IJABR Vol. 17 (1): 161 - 170 (2026)

Original Article

Thermophillic anaerobic digestion of bovine biomass and fruit waste for an improved methane generation, biodegradability and digestate quality

***[1]Haruna, M., [1]Alfa, A. Y., [1]Usman, S. B. and [2]Abubakar, Y. D.**

[1]Chemical Engineering Department, Federal Polytechnic, Bida.
[2]Biological Sciences Department, Federal Polytechnic, Bida.

Submitted: January 2026; Accepted: April 2026; Published: June 2026

ABSTRACT

The increasing cost of fossil fuel combined with the adverse environmental impact of global warming and exhaust emissions, has heightened interest in alternative energy sources. Among these alternatives suggested bio-methane production from biomass has shown considerable promise. This study evaluated the thermophilic anaerobic digestion of cow dung (C/D) and fruit waste (F/W) to determine methane yield, substrates biodegradability, and residual quality to propose optimal operating condition. A batch anaerobic digestion was conducted in two 120-litre polyethylene tanks at 40 – 56^{o}C temperature using substrate with initial COD and BOD of 52,000 mg/L and 20,000 mg/L for C/D and 57,000 mg/L and 23,000 mg/L for F/W respectively. Ultimate analysis was performed before and after the digestion to know the elemental changes. The produced bio-methane was measured by water displacement and converted to volume using biogas density of 1.08 g/L for 60% CH_4 at 30^{o}C. Both substrates show high degradability with BOD/COD ratios of 0.38 for C/D and 0.40 for fruit waste. Maximum bio-methane yield of 30.43 mL/gVS was obtained for C/D at 43.0^{o}C while F/W yielded 25.2mL/gVS at 55 ^{o}C. Yields reduce by 33% for C/D and 25% for F/W due to thermophilic enzymes destruction at elevated temperature. The ultimate analysis revealed carbon reduction of 28.9% for cow dung and 36.3% for fruit waste, confirming its conversion to methane and other gases. Fruit waste exhibited higher biodegradability and higher methane yield at 52.5^{o}C, while cow dung shows greater process stability across the temperature range of 50–53^{o}C beyond which the yield declined significantly. These findings support the valorization of these agro-wastes for renewable energy and nutrient recovery purposes.

Keywords: bio-methane, thermophilic, anaerobic digestion, biodegradability, valorization.

***Corresponding author's email**: mtharuna05@gmail.com, 08039724055

INTRODUCTION

The escalating demand for energy and power has increased concurrently with global population growth [1] and the rapid depletion of non-renewable energy sources, coupled with their associated emissions, present a serious threat to environmental sustainability. In recent times researchers focused on developing alternative energy generation methods to meet up with daily energy requirement [2]. There were assertions that bio methane derived from biological matter could offer viable solution to the menace [3]. Biological matter encompasses all plant and animal residues, measurable in fresh or dry weight, such as dry foliage, timber, excrement, combustible oils, and fats from living organisms [4]. These renewable energy sources produce electricity and heat [5;6]. General trend of mismanaging biomass, agricultural waste, and organic effluents in most of the developing countries of the world pose environmental risks to the living [7].

Biogas has been an eco-friendly fuel derived from biological resources have garnered attention as alternative these days. Decomposing organic materials via anaerobic digestion yields biogas, a green energy resources reach in bio methane [8; 36]. Bio methane obtained from anaerobic digestion has 37.3MJ/m[3] energy content, 6 -12% explosion limits, 650-750°C ignition temperature, 0.847-1.004 specific gravity, and 4740-7500Kcal/NM[3] calorific value [10].

Biomass-based energy is renewable, cleaner, and minimizes organic waste pollution [4]. The technology which converts waste into energy, provides economic benefits, environmental sustainability, and nutrient-rich fertilizer for agricultural applications [12]. Bio methane gas originates from anaerobic microbial degradation of organic materials [13]. Anaerobic digestion involves four basic steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [36].

