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Anaerobic co-digestion of Cow Manure and Food Waste: An investigation of biogas yield from feedstock percentage variation

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ABSTRACT

An increase in energy consumption is projected as a result of the world's unending population growth. As a result, many are likely to rely heavily on fossil fuels. Biogas is a viable choice because it is a green fuel and also sustainable. In this study, cow manure (CM) and food waste (FW) consisting of yam and plantain peels were collected, digested, and co-digested in the following proportions: 15%:85%, 25%:75%, and 35%:65%. Five (5) AD reactors of the same capacity (25 liters) were used to digest and co-digest CM and FW. The experiment was designed to discover the best proportion variation of CM to FW that will yield the greatest results. The results reveal that digestion of FW without seeding with CM takes a lengthy time to complete. In addition, co-digestion of FW with CM serving as a seeding agent took a shorter time. It was discovered that the percentage variation of co-digestion of CM (25%) to FW (75%), as opposed to the percentage variation of co-digestion of CM (15%) to FW (85%) and the percentage variation of co-digestion of CM (35%) to FW (65%), resulted in the highest biogas yield.

Keywords: Cow Manure, Food Waste, Biogas Yield, Percentage Variation, Anerabic Co-digestion

1. INTRODUCTION

The global energy demand is rising and the European Union (EU) has responded by setting striving goals for growing part of renewable energies and thus, reducing greenhouse gas (GHG) emissions. Biogas produced from the co-digestion of cow manure (CM) and food waste (FW) can make a significant contribution to realizing these goals. The world population has increased in the past decade and Nigeria the most populated country in sub-Saharan Africa countries is not exceptional. This has led to a demand for more energy consumption than ever before. Presently, energy generation from Nigeria is largely from fossil fuels which is not only scarce but has contributed to more environmental pollution as a result of emission of GHGs. Besides, energy is a basic prerequisite and need for man's everyday life.

The majority of countries particularly developing nations experience energy problems resulting from over-dependence on fossil fuels (Azam et al., 2021; Gürsan and De-Gooyert, 2021; Mohammad et al., 2021). Also, the energy drivers of all nations are energy security, environmental protection, and economic growth. It is projected that for the next 10 decades; fossil fuel sources will be exhausted (Moreau and Vuille, 2018). The continuous dependence on fossil fuels and environmental-related issues especially the emission of GHG and climate change has shift attention to environmentally friendly energy sources such as biogas (Kumar et al., 2018; Orhorhoro et al., 2022). Researchers have demonstrated that biogas is a potential renewable energy source for industrial as well as domestic applications and an effective solution to the global energy crisis (Orhorhoro et al., 2017; Achinas et al., 2017).

The anaerobic digestion (AD) process involves the use of particular bacteria to biologically break down organic materials in the absence of oxygen Carlini, (2021), Mudzanani et al., (2022) and four categories of bacteria interact with each other for the production of biogas, which include hydrolytic, acidifying, acetogen, and methanogenic bacteria. However, the stages that make up the complete AD process include hydrolysis, whereby the hydrolytic bacteria attack the multipart organic matter (mainly consisting of proteins, carbohydrates, and lipids) and break it down into monomers and oligomers. The next phase is acidogenesis, a phase where the already-produced soluble monomers are transformed into volatile fatty acids, alcohols, and ketones.

In the acetogenesis phase, the acetogen bacteria react with the afresh generated compounds to produce acetic acids (CH3COOH), carbon dioxide (CO2), and hydrogen (H2). In the methanogenesis phase, methane (CH4) is produced through the uptake of acetic acid and hydrogen (Carlini, 2021). This process comprises two separate groups of bacteria: Hydrogenotrophic bacteria, which allow anaerobic oxidation of hydrogen, and acetoclastic bacteria, which permit anaerobic dismutation of acetic acid, resulting in the production of methane and carbon dioxide (Ebunilo et al., 2015; Pellera and Gidarakos, 2017; Barua et al., 2019; Nganyira et al., 2022). Wet digestion technology or dry digestion technology can be used for the AD processing of FW.

Nevertheless, in contrast to wet digestion technology, which begins with FW either as a pumpable slurry primarily composed of water or as a pumpable combination, dry digestion is only practical for FW with a high fiber content. Wet AD technology can be utilized to treat FW using fixed-dome plants, floating-drum plants, polyethylene tube digesters, balloon digesters, etc. (Orhorhoro et al., 2019). Biogas is a composition of gases that consists mainly of methane (40%–75%), carbon dioxide (25%–60%), remnants of nitrogen, hydrogen sulphide, and hydrogen (Čater et al., 2014; Bharathiraja et al., 2018; Kainthola et al., 2019). Eventually, all organic waste biologically decomposes to generate biogas through the AD process, leading to sustainable waste management.

Biogas production is an important technology for attaining sustainable energy outputs without causing negative effects on the environment, especially when generated through AD and recovered efficiently (Fathya et al., 2014). This technology is capable of processing large quantities of organic waste (Ebunilo et al., 2016a; Ingabire et al., 2023). As a result of environmental concerns and policy measures, the focus is now on the use of FW and other biodegradable organic matter as renewable feedstock for electricity generation, and fuel production (Kumar et al., 2018; Moreau and Vuille, 2018). Anaerobic digestion and biogas fuel resources have been enhanced by growing organic waste generation, and global warming threats (Kumar et al., 2018). The main use of biogas is for electricity generation, thermal applications like cooking, heating, and lighting, and the production of biofuels.

An estimated 7000 MW of electric power is generated from biogas production yearly (Pasternak, 2021). Food waste is usually that portion of meal discarded by homes and cafeterias. It is also a food matter discarded as a result of sales and distribution. It could also be peels and trimmings from the preparation of food activities in kitchens and restaurants (Ebunilo et al., 2015). It is also the edible part of plants and animals' harvests for human consumption but not ultimately consumed. Dumping of untreated FW in dumpsites which is a common practice causes environmental problems (Ebunilo et al., 2016a; Frauke et al., 2017; Orhorhoro et al., 2019). Indiscriminate waste disposal causes serious environmental health problems and promotes insect vectors like mosquitoes and flies, rats and mice, flooding of streams, development of aquatic weeds, odor problems, nuisance, and so on (Nimas et al., 2017).

