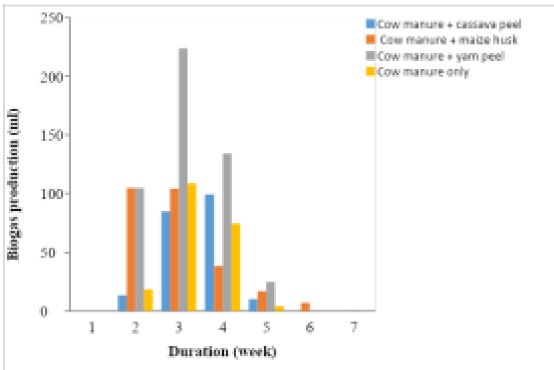

Figure 2: The average biogas production rate during anaerobic digestion experiment

When cow manure was co-digested with cassava peel, the biogas production curve showed a slow and low effect on the increasing rate and volume of biogas production. The production of biogas began in the second week with a volume of 13.50 ml and reached a maximum volume of 99.00 ml. After the fifth week, there was no further production of biogas. The control group, which only used cow manure, showed a similar biogas production curve, starting in the second week and reaching a peak of 108.5 ml during the third week. The total biogas volume produced during the seven-week period was 205.4 ml. These results suggest that the addition of cassava peel as a co-digestate had little to no effect on the volume of biogas produced.

Biogas Production Potential of Cow Manure and Crop Residue

To increase biogas production or compensate for its decline, a semi-continuously fed biogas reactor can be fed with easily handled and automatically digestible co-substrates. In this study, Maize husk, Cassava peel and Yam peel were chosen as co-substrates because they are readily available in large quantities, can be stored intermittently, and have a high potential for methane production. It was hypothesized that feeding these crop residues to the biogas digesters as co-substrates would enhance biogas production without any adverse effects.

A bar chart in Figure 2 illustrates the weekly biogas rates of cow manure during anaerobic digestion and when co-digested with crop residues. The chart indicates that co-digestion with crop residues increased the rate of biogas production compared to cow manure digestion alone. On a daily basis, the biogas production significantly increased. In contrast, during the digestion period of the cow manure-only-fed digester, the weekly biogas production reached its minimum value of 108.5 ml in the third week.

Compared to the other crop wastes (maize husk, cassava peel, and cow manure), yam peel produced slightly more biogas during the first week of co-digestion with cow manure, but then produced the most biogas during the third week. However, around 50% of the biodegradable compounds were digested during the first week and biogas production decreased over the next four weeks before leveling off to nearly zero. After two weeks of digestion, yam peel as a co-digestate yielded more cumulative biogas than the other crop wastes studied. In conclusion, the biogas produced from yam peel as a co-digestate likely has a higher average methane content than that of cow manure, making it a more efficient biogas producer.

Anaerobic Co-Digestion of Cow Manure with Crop Residue for the Improvement of Biogas Production

Energy is vital for economic and social development, and the way energy is produced, distributed, and used can have negative environmental impacts. To address this, most industrialized nations aim to reduce energy-based environmental pollution by promoting the use of renewable energy sources. In Europe, the European Council has set targets for the contribution of renewable energies to be 20% of total energy consumption and a minimum of 10% of total gasoline and diesel consumption for transport by

2030. Policies have been established within EU member states to promote the use and development of energy from renewable resources, including energy pricing measures, investment subsidies, and defined energy source quota obligations. Biomass, including solid wastes from agriculture, food processing, and municipal activities, is a potential source of renewable energy. Anaerobic digestion is a reliable technology to convert organic solid wastes to methane for energy production, and it can help reduce greenhouse gas emissions as part of municipal policies. However, building new anaerobic digesters is not always possible due to financial and operation regulation reasons. Co-digestion of organic municipal solid waste with other types of wastes can optimize the existing anaerobic digesters and maximize renewable energy production, while also improving organic municipal solid waste management and making the operation of anaerobic digesters more economically feasible.

The practice of co-digestion in which solid waste is combined with other waste streams provides several benefits. It improves the production of biogas due to positive synergies established in the digestion medium and leads to better management of mixed waste streams. To ensure stable performance in the anaerobic digester, a balanced nutrient composition, appropriate carbon to nitrogen ratio and stable pH are crucial. Studies have shown that optimizing the carbon to nitrogen ratio during co-digestion leads to an increase in methane yield. The addition of inorganic compounds like clays and iron compounds has also been reported to counteract the inhibitory effect of ammonia and sulfide. Improved buffer capacity is another advantage of co-digestion. However, selecting the type of waste to be used as a co-substrate and the waste stream ratio without considering their specific characteristics can lead to a process upset and significant reduction of biogas production.