1. Hydrolysis

$$(C_6H_{10}O_5)_n + H_2O \longrightarrow n(C_6H_{12}O_6) \quad (1)$$

Complex carbohydrate Simple Sugar

2. Acidification

$$C_6H_{12}O_6) \xrightarrow{\text{Acetobacter}} 3(CH_3COOH) \quad (2)$$

3. Methanation

$$3(CH_3COOH) \xrightarrow{\text{Methanogens}} CH_4\,(g) + CO_2\,(g) \quad (3)$$

The third stage can be achieved in two ways:

$$CO_2\,(g) + 4H_2\,(g) \xrightarrow{\text{Reduction}} CH_4 + H_2O \quad (4)$$

$$3(CH_3COOH) \xrightarrow{\text{Methanogens}} CH_4 + CO_2 + \text{other gases} + \text{Residue} \quad (5)$$

Upgrading the raw biogas to bio-methane call for more attention in recent times [14]. The International Energy Agency, projects that biogas and bio methane could reach supply of nearly 1,500TWh by 2030 under a net zero scenario, representing almost fourfold increase from about 400TWh in 2000 [15]. Similarly, the World Biogas Association projects 1,000TWh by 2030 with appropriate government policy in place and needed investment support [16].

Energy production underpins human development, productivity and economic growth [9; 22]. Renewable energy sources include hydro, geothermal, solar, wind, ocean, and bioenergy [18]. Despite abundant untapped organic waste potentials, many developing countries such as Nigeria have yet to fully exploit the benefit in biogas technology [20]. The benefits derived include high calorific value and its suitability for heat and electricity generation [21] purified biogas can also serve as a supplement to or substitute for, natural gas as a vehicular fuel [9].

Cow dung can be defined as undigested residue of consumed food material being excreted by herbivorous bovine animal species. Being a mixture of feces and urine in the ratio of 3:1, it mainly consists of lignin, cellulose and hemicelluloses. It is a lignocellulosic biomass rich in organic matter, containing cellulose, hemicellulose, lignin and microbial biomass, which makes it suitable substrate for anaerobic digestion [26]. The cow dung wet basis it contains 80 – 85% moisture, while the dy matter comprises of approximately 38 – 42% carbon, 1.0 -2.5% nitrogen, and 12 -25 ash [36]. Its carbon to nitrogen ratio C/N of 18 – 25:1 favors digestion and high content of methanogenic bacteria. Cow dung seves as an effective inoculum and primary feedstock for biogas production [22]. It also contains 24 different minerals like nitrogen, potassium, along with trace amount of Sulphur, iron, magnesium, copper, cobalt and manganese [23].

Fruit waste refers to the biodegradable organic materials discarded during harvesting, processing, distribution and consumption of fruits, including peels, pulp, seeds, pumice, and overripe or damage whole fruits [24]. It is known by high moisture content of 75 – 90% high volatile solids, and already fermentable carbohydrates but has low C/N ratio of 15 – 35:1 and pH of 3 – 5 due to organic matter that is present [25]. Common examples include orange peels, pineapple peels, banana peels and mango waste, that are usually generated from market and juice processing plant. High biodegradable fruit waste often requires co-digestion with nitrogen rich or buffering substrate like cow dung to prevent acidification during anaerobic digestion [26].

Cow dung and fruit waste that are discharged in an open dump, decomposes and releases methane which is 28 times more potent than carbon dioxide [6]. Anaerobic digestion captures this methane as biogas instead of releasing it to environment. It can also provide lightning and cooking fuel. Biogas production from cow dung and fruit waste addresses most of the energy challenges, thereby reducing environmental pollution and generating nutrient rich fertilizer, contributing to sustainable waste management and rural development [26].