Thus, there is a need to treat it and bring it back to the cycle of life to maintain ecological harmony. Another serious problem of FW is the generation of landfill leachate. Landfill leachate as reported by Orhorhoro and Oghoghorie, (2023) is a liquid that leaks from the landfill and enters the environment. Once it enters the environment, it becomes a risk for mixing groundwater near the site and beyond. However, FW has high energy content and it offers good potential as feedstock for power generation. Nevertheless, the adoption of biogas technology can reduce the emission of GHGs due to its application as a renewable resource (Sarkar et al., 2020; Kabeyi and

Oludolapo, 2020). For instance, 0.29% of overall energy usage in Switzerland for the year 2014 was in the form of biogas and it accounted for close to 8% of the overall renewable energy production (Abanades et al., 2022).

Besides, biogas usage can reduce over dependence on solid biomass like firewood as cooking fuel. Based on estimation, biogas has the potential to provide clean cooking fuel for about 200 million people by the year 2040, predominantly in Africa and Asia. Thus, biogas has an important role in the actualization of the social development goals (SDGs) (Machado et al., 2021). With upgrades and proper purification, biogas produces biomethane as a superior fuel to unprocessed biogas (Moreau and Vuille, 2018). This makes biogas a dependable energy resource in the energy evolution to green and little carbon energy and electricity mix (Barragán-Escandón et al., 2020; Krupin et al., 2020; Akbulut et al., 2021). Therefore, biogas has a vital role to play in the international energy evolution due to the demand to transform the global electricity systems from fossil fuel-based generation to minimum carbon and renewable energy-based power generation.

With huge biodegradable organic waste feedstocks to biogas conversion potential, biogas will play an extremely important role in energy conversion as a renewable energy fuel resource and feedstock for industrial production of chemical fuels and renewable products (Prussi et al., 2019; Das et al., 2020; Ouahabi et al., 2021; Abanades et al., 2022). The use of a single substrate without co-digestion in AD process is not encouraged due to nutritional imbalance and the absence of a variety of microbes (Kabeyi and Oludolapo, 2020; Orhorhoro, and Oghoghorie, 2024). Furthermore, single substrate digestion has some impediments arising from particles. For instance, waste from crops and agro-industrial are periodic feedstocks that lack nitrogen (N), just as cow dung has low organic loads with a higher concentration of N, which are potential inhibitors of the methanogenic stage (Mata-Alvarez et al., 2014; Xie et al., 2018).

According to Harpreet et al., (2023), anaerobic co-digestion results in major variations in the quality of biogas generated. Similarly, Fu et al., (2022) reported that co-digestion of a feedstock of a CM and biowastes from rice husk or vegetable peelings led to an improved biogas yield. For optimization of biogas production, various pretreatment technologies have been applied and these techniques speed up the AD process (Paramagurua et al., 2017; Alvarez-Chavezet et al., 2019, Mudzanani et al., 2022; Orhorhoro and Oghoghorie, 2024). Pretreatment of feedstocks enhances the microbial activity of holocellulose thereby intensifying the hydrolysis stage which is the starting phase of the AD process (Čater et al., 2014).

Subsequently, the improvement of biogas yield from FW may be enhanced through the addition of extra substrate (inoculum) into the digester that can equally serve as a seeding agent, thereby controlling their untapped biogas prospects Alvarez-Chavez et al., (2019) and this approach is called co-digestion (Szaja et al., 2020). The addition of an inoculum helps to improve process stability through enhancement of nutritional balance and neutralizing chemical inhibitors in the substrate (Alvarez-Chavez et al., 2019).

2. MATERIALS AND METHODS

The FW that consists of yam and plantain peels with C/N ratios of 36 and 31 Nimas et al., (2017) was collected from households in Okada town, Nigeria. For optimum biogas yields, adjusting the C/N ratio is desirable and this was achieved in this study by co-digestion of CM (C/N ratio of 24) (Tanimu et al., 2014). The CM was collected from a cow farm located around an abattoir in Benin City, Nigeria. The collected FW was mechanically pretreated before charging into the AD reactors. The main purpose of the pretreatment is to enhance feedstock degradation and, thus, optimum biogas yield. The pretreatment process was started by cleaning and sorting the FW. All impurities, such as plastic and every other material that cannot be digested as they form solid deposits at the bottom of the digester, leading to a loss of digestion space, were removed.

Thereafter, the FW is ground into fine particles to enhance easy and fast decomposition. The process of adding slurry-containing bacteria to freshly created slurry is known as biogas seeding. Without seeding, biogas production takes several days; however, with seeding, biogas production begins nearly instantly (Frauke et al., 2017). Thus, the use of CM acted as a seeding agent in this study. Besides, the experiment was subjected to an optimum mesophilic temperature range of 36^0C-38^0C as reported by Ebunilo et al., (2016b) and the pH reading was closely monitored. Five (5) different AD reactors of the same capacity (25 liters) were used to digest and co-digest FW and CM. The experiment was carried out to determine the best percentage variation of CM to FW. The mass and composition of FW used were the same throughout the investigation. The experimental setup of the AD rectors is shown in (Figure 1). The anaerobic digestion reactor (ADR) arrangements are as follows:

ADR1: Digestion of 20 kg of FW only

ADR2: Digestion of 20 kg of CM only
ADR3: Co-digestion of 20 kg of feedstocks (15% CM and 85% FW)
ADR4: Co-digestion of 20kg of feedstocks (25% CM and 75% FW)
ADR5: Co-digestion of 20kg of feedstocks (35% CM and 65% FW).