Gas Production from Field Setup

The graph below depicts biogas production from the mixture of chicken manure and cassava peel shows a gradual increase in biogas production from the first week, with a steady increase in yield until the end of the third week. Thereafter, biogas yield decreased gradually from the fourth week until the seventh week when biogas production ceased. The peak biogas production occurred during the fourth week, with a yield of 52.00 ml, while the total biogas production for the seven week period was 153 ml

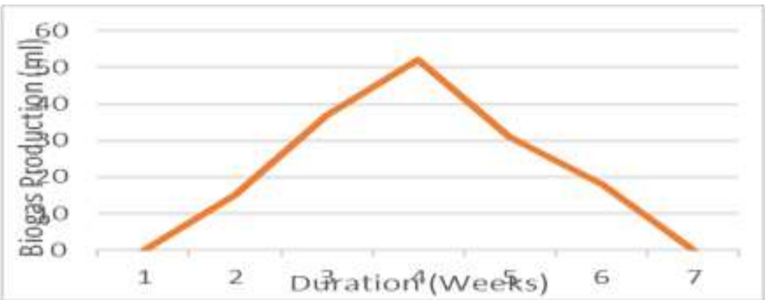

Fig 3: Volume of biogas produced after each week

Conclusion

This study investigated sustainable waste management, by using anaerobic digestion to produce biogas from cow dung using agricultural wastes in a non-continuous feeding approach and the stability of the substrates individually and collectively. The findings indicate that agricultural crop residue can be used as a co-substrate in the anaerobic digestion of biowaste. Co-digestion of different forms of waste can also be a feasible technique for optimizing existing anaerobic digesters, increasing renewable energy output, and improving municipal solid waste management. The co-digestion experiment produced promising results: using maize husk, yam peel, and cassava peel as co-substrates resulted in a linear rise in both biogas output and rate. The findings imply that co-digesting crop residue with cow dung improves biogas generation, especially when maize husk and yam peel are added as co-substrates. This co-digestion method not only increases the output of methane but also improves the digestate's buffer capacity.

In summary, the study's investigation suggests that anaerobic digestion of biowaste offers considerable waste stabilization and biogas recovery benefits. Crop residue and cow dung combined in an anaerobic digester significantly increase biogas output; proper co-substrate selection is critical for steady process efficiency.

Recommendations

Careful consideration should be given to the selection of co-substrates for co-digestion, as using incompatible waste types can lead to process upsets and significant reductions in biogas production. The balance of nutrients, an appropriate C/N ratio, and a stable pH are essential prerequisites for stable process performance in an anaerobic digester.

Future research should focus on developing more efficient and cost-effective methods for treating organic solid waste and maximizing renewable energy production. This could include exploring new waste treatment technologies, improving the performance of existing technologies, and developing more effective policies to support the use of renewable energy.

The government could collaborate with private firms to provide necessary laboratory equipment and funding for students' projects. Such an enabling environment would encourage further studies on anaerobic digestion of organic solid waste, leading to a more comprehensive understanding and knowledge of the subject matter.

It is recommended that the government establish policies that promote the adoption of biogas as a replacement for fossil fuels and encourage the utilization of other valuable byproducts, such as compost, which can help offset the costs of managing agricultural waste.

The adoption of these recommendations can lead to several potentially positive outcomes, such as:

Improved Biogas Production: Anaerobic digester performance thrives on a trifecta of carefully selected co-substrates for co-digestion, optimal C/N ratios, and stable pH levels. This can contribute to increased renewable energy production and reduced reliance on fossil fuels.

Advancements in Waste Treatment Technologies: Further research and development in waste treatment technologies can lead to more efficient and cost-effective methods for treating organic solid waste. This could result in improved waste management practices and increased renewable energy production from organic waste substrates.

Enhanced Knowledge and Understanding: Collaboration between the government and private firms to support research on anaerobic digestion of organic solid waste can lead to a more comprehensive understanding of the subject matter. This could result in the development of innovative solutions and technologies for sustainable waste management and renewable energy production.

Policy Support for Renewable Energy: The establishment of policies promoting the adoption of biogas as a replacement for fossil fuels and encouraging the utilization of valuable byproducts such as compost can create a supportive environment for renewable energy initiatives. This could lead to increased investment in biogas production and utilization, as well as improved waste management practices.

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