MATERIALS AND METHODS

Digester setup

This study employed batch digestion process, in which a 120L polyethylene terephthalate (PET) digester was fabricated to allow easy feeding of the substrates into digestion chamber. The digester was fitted with a gas outlet port at the top and another separate port for thermometer where digester temperature is monitored. The two substrates were subjected to Biochemical Oxygen Demand BOD and Chemical Oxygen Demand COD and Ultimate analysis for discharge into the digester. The fresh cow dung (25 kg) obtained from a slaughterhouse in Bida, Local Government Area of Niger State, and fruit waste also sourced from Bida market. Each substrate was mixed with 25 liters of water to produce homogenous slurry after pretreatment. Each digester was filled to 75% capacity to maintain headspace for gas accumulation. The gas was collected from the digesters through a flexible hose connected from the top to gas collection bags. The gas produced was then channeled in series to 1 liter scrubber filled with water for carbon dioxide removal followed by an iron sponge column for hydrogen sulfide removal before it was passed to water displacement unit where the upgraded gas was measured through inverted 1000-mL measuring cylinder. The volume was correlated to standard temperature and pressure (STP: 0^oC, 1atm) and expressed as mL/gVS added [6].

Sample analysis

The Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) analysis were carried out on the substrate before and after while the quantity of the produced bio-methane was measured through inverted cylinder after the biogas upgrading. This was carried out at Civil Engineering Water Laboratory, Federal Polytechnic, Bida.

Determination of Biochemical oxygen demand

Biochemical oxygen demand (BOD) was used to measure how much oxygen the bacteria need to break down organic matter. According to APHA Standard method 5210B [27] fresh cow dung and fruit waste were homogenized separately with distilled water at ratio of 1:100 and 1:50w/v, respectively. They were filtered through a 2mm sieve to obtain stock suspensions. The stock was serially diluted with aerated dilution water containing nutrient buffer and microbial seed to achieve target dissolved oxygen depletion of 2 – 7 mg/L. the diluted sample were incubated in 300mL BOD bottles at 20±1°C for 5 days. Initials and final dissolve oxygen concentrations were measured using a calibrated DO meter (model Pro20). BOD was calculated after correcting for blank depletion. All analyses were performed in triplicate [25].

Determination of Chemical Oxygen Demand

Chemical oxygen demand (COD) was determined by the close reflux colorimetric method (APHA 5220 D, 2017). Aliquots of 2.0 mL diluted sample were oxidized with potassium dichromate in concentrated sulfuric acid containing silver sulfate catalyst and mercury sulfate at 150°C for 2h. After cooling, absorbance was measured at 600nm using a UV-Vis spectrophotometer (Model UV-1800). The COD values were obtained from calibration curve prepared in potassium hydrogen phosphate standards (0 – 1500mL). The samples with COD exceeding 900mg/L were diluted before digestion [34].

Daily monitoring of operational temperature

In order to study and determine the most feasible local environment conditions to optimally operate the developed biogas facilities, various physical and chemical parameters were monitored to check the status of the digester. Readings were taken daily of ambient and digester temperature. The temperature inside the digester changed in response to change in the ambient temperature. The average temperature found inside and outside the digester was about (40^0C) and (55^0C) respectively [2

5].

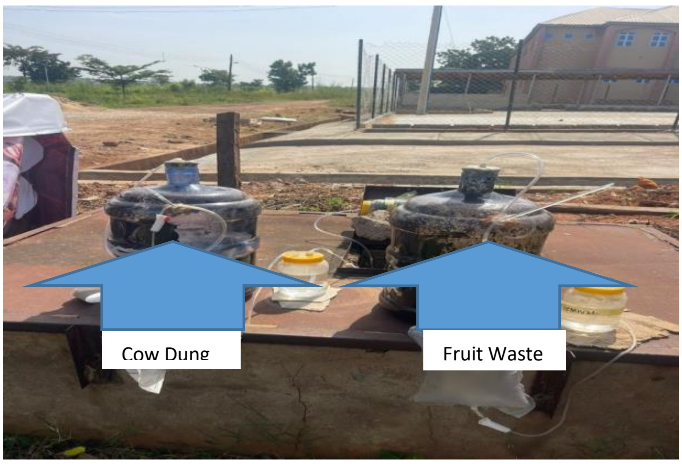

Plate 1 Experimental set up

RESULTS AND DISCUSSION

Biochemical Oxygen Demand and Chemical Oxygen Demand.