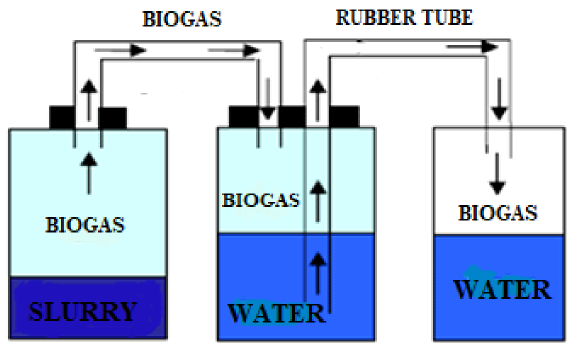

Figure 1 Experimental setup

3. RESULTS AND DISCUSSION

The results obtained from the different reactors are shown in (Figures 2–7). Figure 2 shows the results of the digestion of 20 kg of FW. Continua biogas generation was observed starting on the 5th day, and the optimum biogas yield (0.0372 m3) was obtained on the 34th day. It took 40 days for the complete anaerobic digestion of the feedstock, unlike ADR2, ADR3, ADR4, and ADR5. The prolonged process can be a result of the absence of CM, which may have served as a seeding agent for the other reactors. Seeding is so imperative that indecorous seeding or without seeding prolongs hydraulic retention time. Seeding shortens hydraulic retention time thereby improving biogas yield. An anaerobic digestion reactor seeded produced eleven times better than the one without seeding material (Frauke et al., 2017).

Figure 3, which shows the results of the digestion of 20 kg of CM, revealed that biogas yield occurs earlier (i.e., on the 3rd day) and finishes on the 25th day. Thus, hydraulic retention time was completed as a result of the fast decomposition of cow manure feedstocks in the reactor, unlike ADR1, ADR3, ADR4, and ADR5. This is also an indication that cow dung can serve as a good seeding agent, especially for substrates that can hardly decompose. Besides, the optimum biogas yield of 0.0228 m3 was obtained on the 22nd day. The composition of the waste may be the cause of the poor biogas yield (CM). Similar to CM, which has low organic loads and a greater concentration of nitrogen (N) that may operate as possible inhibitors of the methanogenic stage, agricultural waste, and agro-industrial waste are often periodic feedstocks deficient in nitrogen (N) (Mata-Alvarez et al., 2017).

Figure 4 shows the results of the graph of biogas yield against the number of days for co-digestion of feedstocks (15% CM and 85% FW). Biogas yield started on the 4th day and ended on the 34th day. The optimal biogas yield was obtained on the 33rd day, and the value is 0.045 m3. This value was higher than the co-digestion of 35% CM and 65% FW (ADR5), digestion of CM only (ADR2), and FW only (ADR1), but lower than the co-digestion of 25% CM and 75% FW (ADR4). Biogas yield began on the fourth day, similar to ADR3, and finished on the 35th day as shown in Figure 5, which is faster than ADR3 and ADR1 but slower than ADR2, which consists entirely of cow dung. The 25% CM in ADR4 allows the operation to be completed faster than the 15% CM in ADR3. Similarly, on the 30th day, the optimum biogas yield was attained, and the value was 0.0466 m3.

This number exceeded ADR1, ADR2, ADR3, and ADR5. This conclusion can be linked to the C/N ratio, pH, and seeding agent because the experiment was carried out at the same optimal mesophilic temperature range. Biogas production is impacted by high or low C/N ratios (Tanimu et al., 2014). The overall C/N ratio after co-digestion must have reached the ideal range for maximum biogas yield (20–30 atoms of carbon for each atom of nitrogen) as a result of the low C/N ratio of CM and the moderate C/N ratio of FW. Each reactor's pH during the first week of digestion and co-digestion was in the acidic range (5.1–5.4 m), as was to be expected. However, after the first week, this pH range changed from an acidic medium to an alkaline medium (8.8–9.8 m). For every reactor, a neutral pH range of 6.8–7.04 m was found beginning on the fourteenth day. ADR4 revealed a better pH range during the reactor testing, which may support the best possible biogas generation.

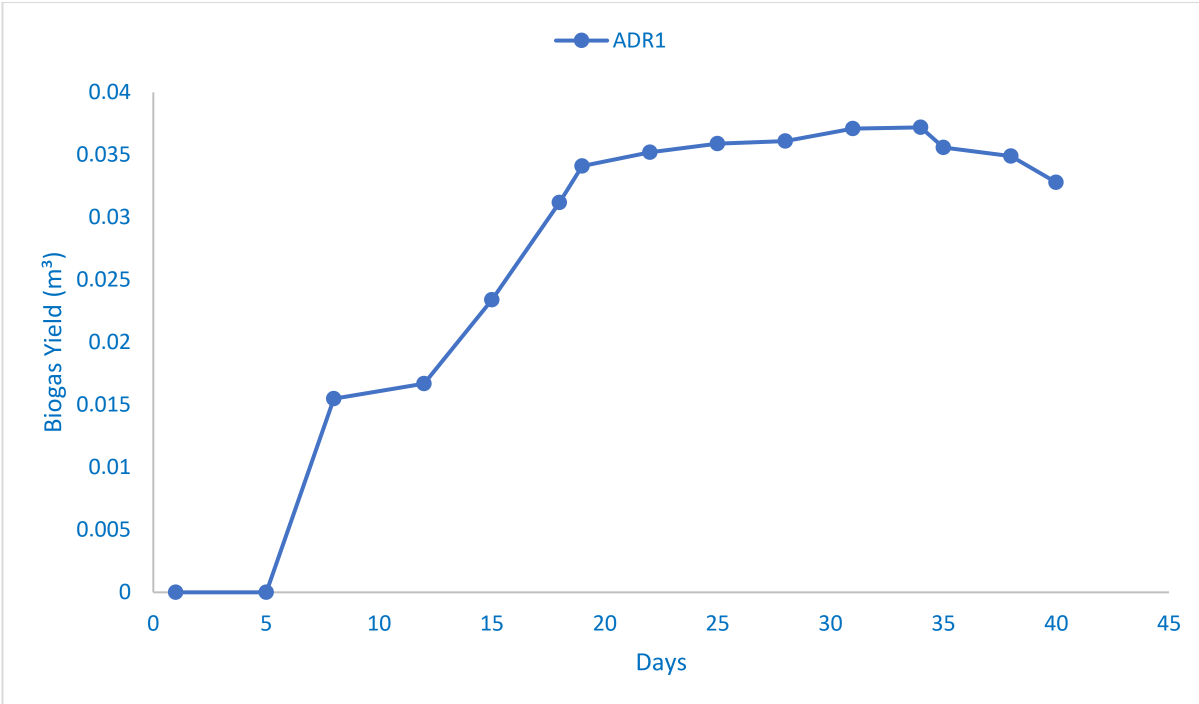

Figure 2 Graph of biogas yield against number of days for digestion of food waste

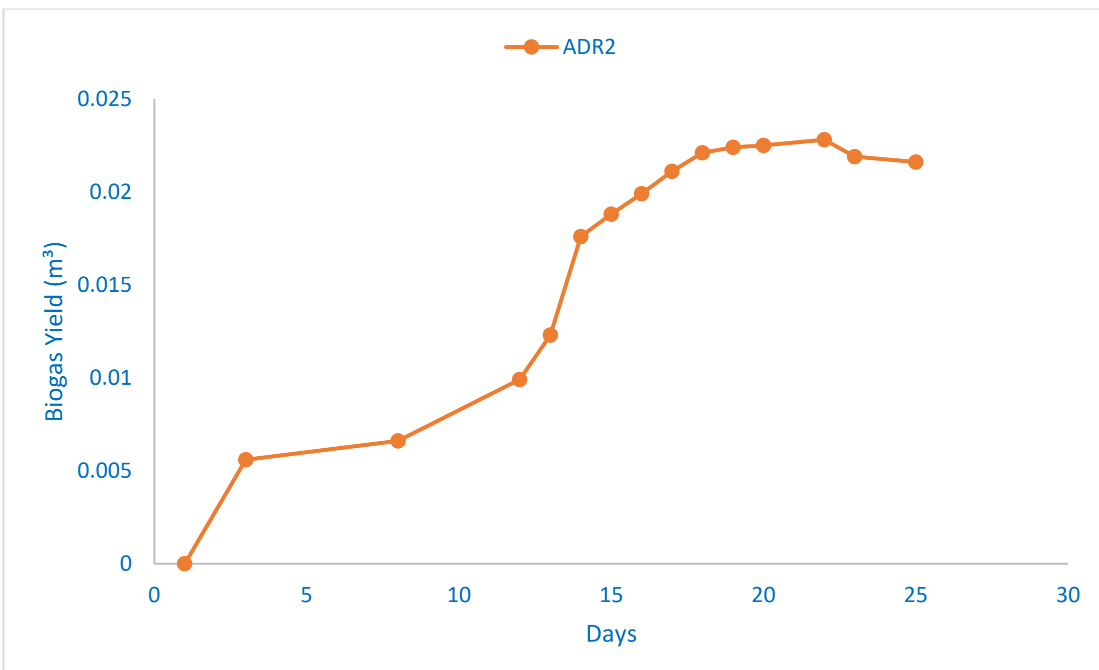

Figure 3 Graph of biogas yield against number of days for digestion of cow dung

Consequently, an unstable methanogenesis phase may be the cause of the low biogas in the other reactors that were set up. The process of producing methane, known as methanogenesis, is extremely sensitive to acidity. Thus, to reduce the toxicity of both free ammonia and free volatile acids, a pH range that is favorable for methane-forming bacteria is needed (Paramagurua et al., 2017). Both high and low pH levels inhibit or cease methane-forming bacteria's activity. A pH of 6 signifies inhibition brought on by elevated VFA concentrations, and it also causes a notable rise in ammonia, which has potent inhibitory effects of its own. Naturally, the pH decreases during the first few days due to acid production during fermentation of acidogenesis. After that, as a result of nitrogen digestion (which forms NH4+), pH steadily rises until stabilizes within neutrality as the biogas production process stabilizes (Paramagurua et al., 2017).

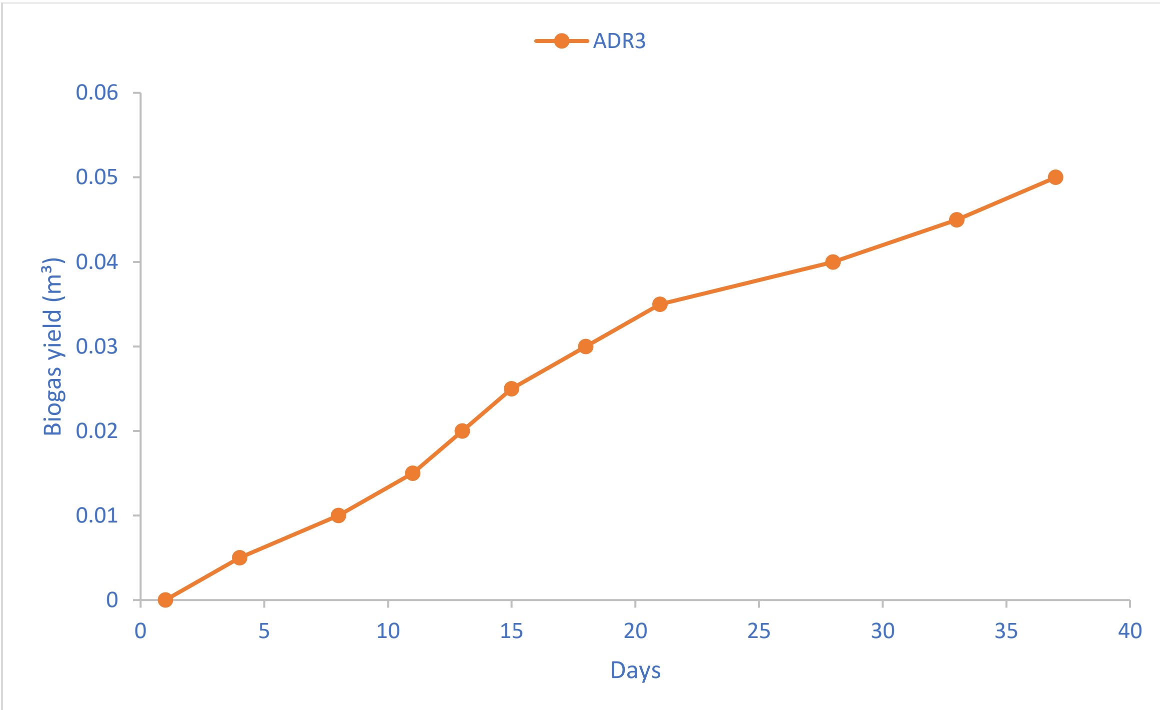

Figure 4 Graph of Biogas yield against number of days for co-digestion of feedstocks (15% of cow dung and 85% of food waste)