Table 1: BOD and COD of cow dung and fruit waste

Substrate	BOD (mg/L)	COD (mg/L)	BOD/COD
Cow dung	20,000	52,000	0.38
Fruit waste	23,000	57,000	0.40

Each substrate shows high organic strength, with COD values of 52,000mg/L for cow dung and 57,000 for fruit waste. These values are consistent with the high organic load that is typical of agricultural food waste [35]. The COD of fruit waste was 9.6% higher than that of cow dung, indicating a greater total organic content. This was attributed to high carbohydrate and sugar content in fruit waste, which contributed to high chemical oxidation demand [28]. In the other hand the BOD values of 20,000 mg/L and 23,000mg/L obtained for cow dung and fruit waste confirm that the two substrate contain substantial biodegradable fractions of components suitable for anaerobic digestion.

Ultimate analysis of cow dung before and after anaerobic digestion.

The elemental analysis of cow dung substrate and the digestate on a dry basis is presented in Figure 1. Anaerobic digestion was carried out for 30 days which caused changes in the ultimate composition of the sample, showing evidence for microbial degradation of organic fraction of the used cow dung.

Figure 1: Ultimate analysis of cow dung and fruit waste before and after digestion

Carbon and hydrogen depletion

The carbon content of organic biomass is critical, determining its potential as substrate for biogas production. Carbon directly influences the amount of organic material available for microbial breakdown during anaerobic digestion. There was a substantial reduction in carbon (44.4%) and 36.3% for cow dung and fruit, at the same times hydrogen decreased by (46.7%) and 25.0% for the two substrates. This observed reduction after digestion falls in line with the report of [26]. This is an indication that, effective conversion of organic carbon and hydrogen into gaseous products, primarily CH_4 and CO_2 during methanogenesis [29;18]. The degree of carbon removal was in line with volatile solid destruction rate of 40 - 45% reported for cattle manure under mesophilic batch conditions [30]. The initial high carbon content of 45.5% indicates carbohydrate rich nature of the substrates while the decline in both H and C notice confirms that carbohydrate, protein, and lipid fractions were hydrolyzed and utilized by the microbial consortium.

Nitrogen, Sulfur and Ash Enrichment

The relative increase in nitrogen of 116.7% and 122.2%, sulfur 50.0%, 68.0% and ash 66.7%, 112% for the cow dung and fruit waste respectively. As C and H in the two substrates were volatilized as biogas, non-degradable inorganic constituents and mineralized nitrogen were retained and enrichment in the digestate occur [28]. The elevated nitrogen content enhances the fertilizer potentials of the digestate, while the increase in ash reflects mineralization of the organic matrix. The rise in sulfur content from 0.4 to 0.6% suggested the potentials for H_2S formation, necessitating gas cleaning prior to use. However, the elevated sulfur level require incorporation of H_2S scrubbing unit that will remove corrosive substances and also remove odor. Sulphur, though present in small quantity, plays a significant role in biogas production process. However, excessive sulphur can lead to the formation of hydrogen sulphide (H_2S), a toxic and corrosive gas that can negatively affect the quality of the biogas produced.

C/N Ratio and Substrate Stability

The laboratory recommended C/N ratio is between 20 - 30:1 as optimum, computation from the ultimate analysis here gave 20.7:1 and 9.6:1 for the substrate and digestate, respectively. The initial ratio of 20.7 fall within the recommended optimum range of 20 – 30:1 for anaerobic digestion [31], indicating nitrogen limitation during start up [9]. The decrease to 9.6 on the post-digested substrate signifies preferential consumption of relative to nitrogen and suggests a well stabilized digestate. C/N ratios below 15 are considered agronomically stable and unlikely to induce soil nitrogen immobilization [32]. The resultant lower C/N ratio and enriched N and mineral content is more suitable for soil amendment than raw cow dung when applied as fertilizer.