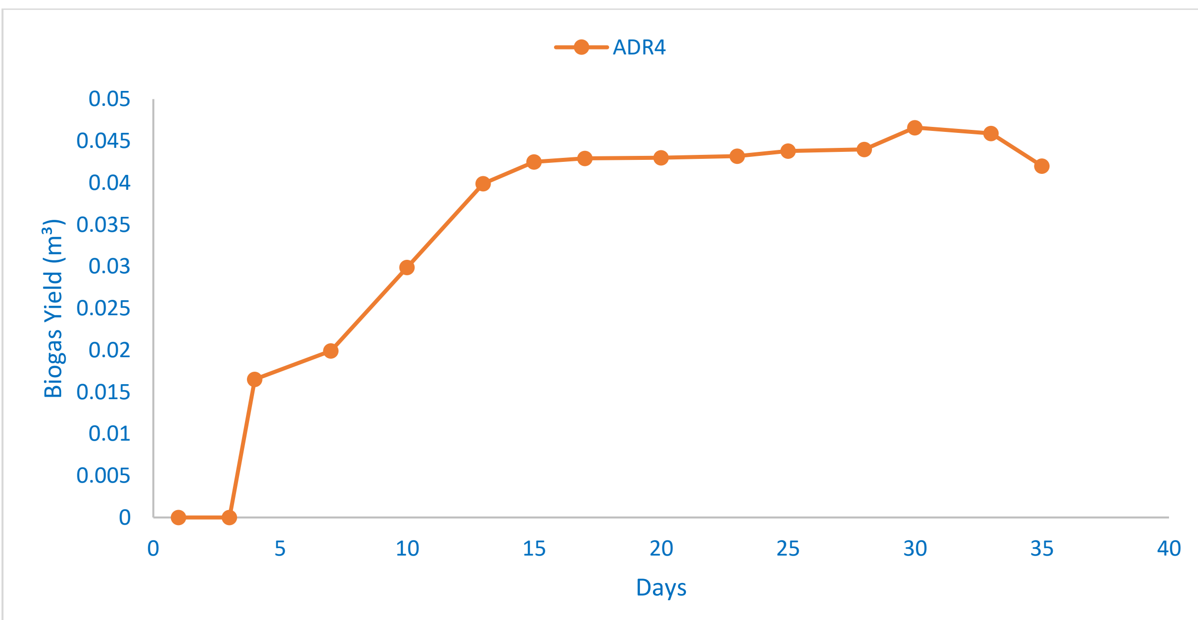

Figure 5 Graph of Biogas yield against number of days for co-digestion of feedstocks (25% CM and 75% FW)

Figure 6 depicts the results of the co-digestion of 20kg of feedstocks (35% CM and 65% FW; ADR5). Biogas yield began on the fourth day and concluded on the 33rd day, which is faster than ADR1, ADR3, and ADR4, but slower than ADR2, which only contains CM. The speedier completion of the procedure in ADR5 is attributed to the 35% CM, as opposed to 15% in ADR3 and 25% in ADR4. Similarly, the best biogas yield was produced on the 29th day, with a value of 0.043 m3. This figure was more than ADRs 1 and 2, but less than ADRs 3 and 4. Figure 7 depicts the findings of a comparative investigation of all digested and co-digested feedstocks (ADR1, ADR2, ADR3, ADR4, and ADR5).

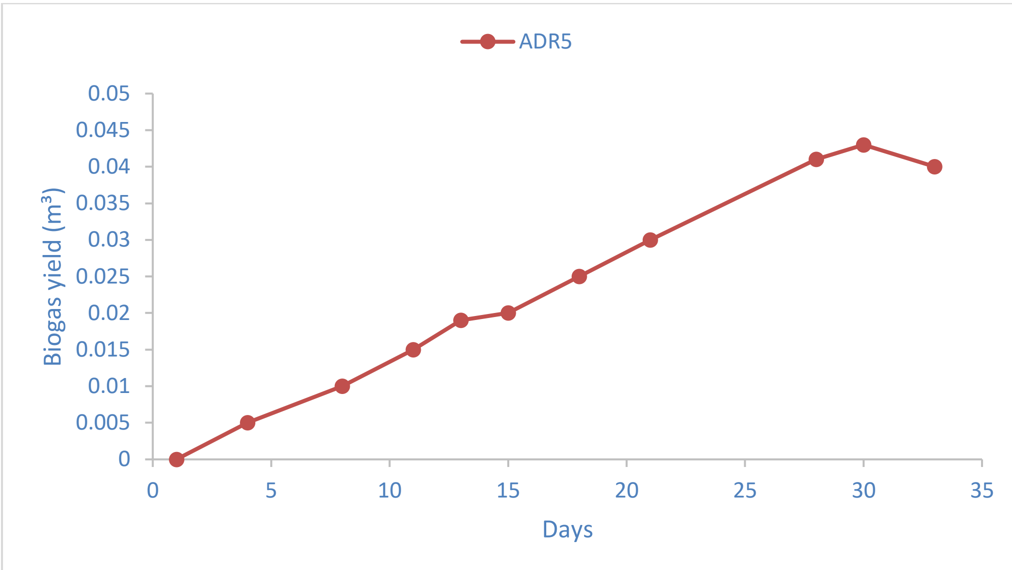

Figure 6 Graph of Biogas yield against number of days for co-digestion of feedstocks (35% CM and 65% FW)

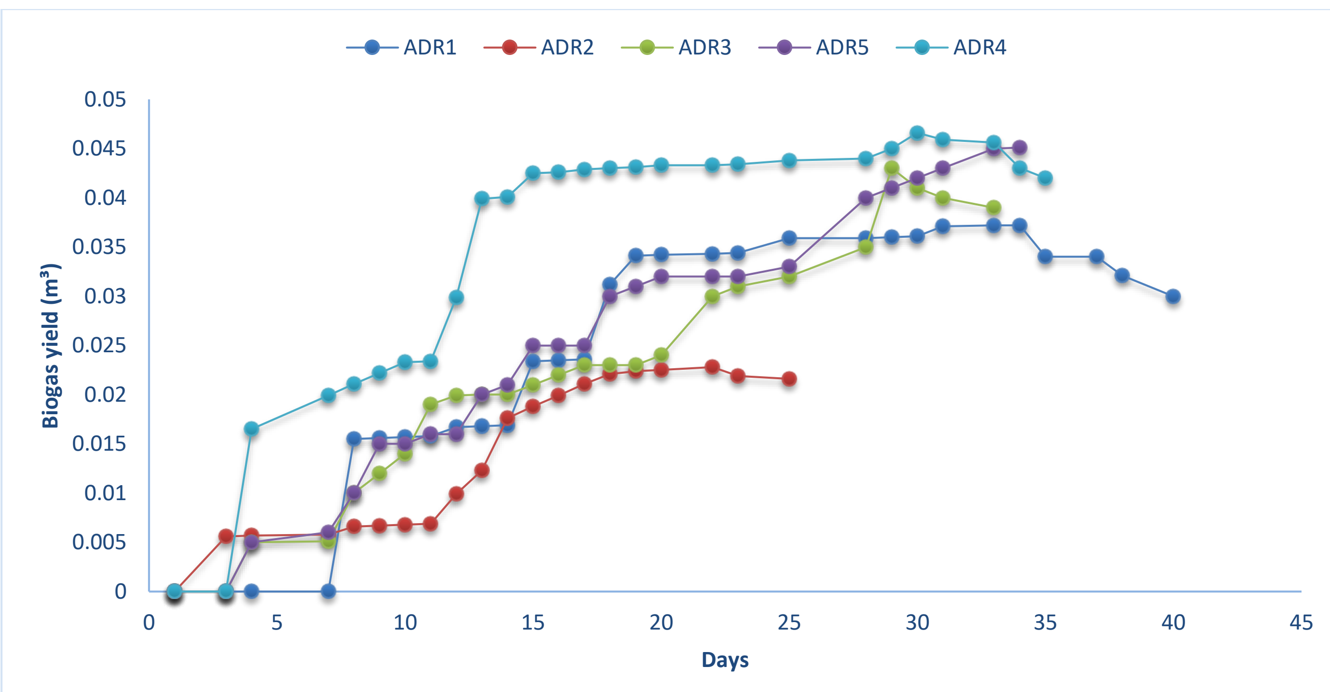

Figure 7 Graph of biogas yield against number of days for all digested and co-digested feedstocks (i.e., ADR1, ADR2, ADR3, ADR4, and ADR5)

According to the analysis of the results, co-digestion of CM and FW feedstock resulted in an optimal increased biogas generation. However, the ADR4 fed with a feedstock combination of 25% CM and 75% FW produced the highest cumulative biogas yield as shown in Figure 8, which was consistent with the findings of (Fu et al., 2022).

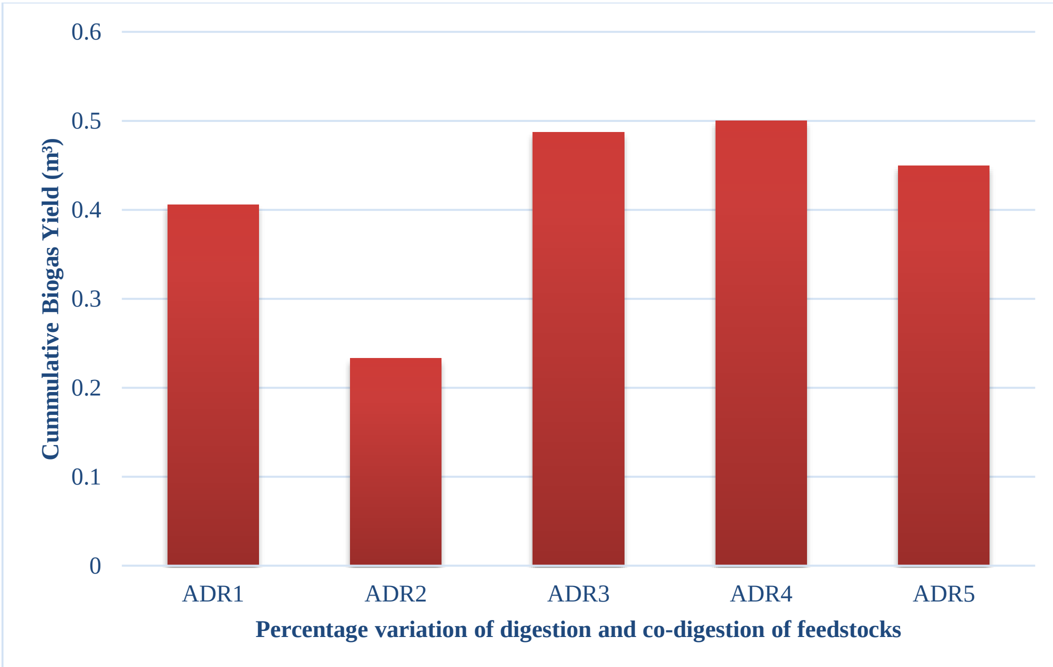

Figure 8 Comparative analysis of cumulative biogas yield.