The C/N ratio for fruit waste decreases from 28.4 to 10.7 these falls below the optimum, but within the range good for soil application. The reduction here was an indication that the digestate will be suitable for agricultural applications. The final ratio of C/N also predicted reduction in risk of nitrogen immobilization when applied to soil. This reduction in C and H and increase N observed in fruit waste, suggest that it is highly biodegradable under this temperature.

Oxygen Content

Oxygen content decreased by 10.3% corresponding to its incorporation into CO_2 and metabolic water H_2O during anaerobic oxidation processes. The sum of which constitutes the constituents found in the digestate sample. In this case it shows a modest decline from 31.2% to 28.0%, reflecting its contribution in CO_2 and water as metabolic by-products formed. For fruit waste the oxygen content decreased from 43.2% to 33.0% during hydrolysis and methanogenesis where the ash content doubled from 8% to 17% an indication that organic matters are not degraded and became concentrated in the residue [32; 30]. Oxygen removal was greater in fruit waste, which decreased from 43.2% to 33.0% (-23.6%) compared to cow dung that was only decreased from 31.2% to 28.0%, (-10.3%), indicating more extensive breakdown of oxygen-rich organic compounds during hydrolysis and methanogenesis of both the fruit waste and cow dung as they are converted to biogas.

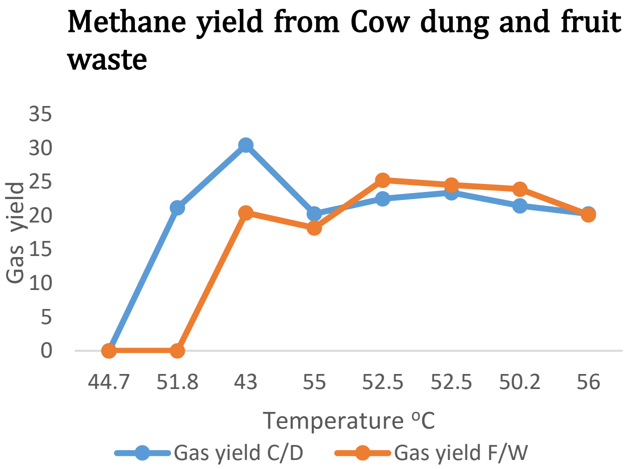

Figure 2: Effect of digester temperature on methane

The result of digester temperature and methane yield are presented in figure 2 above. It was evidenced from it that temperature significantly affects methane yield during thermophilic anaerobic digestion, with optimal performance observed at 43 °C. The inverse relation and bio-methane yield indicates that thermophilic digestion is most efficient under 55 °C for cow dung substrate. The microbes are inhibited above 55°C because of denaturation. It was evidence that the yield drops from 30.42mL/gVS at 43 °C to 20.25mL/gVS at 55 °C confirming the upper temperature limit for this substrate. High temperature increases hydrolysis rate, but methanogens cannot keep up at temperature above 55°C. This is because of volatile fatty acid (VFA) accumulation, which lead to a drop in pH that will further inhibit methanogens [28] in batch system this is compounded by lack of buffering. The 33% yield drop observed is consistent with the 30 – 40% reduction reported by [33] for temperature above 55°C for cattle manure. The greater oxygen removal observed in fruit waste (-23.6%) compared to (-10.3%) for cow dung, indicates more extensive conversion of oxygenated organic matter into biogas. This higher loss of oxygen rich functional group during hydrolysis and methanogenesis correspond directly to the higher methane yield from fruit waste, as degradable substances were transformed into methane and carbon dioxide [34].