4. CONCLUSION

The percentage variation of co-digestion of 25% CM to 75% FW, as opposed to the percentage variation of co-digestion of 15% CM to 85% FW and the percentage variation of co-digestion of 35% CM to 65% FW, resulted in the highest biogas yield. Above and beyond, ADR4 had the highest cumulative biogas yield when compared to ADR1, ADR2, ADR3, and ADR5. This confirms that if CM is to be co-digested with FW, the ratio should be 25% to 75%. Co-digestion will also be required to improve and accelerate the digestion process, resulting in a shorter hydraulic retention time. This study has shown that when FW is co-digested with CW, the process is finished in the quickest amount of time possible.

Author Contributions

Authors contributed equally in every section of the study.

Informed consent

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

Ethical approval

Not applicable.

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Data and materials availability

All data associated with this study are present in the paper.

REFERENCES

1. Abanades S, Abbaspour H, Ahmadi A, Das B, Ehyaei MA, Esmaeilion F, El-Haj-Assad M, Hajilounezhad T, Jamali DH, Hmida A, Ozgoli HA, Safari S, AlShabi M, Bani-Hani EH. A critical review of biogas production and usage with legislations framework across the globe. Int J Environ Sci Technol (Tehran) 2022; 19(4):3377-3400. doi: 10.1007/s13762-021-03301-6
2. Achinas S, Achinas V, Euverink GJW. A technological overview of biogas production from biowaste. Eng 2017; 3(3): 299–307. doi: 10.1016/J.ENG.2017.03.002
3. Akbulut A, Arslan O, Arat H, Erbas O. Important aspects for the planning of biogas energy plants: Malatya case study. Case Stud Therm Eng 2021; 26:101076. doi: 10.1016/j.csite.2021.101076
4. Alvarez-Chavez BJ, Godbout S, Palacios-Rios JH, Le-Roux É, Raghavan V. Physical, chemical, thermal and biological pretreatment technologies in fast pyrolysis to maximize bio-oil quality: A critical review. Biomass Bioenergy 2019; 128: 105333. doi: 10.1016/j.biombioe.2019.105333
5. Azam A, Rafiq M, Shafique M, Yuan J. Renewable electricity generation and economic growth nexus in developing countries: An ARDL approach. Economic Research-Ekonomska Istraživanja 2021; 34(1):2423–2446. doi: 10.1080/1331677X.2020.1865180
6. Barragán-Escandón A, Olmedo-Ruiz JM, Curillo-Tigre JD, Zalamea-León EF. Assessment of power generation using biogas from landfills in an equatorial tropical context. Sustainability 2020; 12(7):2669. doi: 10.3390/su12072669
7. Barua VB, Rathore V, Kalamdhad AS. Anaerobic co-digestion of water hyacinth and banana peels with and without thermal pretreatment. Renew Energy 2019; 134:103–112. doi: 10.1016/j.renene.2018.11.018
8. Bharathiraja B, Sudharsana T, Jayamuthunagai J, Praveenkumar R, Chozhavendhan S, Iyyappan J. Biogas production–A review on composition, fuel properties, feed stock and principles of anaerobic digestion. Renew Sustain Energy Rev 2018; 90:570–582. doi: 10.1016/j.rser.2018.03.093
9. Carlini M. Beer spent grains biomass for biogas production: Characterization and anaerobic digestion-oriented pre-treatments. Energy Rep 2021; 7(Suppl 5):921–929. doi: 10.1016/j.egyr.2021.07.049
10. Čater M, Zorec M, Marinšek-Logar R. Methods for improving anaerobic lignocellulosic substrates degradation for enhanced biogas production. Springer Sci Rev 2014; 2(2):51–61. doi: 10.1007/s40362-014-0019-x
11. Das S, Sherpa MT, Najar IN, Thakur N. Biomethane. Environ Sustain 2020; 3(4):453. doi: 10.1007/978-981-13-8307-6_5
12. Ebunilo PO, Aliu SA, Orhorhoro EK. Comparative Analysis of Biogas Yield from Different Composition of Domestic Wastes from Benin City, Nigeria. J Adv Appl Sci 2015; 4(5):169-177.
13. Ebunilo PO, Orhorhoro EK, Adegbayi OA. Investigation of the purification of biogas from domestic wastes using local materials in Nigeria. Int J Sci Eng Res 2016a; 7(2):505–515.
14. Ebunilo PO, Orhorhoro EK, Oboh V, Onochie PU. Effect of Temperature on Biogas Yields Using South-South Nigeria as a Case Study. Int J Technol Enhancements Emerg Eng Res 2016b; 4(3):50-54.
15. Fathya S, Assia K, Hamza M. Influence of inoculums/substrate ratios (ISRs) on the mesophilic anaerobic digestion of slaughterhouse waste in batch mode: Process stability and biogas production. Energy Procedia 2014; 50:57–63. doi: 10.1016/j.egypro.2014.06.007
16. Frauke PCM, Gerd-Christian M, Wolfgan B. Effects of Biogas Substrate Recirculation on Methane Yield and Efficiency of a Liquid-Manure-Based Biogas Plant. Energies 2017; 10(3):1-11. doi: 10.3390/en10030325
17. Fu R, Zhang Y, Yang X, Chen W. Study on biogas production from corn straw pretreated by compound microorganisms. Energy Rep 2022; 8:279–285. doi: 10.1016/j.egyr.2022.05.068
18. Gürsan C, De-Gooyert V. The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition. Renew Sustain Energy Rev 2021; 138:110552. doi: 10.1016/j.rser.2020.110552
19. Harpreet S, Tejas P, Aditya K, Sumit T. Recent advances in biogas production using various bio-waste's and its potential application: An overview. Mater Today Proc 2023. doi: 10.1016/j.matpr.2023.04.484
20. Ingabire H, Twizerimana M, M'Arimi MM. Effect of co-digestion with water hyacinth, inoculum concentration and dilution on biogas production of fish waste. Energy Rep 2023; 9:286–290. doi: 10.1016/j.egyr.2023.05.072