CONCLUSION

This study evaluated the effect of thermophilic anaerobic digestion of bovine and fruit waste biomass for sustainable biogas production, with emphasis on methane yield, substrate biodegradability and digestate quality. Each substrate shows significant methane production under thermophilic conditions. The optimum temperature for cow dung was 43°C yielding 30.43mL/gVS while fruit waste had maximum yield of 25.2mL/gVS at 55.0 °C. The decline of 33% in yield observed at 56.0 °C is attributed to enzyme denaturation of thermophilic methanogenic microbes above 55 °C [28]. In conclusion, the two substrates are viable feedstock for thermophilic anaerobic digestion and subsequent digestate valorization. Fruit waste offers higher methane potentials per unit mass, while cow dung provides more of process stability. The study shows that anaerobic digestion effectively reduces organic matter by converting into renewable energy and nutrient rich residual, supporting sustainable waste management and energy recovery. These could be a breakthrough for cleaner energy, reduced emissions, and a healthier planet.

REFERENCES

1. Chaiprasert P. (2011). Biogas production from agricultural wastes in Thailand. *Journal of*

sustainable energy and environment. P. 63 – 65.

2. Rai M, Da Silva SS., (2017). Nanotechnology for Bioenergy and Biofuel production. Green chemistry and sustainable technology. Cham, *Scotland; springer*; 2017. Available from; https://doi.org/10.1007/978 - 3 - 319 – 45459 -7.
3. Maciejewska A, Veringa H, Sanders J, Peteves S.D., (2006). Co-firing of Biogas with coal: constraints and Role of Biomass pre – treatment, *DG JRG institute for energy report,* Eur 22461 EN; 2006.
4. Dubey, R.C (2012). A Textbook of Biotechnology. S. Chand and Company Ltd. New Delhi Energy 84: 664- 670.
5. Vanloo S, Koppen J., (2008). The handbook of biomass combustion and coffering. London; earth scan; 2008.
6. Lee S, Shah Y. T. (2013). Biofuels and Biogas; process and Technologies. Boca Raton FL: CRC Press; 2013. Pp.10-20.
7. Panwar, N. L, Kaushik SC, Kothari, S., (2011). Role of renewable energy sources in enivoronmental protection: A review. *Renewable and Sustainable energy reviews*. 2011:15(3):1513 – 1524.
8. Demirbas A., (2010). Methane Gas Hydrate: as a natural gas source. In: Methane gas hydrate. *Green Energy and Technology*. 1st ed. London. Springer.
9. Orlygosson, J., (2020). Anaerobic digestion of organic waste for biogas production: A review of thermophilic processes. *Review in environmental Science and Bio/Technology, 19(4), 723 – 742.*
10. Sakhawat A, Naseem Z, Zahida N, Shumaila U., (2013). Impact of Biogas technology in the development of rural population. *Pakistan Journal of analytical and environmental chemistry.* 2013; 14(2):65 – 74.
11. Angelidaki, I., Treu, L., Campanaro S., & Kougias, P. G. (2003). Anaeobic dogestioon recent advances and future perspectives. *Bioresource Technology* 382, 1291829.
12. Aghar, M., & Anwar, S. (2011). Biogas production from co-digestion of cow dung and fruit waste. *International Journal of Environmental Science and Development*, 2_ (3), 182 -185.
13. Biogas Digester. *International Journal of Applied Engineering and sciences.*
14. Sun, Y. (2015). Anaerobic digestion of agricultural wastes. *A review Renewable and Sustainable Energy Reviews,* 52, 1191-1202.
15. International Energy Agency (2022). *World energy outlook* 2022.IEA.
16. World Biogas Association. (2023) Global potential of biogas: Pathways to 2023. worldbiogasassociation.org
17. Owusu P. A, Asumadu-Sarkodie, S. (2016). A review of renewable energy resources, sustainability issues and climate change mitigation. *Cogent engineering*, 3(1): 1167990. Doi:10.1080/23311916.2016.1167990.
18. Balat, M., (2007). An overview of biofuels and policies in the Eurpean Union. *Energy sources, Part B*: economic,