21. Kabeyi MJB, Oludolapo OA. Characteristics and applications of geothermal wellhead powerplants in electricity generation. 31ST Annual Southern African Institution for Industrial Engineering Conference, 2020; 4422.
22. Kainthola J, Kalamdhad AS, Goud VV. A review on enhanced biogas production from anaerobic digestion of lignocellulosic biomass by different enhancement techniques. Process Biochem 2019; 84:81–90. doi: 10.1016/j.procbio.2019.05.023
23. Krupin V, Wąs A, Sulewski P, Popadynets N, Malak-Rawlikowska A, Szymańska M, Skorokhod I, Wysokiński M. The potential of agricultural biogas production in Ukraine-impact on GHG emissions and energy production. Energies 2020; 13(21):5755. doi: 10.3390/en13215755
24. Kumar R, Jilte R, Ahmadi MH. Electricity alternative for e-rickshaws: an approach towards green city. Int J Intell Enterp 2018; 5(4):333–344.
25. Machado PG, Teixeira ACR, Collaço FMA, Mouette D. Review of life cycle greenhouse gases, air pollutant emissions and costs of road medium and heavy-duty trucks. WIREs Energy Environ 2021; 10(4). doi: 10.1002/wene.395
26. Mohammad M, Mohamad-Ishak WW, Mustapa SI, Ayodele BV. Natural gas as a key alternative energy source in sustainable renewable energy transition: a mini-review. Front Energy Res 2021; 9. doi: 10.3389/fenrg.2021.625023
27. Moreau V, Vuille F. Decoupling energy use and economic growth: Counter evidence from structural effects and embodied energy in trade. Appl Energy 2018; 215:54–62. doi: 10.1016/j.apenergy.2018.01.044
28. Mata-Alvarez J, Dosta J, Romero-Güiza MS, Fonoll X, Peces M, Astals S. A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renew Sustain Energy Rev 2014, 36:412–427. doi: 10.1016/j.rser.2014.04.039
29. Mudzanani K, Iyuke SE, Daramola MO. Co-digestion of wastewater treatment sewage sludge with various biowastes: A comparative study for the enhancement of biogas production. Mater Today Proc 2022; 65(4). doi: 10.1016/j.matpr.2022.05.539
30. Nganyira PD, Shao GN, Emmanuel JK. Evaluating the potential applications of brewers' spent grain in biogas generation. food and biotechnology industry: A review. Heliyon 2022; 8(12):e11140. doi: 10.1016/j.heliyon.2022.e11140
31. Nimas MSS, Minming Z, Zhezi Z, Dongke Z. Effect of Biochar Addition and Initial pH on Hydrogen Production from the First Phase of Two-Phase Anaerobic Digestion of Carbohydrate Food Waste. Energy Procedia 2017; 105:379-384. doi: 10.1016/j.egypro.2017.03.329
32. Orhorhoro EK, Ebunilo PB, Sadjere EG. Effect of Organic Loading Rate (OLR) on Biogas Yield Using a Single and Three-Stages Continuous Anaerobic Digestion Reactors. Int J Eng Res Afr 2017; 39:147-155.
33. Orhorhoro EK, Erameh AA, Lindsay EE. A Comprehensive Review on Anaerobic Digestion Plant. Nigerian J Eng Sci Res 2019; 2(1):13-28.
34. Orhorhoro EK, Lindsay EE, Oyejide JO. Analysis and Evaluation of a Three-Stage Anaerobic Digestion Plant for Management of Biodegradable Municipal Solid Waste. Int J Eng Res Afr 2022; 60:75-87. doi: 10.4028/p-a24obb
35. Orhorhoro EK, Oghoghorie O. Assessment of Physicochemical Properties of Municipal Solid Waste Leachate from Dumpsites in Ovia North-East Local Government Area, Nigeria. J Energy Technol Environ 2023; 5 (4):9-18.
36. Orhorhoro EK, Oghoghorie O. Enhancing biogas yield through anaerobic co-digestion of animal manure and seaweed. Prog Energy Environ 2024; 28:1-22. doi: 10.37934/progee.28.1.122
37. Ouahabi YR, Bensadok K, Ouahabi A. Optimization of the Biomethane Production Process by Anaerobic Digestion of Wheat Straw Using Chemical Pretreatments Coupled with Ultrasonic Disintegration. Sustainability 2021; 13(13):7202. doi: 10.3390/su13137202
38. Paramagurua G, Kannanb M, Lawrencec P. Effect of pH on Biogas Production through Anaerobic Digestion of Food Waste. J Adv Eng Res 2017; 4(1):59-62.
39. Pasternak P. Chapter 9- Electrochemical approach for biogas upgrading. Emerging Technologies and Biological Systems for Biogas Upgrading, N Aryal, LDM Ottosen, MVW Kofoed, and D Pant, Eds. Academic Press 2021; 223–254.
40. Pellera FM, Gidarakos E. Microwave pretreatment of lignocellulosic agroindustrial waste for methane production. J Environ Chem Eng 2017; 5(1):352–365. doi: 10.1016/j.jece.2016.12.009
41. Prussi M, Padella M, Conton M, Postma ED, Lonza L. Review of technologies for biomethane production and assessment of Eu transport share in 2030. Clean Prod 2019; 222:565-572. doi: 10.1016/j.jclepro.2019.02.271
42. Sarkar S, Hossain A, Skalicky M, Brestic M, Saha S, Garai S, Ray K, Brahmachari K. Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability 2020; 12(23):9808. doi: 10.3390/su12239808
43. Szaja A, Montusiewicz A, Lebiocka M, Bis M. The effect of brewery spent grain application on biogas yields and kinetics

in co-digestion with sewage sludge. PeerJ 2020; 8:e10590. doi: 10.7717/peerj.10590

44. Tanimu MI, Ghazi TIM, Harun RM, Adris I. Effect of Carbon to Nitrogen ratio of food waste on biogas methane production in a batch mesophilic anaerobic digester food waste. Int J Chem Environ Eng 2014; 5:39–44.
45. Xie S, Higgins MJ, Bustamante H, Galway B, Nghiem LD. Current status and perspectives on anaerobic co-digestion and associated downstream processes. Environ Sci Water Res Technol 2018; 4(11):1759–1770.