Planning and Policy, 2(2), 167 - 181

19. Weiland, P. (2010). Biogas production: Current state and perspectives. *Applied Microbiology and Biotechnology,* 85(4), 849-860.
20. Igoni A. H., Ayotamuno M. J., Eze C. L., Ogaji S. O. T., & Probert S. D. (2008) Design of anaerobic digester for producing biogas from municipal solid waste. *Applied energy*, 85(6). 430 – 438.
21. Suyitno, S., Dharmalingam, S., & Zainal, Z. A. (2010). Production of biogas and performance of biogas stove. *Journal of Applied Science,* 10(12), 1168-1172.
22. Saggagi, B. S., Garba, B., & Usman, N. S. (2009). Studies on biogas production from fruit and vegetable waste. *Bayero Journal of Pure and Applied Sciences*, 2(1), 115 – 118.
23. Mohammed, S.H., (2015). Biogas Production from Cow Dung. http://khartoumspace.uofk.edu/hanle/ 123456789/14406. Retrieved 10th November, 2016.
24. Parawira, W., Murto M., Zvauya R., & Mattiasson B. (2004). Anaerobic batch digestion of solid potato waste alone and in combination with sugar beet leaves. *Renewable Enegy*, 29-(11),1811-1823
25. *Bouallagui, H., Tauhaami Y., Ben Chiekh, R., & Hamdi, M. (2005). Bioreactor Performance in anaerobic digestion of fruit and vegetable waste _Process biochemistry, 40_(3-4), 989 – 995.*
26. Iyagba E. T., Mangibo I. A., & Mohammad, Y. S. (2009). The study of cow dung as co-substrate with rice husk in biogas production. *Scientific Research and Essay*, 4-(9), 861 – 866.
27. American Public Health Association, American Water Works Association & Water Environment Federation. (2017). *Standard methods for the examination of water wastewater* (23rd ed.). American Public Health Association.
28. Meta-Alvarez, G., Macias-Corral, M., Oliva-Aviles, A., & Vela-Garduna, J. (2014). Anaerobic co-digestion of cow manure and fruit waste: effect of substrate ratio on biogas production. *Renewable Energy*, 71, 532-538.
29. Nasir, I. M., Ghazi T. I. M., & Omar, R. (2012). Production of biogas from solid organic waste via anaerobic digestion: A review. _*Applied Microbiology and Biotechnology*, 95_(2), 321-329.
30. Möller, K., & Müller, T. (2012). Biogas production from organic waste. *Waste Management & Research,* 30(1), 62-72.
31. Zhang, L., Lee, Y. W., & Jahng, D. (2013). Anaerobic co-digestion of food waste and sewage sludge: effect of substrate ratio on biogas production. *Bioresource Technology*, 134, 350-356.
32. Teglia, C., Tremier, A., & Martel, J. L.(2013). Characterization of solid digestates: Part review of existing indicator to assess solid digestates agricultural use. *Waste and Biomass Valorization,* 4_(1), 1-15.

33. Khalid, A., Arif, M., & Sadiq, M. B. (2011). Anaerobic digestion of cow dung: A review. Renewable and Sustainable Energy Reviews, 15(6), 3495-3503.
34. Li, Y., Park, S. Y., & Zhu, J. (2011). Solid state anaerobic digestion for methane production from organic waste._*Bioresource Technology*, 102_(10), 5927 – 5934. doi.org
35. Sevillano, C; Pesantes, A; Carpio, E. P; Martinez, E; Gomez, X. (2021). Anaerobic Digestion for Producing Renewable Energy – The Evolution of this Technology in a New Uncertain Scenario. *Entropy 2021*, 23, 145.
36. Ukpai P. A., & Nnabuchi, M. N., (2012). Comparative study of biogas production from cow dung and cassava peeling using 45 liters biogas digester. *Advances in Applied Science Research,* 3(3), 1864-1869.
37. Ngan N. V. C, Gummert M, Hung N, Chivenge P, Douthwaite B, (2020). Co-digestion approach for enhancement of biogas production by mixture of untreated napier grass and industrial hydrolyzed food waste. *Bioresourse Technology Reports*, 11, 100500.